Honduran Institute of Earth Sciences (IHCIT)
Civil Engineering Department

COMPENDIUM
2nd Central American and Caribbean Landslide Congress

July 18th- 20th, 2016 / 8:00 AM - 4:00 PM
Tegucigalpa, Honduras.

INFORMATION AND REGISTRATION
Email: ihcit@unah.edu.hn with copy to: le_torresb@yahoo.com
www.ihcit.unah.edu.hn
Call the phone number: 2235-3030

PARTICIPATING COUNTRIES

Germany-Colombia-Mexico-Guatemala-El Salvador-Honduras-Nicaragua-Costa Rica-Panama-Cuba-Japan

Earth science at the service of the community

ICL   JICA   FACULTAD DE INGENIERÍA UNAH   FACULTAD DE CIENCIAS UNAH   UNAH UNIVERSIDAD NACIONAL AUTÓNOMA DE HONDURAS

Special Issue:
Second Central American and Caribbean Landslide Congress
18-20 July 2016
Tegucigalpa, Honduras

Organizing Commite

LIDIA TORRES

ELIAS GARCIA-URQUIA

NELSON SEVILLA

Revision Commite

ELIAS GARCIA-URQUIA

LIDIA TORRES

TAKESHI KUWANO

TAKASHI HARA

SATORU TSUKAMOTO

ELISABETH ESPINOZA

OSCAR ELVIR

MARCIO ALVARADO

Editor

LAURA SALGADO

Acknowledgements

Contents

Preface: Landslide research experiences in the Central American and Caribbean region

Elias Garcia-Urquia, Lidia Torres, Takeshi Kuwano, Takashi Hara, Satoru Tsukamoto, Elisabeth Espinoza, Oscar Elvir, Marcio Alvarado

Abstract Tegucigalpa, Honduras was the venue of the of the 2nd Central American and Caribbean Landslide Congress, which was organized by the National Autonomous University of Honduras (UNAH) with the sponsorship of the Japan International Cooperation Agency (JICA). In the framework of this event, a group of researchers from Central America, the Caribbean, South America and Japan have shared their landslide experiences in order to disseminate the applicability of several methodologies for the assessment of landslide susceptibility, hazard and risk at various spatial scales. The event was ideal for the establishment of possible collaborations for the strengthening of the landslide research in the region. This introductory article summarizes the main findings of the research works presented in the event. The first part of this article provides a summary of the landslide studies promoted by JICA in Tegucigalpa. In the second part, important aspects of the landslide research in the Central American and Caribbean region are discussed.

Keywords landslides, Tegucigalpa, Honduras, Central America, Caribbean

Introduction

The Central American region is constantly being hit by hurricanes, tropical storms and earthquakes, which have triggered numerous landslide episodes throughout history. In October of 1998, Hurricane Mitch, considered to be one of the most devastating and deadliest hurricanes (ECLAC, 1999), triggered several hundred landslides in Honduras (Harp et al., 2002), El Salvador (Crone et al., 2001), Nicaragua (Cannon et al., 2001) and Guatemala (Bucknam et al., 2001). Although it is intuitive to think that landslides are inevitable during high-magnitude episodes like Hurricane Mitch, regional experiences have shown that landslides are being triggered by ordinary rainfall events and with a higher frequency than in the past. The fact that a recent study has revealed that Honduras, Nicaragua and

Guatemala stand out as three of the top ten countries worldwide most affected by natural disasters (Kreft, 2014) gives evidence that the countries of the region are lacking preparedness to natural hazards.

JICA's landslide research in Tegucigalpa, Honduras

The passage of Hurricane Mitch caused severe damages in Tegucigalpa, the capital city of Honduras (Harp et al., 2002; JICA, 2002). Three major landslides took place, one of which dammed the Choluteca river and caused severe flooding upstream (Muñoz, 2016).For this reason, JICA decided to carry out a master plan to generate enough landslide data to assess the landslide vulnerability of Tegucigalpa as well as to propose structural and non-structural countermeasures in the most critical landslide sites (JICA, 2002).

Since then, JICA has continuously supported landslide research in Honduras. For example, in 2013, JICA conducted an aerial photograph survey to enable the mapping of the landslide bodies in Tegucigalpa (Yamagishi et al., 2014). This allowed staff members of the Polytechnic University of Honduras (UPI) and UNAH to produce a thorough landslide inventory map. This inventory map has been used to produce a landslide susceptibility map for the city, based on the matrix method, to highlight the landslide-prone areas (Garcia-Urquia & Yamagishi, 2016).

The latest research initiative proposed by JICA is the implementation of pilot projects in two neighborhoods in Tegucigalpa recently affected by landslides (Kuwano et al., 2016). Fig. 1 shows photographs of the training and fieldwork sessions in the Nueva Santa Rosa and El Eden neighborhoods. For both neighborhoods, L. Torres et al. (2016) stress the importance of developing landslide inventories for future studies. Hirota (2016) has investigated how the relationship between geology and landform brings about landslide occurrence in these two neighborhoods. Sato et al. (2016) has proposed the use of high-resolution topographical data to complement the

information collected in field surveys for the establishment of profiles and slip surfaces in the Nueva Santa Rosa neighbourhood. García et al. (2016) presents the implementation of a methodology for landslide susceptibility assessment in urban environments, showing El Eden neighborhood as an example.

Fig. 1 a. Training session in stereoscopy for the landslide inventory mapping of two neighborhoods recently affected by landslides in Tegucigalpa, Honduras. b. Fieldwork inspection in one of the landslide sites of the Nueva Santa Rosa neighborhood, which experienced a major activation in 2012. The reconnaissance was done in April, 2016

Other landslide studies in Honduras

Tegucigalpa's high vulnerability to landslides has attracted the attention of other cooperation organizations for the development of research studies. On the one hand, the humanitarian organization GOAL is working on the implementation of the Barrio Resiliente (BR or Resilient Neighborhood) program to improve the preparedness of some neighborhoods in Tegucigalpa against future landslide episodes (McCaul & Nuñez, 2016). GOAL has also conducted detailed geological and geomorphological studies in a sector considered to be highly vulnerable to landslides (Tejeda et al., 2016). On the other hand, the Interamerican Development Bank has focused their landslide susceptibility research in the areas surrounding the El Pedregal Lagoon and El Picacho Hill (Suárez, 2016).

Landslides are also common in other mountainous areas of the country. When these affect urban and rural settlements, researchers have found it necessary to carry out susceptibility assessments, despite the lack of necessary data. For example, Elvir (2016) used the combined factors method to develop a landslide susceptibility map for the Ajuterique region to the west of Honduras. Meanwhile, Morales et al. (2016) applied a methodology to assess the landslide vulnerability of the Carrizal-Semane community in the southwest of Honduras. This research team also participated in the training of community leaders so they would evaluate the landslide vulnerability on their own.

Important aspects of the regional studies

Landslide susceptibility and risk mapping

One of the main aspects the experts focused on was the development of landslide susceptibility maps. Braun et al. (2016) proposes the use of geomorphometry, statistics and data mining for the development of susceptibility maps. Although the methodology was applied in the former mining town of Maily-Say, Kyrgyzstan, it has the advantage of being easily adapted to the Central American and Caribbean context, especially in data-scarce areas. On the other hand, due to the simplicity and suitability of the methodology, the Mora and Vahrson method has been used for a landslide susceptibility assessment in the Jamapa and La Antigua basins in Mexico (G. Torres et al., 2016) and in the Juco Basin in Costa Rica (Salazar-Mondragón, 2016).

For landslide risk assessment, the methodology proposed by the Environmental Agency of the Ministry of Science, Technology and Environment of Cuba has been applied with success. It has been used in the Petit Goave in Haiti (Hernández et al., 2016) as well as in the Granma province (Hernández & Sam, 2016) and Villa Clara province (Viera & Pichardo, 2016) in Cuba. Paz et al. (2016) determine the global vulnerability and risk estimation of Chiapas, Mexico by considering the socioeconomic, demographic and physical vulnerability of the study area.

Techniques for landslide data generation

Susceptibility mapping requires the use of conventional topographical, geological and geomorphological maps as well as the execution of field surveys and laboratory tests for validation. Many researchers have also relied on aerial photograph interpretation for the development of landslide inventories that are used for susceptibility mapping. Nowadays, LiDAR (Light Detection and Ranging) is a popular technique for landslide studies too, as shown by Tejeda et al. (2016) and Aguilar & Arce (2016) in Honduras. Other techniques include electric resistivity tomography, which was employed to study several landslide sites in Tegucigalpa (Vargas, 2016) and El Salvador (Alfaro, 2016). In cases where landslide modelling is performed, researchers need to generate enough hydrological, geotechnical and topographical data to perform the simulations. For example, (Aristizábal et al., 2016) compared two physically based models (SHIA_Landslide and Shalstab) to assess rainfall-induced landslides in Colombia.

Landslide education programs

A key aspect that has been given relevance in this event was the socialization of landslide vulnerability to different target groups. For instance, Faber et al. (2016) developed a simple methodology to assess the risk of small landslides in several communities in Guatemala City. People were trained to use an easy evaluation chart so that they could assess the landslide risk of their own community without the need of expert judgment. On the other hand, Moncada & Yamagishi (2016) provide a detailed description of a multi-hazard project where participants had the opportunity to undergo virtual and conventional learning sessions about landslide inventory mapping and characterization. These participants would then replicate the hazard assessment methodologies in their countries. Finally, (Sánchez, 2016) shows the importance of the social construction of risk; topics such as housing atomization and risk transfer are discussed in detail.

Landslides and Climate Change

Climate change is said to have a direct influence on the rainfall regime, which is considered to be the main trigger of landslides in the region. Therefore, researchers have tried to link climate change and landslides through the occurrence of anomalous rainfall events that increase the frequency and magnitude of the landslides. Moreiras & Vergara (2016) have investigated the effect of climate change on the slopes in the Central Andes. Meanwhile, Montoya (2016) has proposed a series of recommendations that could help in the mitigation of the effects of climate change on the slopes of El Salvador.

Concluding remarks

Latin America has the highest urbanization rate in the world (United Nations, 2012). Therefore, it is expected that population pressures on the major urban areas of the region will increase the occurrence of landslides if there are no proper urban expansion plans. Unfortunately, in many countries, territorial policies prohibiting expansion on landslide-prone areas do exist, but these are not properly enforced. Usually, the urban poor establish themselves in these areas and contribute to the destabilization of the slopes through actions like deforestation, construction of weak households, and uncontrolled water management (Garcia-Urquia, 2015). While it is true that the region is exposed to severe hazards capable of triggering landslides (i.e. strong hurricanes and powerful earthquakes as stated by (Chichaco, 2016)), the preparedness of society is equally decisive in the aftermath of disasters. As long as a disaster response approach prevails over prevention, the societies of the region will continue to suffer negative effects of landslide-triggering hazards, even from ordinary rainfall events or low-magnitude seismic activity.

To date, researchers have developed numerous techniques for the spatial assessment of landslides at different scales. However, few regional studies analysing the temporal aspect of landslide occurrence have been conducted. Rainfall thresholds for landslide occurrence are the basis for early warning systems (Garcia-Urquia, 2016; Garcia-Urquia & Axelsson, 2015) but unfortunately little emphasis has been given to this aspect during the Congress. Because the construction of structural mitigation measures is not possible in all landslide sites due to their high costs, local authorities need to rely more on non-structural measures to reduce the consequences of landslides. Therefore, local authorities, researchers and the population living in risk areas need to strengthen their bonds to cope with the landslide hazard of the region.

Acknowledgments

References

Aguilar, C., & Arce, J. (2016). *Implementation and future of LIDAR Technology for identification and study of landslides in Honduras.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Alfaro, A. (2016). *Electric Resistivity Tomography in landslide and infrastructure characterization in El Salvador.* Paper presented at the Second Central American and Caribbean Landslide Congress,, Tegucigalpa, Honduras.

Aristizábal, E., García, E., & Martínez, H. (2016). *Modeling of landslides triggered by rainfall in the Colombian tropical and mountainous terrains.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Braun, A., Havenith, H. B., & Fernández-Steeger, T. (2016). *Geomorphometry, statistics and data mining for landslide susceptibility mapping in data scarce areas.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Bucknam, R. C., Coe, J. A., Chavarria, M. M., Godt, J. W., Tarr, A. C., Bradley, L. A., Rafferty, S., Hancock, D., Dart, R. L., & Johnson, M. L. (2001). Landslides triggered by Hurricane Mitch in Guatemala - inventory and discussion: U.S. Geological Survey Open File Report 01-0443.

Cannon, S., Haller, K., Ekstrom, I., Schweig, E., Devoli, G., Moore, D., Rafferty, S. A., & Tarr, A. (2001). Lanslide response to Hurricane Mitch rainfall in seven study areas in Nicaragua: U.S. Geological Survey Open-File Report 01-0412-A.

Chichaco, E. (2016). *Unstable zones in the highways and roads of Panama.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Crone, A. J., Baum, R. L., Lidke, D. J., Sather, D. N. D., Bradley, L. A., & Tarr, A. C. (2001). Landslides induced by Hurricane Mitch in El Salvador - an inventory and descriptions of selected features: U.S. Geological Survey Open-File Report 01-0444.

ECLAC. (1999). *Honduras: Assessment of the Damage Caused by Hurricane Mitch, 1998. Implications for Economic and Social Development and for the Environment.* Retrieved from Mexico: http://www.eclac.org/cgi-bin/getProd.asp?xml=/publicaciones/xml/6/15506/P15506.xml&xsl=/mexico/tpl-i/p9f.xsl&base=/mexico/tpl/top-bottom.xsl

Elvir, O. (2016). *The combined factors method for mapping susceptibility to landslides: a case of application.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Faber, E., Moreland, B., McDougall, S., Hunter, S., Hockin, L., & Strouth, A. (2016). *Development of risk rating system for small-scale landslides affecting settlements in Guatemala City.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Garcia-Urquia, E. (2015). *The Use of Press Archives in the Temporal and Spatial Analysis of Rainfall-Induced Landslides in Tegucigalpa, Honduras, 1980-2005.* (Doctoral Degree), Uppsala University, Uppsala, Sweden.

Garcia-Urquia, E. (2016). Establishing Rainfall Frequency Contour Lines as thresholds for rainfall-induced landslides in Tegucigalpa, Honduras, 1980-2005. *Nat Hazards, 82*(3), 2107-2132. doi:10.1007/s11069-016-2297-x

Garcia-Urquia, E., & Axelsson, K. (2015). Rainfall thresholds for the initiation of urban landslides in Tegucigalpa, Honduras: An application of the critical rainfall intensity. *Geogr Ann Ser A Phys Geogr, 97*(1), 61-83. doi:10.1111/geoa.12092

Garcia-Urquia, E., & Yamagishi, H. (2016). *The use of the matrix method for the landslide susceptibility mapping of Tegucigalpa, Honduras.* Paper presented at the 2nd Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

García, J., Hirota, K., Tsukamoto, S., Funes, M., Véliz, V., & Cardona, A. (2016). *Landslide susceptibility analysis in urban environments: a case study in Tegucigalpa, Honduras.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Harp, E. L., Castañeda, M., & Held, M. D. (2002). Landslides triggered by Hurricane Mitch in Tegucigalpa, Honduras: U.S. Geologic Survey Open File Report 02-0033.

Harp, E. L., Hagaman, K. W., Held, M. D., & McKenna, J. P. (2002). Digital inventory of landslides and related deposits in Honduras triggered by Hurricane Mitch: U.S. Geological Survey Open File Report 02-0061.

Hernández, E., Pichardo, L., Pedroso, I., Candebat, D., & Sylvaince, N. (2016). *Landslide risk assessment in the commune of Petit Goáve, Republic of Haiti.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Hernández, E., & Sam, Y. (2016). *Technical and prospective evaluation of landslide risk in Granma province, Cuba.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Hirota, K. (2016). *Preliminary report: relationship between geology and landform for landslides of Tegucigalpa, Honduras.* Paper presented at the Second Central

American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

JICA. (2002). *The Study on Flood Control and Landslide Prevention in Tegucigalpa Metropolitan Area of the Republic of Honduras*. Retrieved from Tegucigalpa, Honduras:

Kreft, S. E., D.Junghans, L.Kerestan, C.Hagen, U. (2014). *Global Climate Risk Index 2015*. Retrieved from http://germanwatch.org/en/9470

Kuwano, T., Hara, T., Tsukamoto, S., Inaoka, M., & Suzuki, H. (2016). *JICA Project for strengthening and capacity building of landslide control and mitigation in Honduras.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

McCaul, B., & Nuñez, A. (2016). *Barrio Resiliente: building resilient cities through resilient neighborhoods.* Paper presented at the Second Central American and Caribbean Landslide, Tegucigalpa, Honduras.

Moncada, R., & Yamagishi, H. (2016). *Educational methodologies implemented in Latin America for landslide inventory and analysis.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Montoya, A. (2016). *Climate change and soils.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Morales, A., Muñoz, D., & Meléndez, J. (2016). *Identification of unstable slope indicators in Carrizal-Semane, Yamaranguila, southwest of Honduras.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Moreiras, S. M., & Vergara, I. (2016). *The role of climate change on slope instability of the Central Andes during the last decades.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Muñoz, A. (2016). *The project for landslide prevention in Berrinche and Reparto in Tegucigalpa.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Paz, J., Gonzales, R., Sandoval, E., & Gómez, M. (2016). *The social construction of risk and landslides in Tuxtla Gutiérrez, Chiapas, México 2016.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Salazar-Mondragón, L. (2016). *Threat Assessment in Juco Basin, Orosi, Paraiso, Cartago, Costa Rica.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Sato, G., Yagi, H., Garcia-Urquia, E., Mullings, M., Kuwano, T., & Isono, K. (2016). *Landslide mapping using a 2 m DEM based on AW3D digital topographic data in Tegucigalpa, Honduras.* Paper presented at the 2nd Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Suárez, G. (2016). *What do we know of landslide hazard in Tegucigalpa, Honduras?* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Sánchez, R. (2016). *Risk as social construct: a comparative view from risk scenarios.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Tejeda, J., McCaul, B., Ruiz, M., & Espinoza, D. (2016). *Landslide susceptibility in the Ulloa Sector in Tegucigalpa, Honduras.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Torres, G., Suárez, M., Dávalos, R., Castillo, S., & Mora, I. (2016). *Landslides susceptibility analysis in the Jamapa and La Antigua basins in Mexico.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Torres, L., Sevilla, N., Hirota, K., Yamagishi, H., & Satoru, T. (2016). *How to make a database of landslides in Tegucigalpa, Honduras.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

United Nations. (2012). World Urbanization Prospects: The 2011 Revision. Retrieved May 16, 2013, from United Nations, Department of Economic and Social Affairs, Population Division http://esa.un.org/unup/CD-ROM/Urban-Rural-Population.htm

Vargas, L. (2016). *Geophysical prospection and layering analysis of a landslide susceptible area.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Viera, F., & Pichardo, L. (2016). *Cuban methodology for landslide hazard, vulnerability and risk studies in Villa Clara province, Cuba.* Paper presented at the Second Central American and Caribbean Landslide Congress, Tegucigalpa, Honduras.

Yamagishi, H., Yagi, H., & Sato, G. (2014). *Landslide hazard mapping of Tegucigalpa, Honduras - capacity building by JICA-JSPS Project (2012 to 2014).* Paper presented at the Proceedings of World Landslide Forum 3, 2-6 June 2014, Bejing, China.

Elias Garcia-Urquia (✉)

National Autonomous University of Honduras, Department of Civil Engineering, Ciudad Universitaria, Boulevard Suyapa , Tegucigalpa, Honduras
e-mail: elias.urquia82@gmail.com

Lidia Torres

National Autonomous University of Honduras, Honduran Insititute of Earth Sciences, Ciudad Universitaria, Boulevard Suyapa, Tegucigalpa, Honduras
e-mail: le_torresb@yahoo.com

Takeshi Kuwano
Kokusai Kogyo Co., Ltd, Disaster and Water Resources Management Division, Tokyo, Japan, +81-3-6361-2452
e-mail: takeshi_kuwano@kk-grp.jp

Takashi Hara
OYO International Cooperation, Geotechnical and Geology Division, Tokyo, Japan, +81-3-5840-5155
e-mail: hara@oyointer.com

Tsukamoto Satoru
Kosukai Kogyo Co., LTD
e-mail: satoru_tsukamoto@jcom.home.ne.jp

Elisabeth Espinoza
National Autonomous University of Honduras, Honduran Insititute of Earth Sciences, Ciudad Universitaria, Boulevard Suyapa, Tegucigalpa, Honduras
e-mail: elisabethespinoza@hotmail.com

Oscar Elvir
National Autonomous University of Honduras, Honduran Insititute of Earth Sciences, Ciudad Universitaria, Boulevard Suyapa, Tegucigalpa, Honduras
e-mail: elvirferman@yahoo.com.mx

Marcio Alvarado
National Autonomous University of Honduras, Department of Civil Engineering, Ciudad Universitaria, Boulevard Suyapa , Tegucigalpa, Honduras
e-mail: marcioae51@yahoo.com

JICA Project for strengthening and capacity building of landslide control and mitigation in Honduras

Takeshi Kuwano, Takashi Hara, Satoru Tsukamoto, Miki Inaoka, Hisashi Suzuki

Abstract Since 2001, the Japan International Coopera-tion Agency (JICA) has been supporting Honduras to combat landslides. JICA prepared a disaster-reduction master plan and carried out landslide prevention work (such as horizontal and catchment well-drilling) under grant-aid, and it also sent researchers and engineers.

In 2015, JICA launched a new project "Assistance for Strengthening and Capacity-building of Professional Techniques for the Control and Mitigation of Landslide in Tegucigalpa Metropolitan Area". The objectives of the Project are to build the landslide management capacity of Universidad Nacional Autónoma de Honduras (UNAH) researchers and Alcaldía Municipal del Distrito Central (AMDC) engineers and to support UNAH and AMDC to establish organizations to implement landslide counter-measures, thereby contributing to the country's landslide disaster mitigation.

In this paper, we present the results and outputs of the components in the Project to understand the activities on landslides that JICA has been conducting, and introduce other JICA projects on landslide and methodology for hazard evaluation on slope disasters in other countries.

Keywords Hazard evaluation, Multivariate statistical analysis, quantification theory, JICA, Capacity-building

History of mitigation measures for landslides

Located in Latin America, the Republic of Honduras has a population of about 8.1 million and a land area of around 112,000 km². It is at high risk of long-term climate change. Moreover, the geological features of the Tegucigalpa metropolitan area make it particularly susceptible to slope disasters, such as landslides, induced by tropical storms or hurricanes during the rainy sea-son from May to November: the area has been developed in a basin surrounded by slopes. A number of natural disasters, including floods and landslides, have occurred in the area, and its citizens—the poor in particular—have often suffered.

JICA have undertaken five projects involving Japanese scientific methods and technologies to reduce hazards on slope disaster in this region, which are 1) Metropolitan landslide prevention plan in the Republic of Honduras, 2) Project on landslide prevention in the Tegucigalpa Metropolitan area, 3) Project on capacity development for disaster risk management in Central America "BOSAI", 4) Hazard geology focusing on the landslides in Tegucigalpa (Yamagishi 2014), and 5) Technical support for landslide studies by Senior Volunteer (Hirota 2015). These projects are thematically consistent, and have been effectual in transferring knowledge of technological models in the areas (Sato et al. 2015).

JICA landslide project

In 2015, JICA dispatched a Consultant Team and Experts to implement a new project "Assistance for Strengthening and Capacity-building of Professional Techniques for the Control and Mitigation of Landslide in Tegucigalpa Metropolitan Area" from February 2015 to August 2016 (approximately 18 months).

Objectives

The objectives of the Project are to build the landslide management capacity of Universidad Nacional Autónoma de Honduras (UNAH) researchers and Alcaldía Municipal del Distrito Central (AMDC) engineers and to support UNAH and AMDC to establish organizations to implement landslide countermeasures, thereby contributing to the country's landslide disaster mitigation.

Activity

The activity of the Project is mainly divided into the following seven components;
1) Provide advice to UNAH on planning the establishment of a Geological Research Organization
2) Provide advice on establishing a national association of landslide research organizations at UNAH
3) Provide advice to AMDC on establishing an organization to implement landslide countermeasures
4) Organize workshops to explain the process flow, from information collection, survey, analysis, design, and countermeasure implementation to maintenance and management

5) Provide advice on establishing a collaborative structure for landslide countermeasures between AMDC and UNAH

6) Transfer technology for creating landslide inventory and its use for AMDC and UNAH

7) Transfer operation, maintenance, and management technology for landslide countermeasures and monitoring facilities to AMDC

Outputs of the JICA project

The seven activities implemented by JICA Consultant Team and JICA Experts in the Project have brought certain achievements to UNAH and AMDC in Honduras. The achievements are summarized in these paragraphs.

1) Planning the establishment of the geological research organization at UNAH

First, the existing plan and schedule for establishing the Geological Research Organization were gained to obtain background information. In addition, the landslide situation and related research activities, as well as the disaster-mitigation strategies of government agencies were grasped to give appropriate advice on this matter. Information and opinions were exchanged not only with those concerned at Instituto Hondureño de Ciencias de la Tierra (IHCIT) of UNAH and also with those at the University of Polytechnic Engineering (UPI), the Institute of Geosciences of Honduras (IGH), and the National Disaster Prevention Committee (COPECO) whom JICA has been helping with landslide capacity development. The geological research environment in the country was thus overviewed.

The information gained was used to give advice at discussions with UNAH on (1) policies of the research organization, (2) its organizational structure, (3) research areas and topics, (4) a plan for recruiting scientists, (5) a research budget calculation and financial resources, and (6) a schedule leading up to the organization's establishment. The advices were compiled into a recommendation report, which was submitted to the relevant organizations in Honduras after agreement was reached at the Joint Coordination Committee.

2) Establishing a national association of landslide research organizations at UNAH

As national disaster prevent systems in Honduras, several laws, acts and regulations such as SINAGER, PEGIRH, PNGIRH 2014-2019 have been established. However many issues still have underling on the coordination system, capacity development, organization strengthening, disaster management and disaster recognition for citizens.

Considering the issues, *The Committee for the Risk Analysis on Slope Disaster in Honduras*, which tackles with natural slope disasters as a national association at UNAH of landslide research organizations, was inaugurated based on a proposal by JICA Consultant Team. The Memorandum of Understanding for the inauguration of the Committee was approved by research institutes and government offices in Honduras. The flow and significance of the activity of the Committee were compiled into a report, which was submitted to the relevant organizations.

3) Establishing an organization to implement landslide countermeasures for AMDC

Although AMDC already has a disaster prevention system in the organization, it does not operate properly because of lack of knowledge, experience and engineers, and inadequacy of collaborative structure and emergency response for landslide disasters.

Therefore JICA Consultant Team proposed strengthening of the landslide disaster prevention system, which is composed of 1) collaboration of various divisions in AMDC, 2) securement of geo-technical engineers, 3) establishment of data collection system, 4) back-up structure, and 5) capacity development. The advices were compiled into a recommendation report, which was submitted to the relevant organizations.

4) Workshops to explain the process flow, from information collection, survey, analysis, design, and countermeasure implementation to maintenance and management

To explain the entire process of implementing landslide countermeasures to the counterparts (C/P) and the relevant personals, technology transfer workshops have been held, and the total participants were more than 100. The workshops covered basic skills related to work in dealing with landslides and detailed programs on the basis of request from C/P, such as photograph interpretation, hazard evaluation, site reconnaissance/analysis, countermeasure planning, database, GIS technology etc. For specific skills that are not covered by the seminars by JICA Experts, the workshops consisting of lectures, exercises, and training have been held with C/P.

UNAH also voluntarily held several workshops for other C/P members about the technology and knowledge that transferred by JICA Consultant Team and JICA Experts.

5) Establishing a collaborative structure for landslide countermeasures between AMDC and UNAH

Insufficiency of geo-technical engineers who understand geology and soil mechanics is a serious issue for management of landslide disaster in AMDC. UNAH, especially IHCIT and Civil Engineering Department have geo-technical engineers and geological researchers to support and advise to AMDC on this issue.

Therefore, AMDC, IHCIT and Civil Engineering Department had several discussions about the issue and made an agreement on technical cooperation on the management and countermeasures for landslide disasters. The Memorandum of Understanding for the matter was approved with the three organizations. The flow and significance of the activity were compiled into a report, which was submitted to the relevant organizations.

6) Technical transfer for creating a landslide inventory and its use for AMDC and UNAH

A landslide inventory has been created at 2 sites (Nueva Santa Rosa, El Eden) as pilot sites, which selected among 17 sites listed by AMDC. Two groups at Nueva Santa Rosa and other two groups at El Eden have conducted the tasks. JICA Expert had several lectures, exercises, and trainings on basic knowledge, photo interpretation, and site analysis for the groups, and followed by prepared detailed landslide distribution maps (S=1/5,000)(Fig.1). The GIS landslide inventory was created for each landslide block based on geology, topography and disaster records.

Fig, 1 Example photo of making a landslide distribution map.

JICA Experts also have held five technical transfer seminars (May and September in 2015, February, May and July in 2016) on these matters.

7) Technical transfer for operation, maintenance, and management for landslide countermeasures and monitoring facilities to AMDC

AMDC is conducting maintenance and monitoring for the landslides and the countermeasure structures installed at the sites. JICA Consultant Team has transferred technologies on device installation, data analysis, data processing and data evaluation on the monitoring for the landslide movement, and instructed the maintenance methodology for drainage wells as countermeasures for the landslides.

The advices and instructions were compiled into a manual of monitoring and maintenance for the landslide countermeasures, which was submitted to the relevant organizations.

Susceptibility evaluation

Among the above mentioned seven activities, susceptibility on the selected two landslides was evaluated for creation of landslide inventory and GIS mapping on the activity 6. Susceptibility evaluation on a landslide is an important factor for consideration of hazard followed by prioritization of countermeasures. In the Project, susceptibility on the landslides was evaluated by using Analytic Hierarchical Process (AHP) method (Yagi et al. 2009).

The AHP is one of the hazard evaluation methodologies on landslides. It decomposes the process of subjective decision of person into a layer structure and expresses the qualitatively. Hierarchical structuring of factors and weighting of the factors that contribute to reactivation of landslides are adopted for landslide hazard assessment in the AHP. The factors and items are determined by brain-storming of experts in geomorphology and landslide investigation works. The first hierarchical level is "landslide hazard evaluation". The factors of the second hierarchical level are, for example, 1) distinctiveness of main scarp, 2) surface feature of landslide body, 3) position of landslide body on the slope, 4) position of cracks in the landslide body, 5) stability conditions of landslide toe. Those correspond to three principle factors such as geomorphological evolution processes, landslide activity and destabilizing possibility. The third hierarchical level consists of the optional items under each geomorphic factor of the second level.

Final weight coefficient for each item is calculated by multiplying values of hierarchical levels. Hazard level is classified into several categories based on the results. According to Yagi et al. 2009, 312 landslides in central Japan were evaluated by the system. The results of AHP hazard rating are concordant with those of subjective evaluation of aerial photo, which means that the system well supports conventional hazard evaluation. The AHP system is able to be used for

primary landslide hazard assessment without detailed field survey.

Thus, hazard evaluation on landslides has been developed and recently applied to several landslide projects in JICA. Here, other hazard evaluation methods on landslide projects in JICA are introduced as references.

Landslide hazard evaluation in other JICA projects

Application of multivariate statistical analysis

The basic factors of landslides do not only depend on topographic features and geological conditions, but also on water condition and landslide history. These items intricately affect the basic factors. The quantification theory, one of multivariate statistical analysis, facilitates analyses for intricate data. This theory enables quantitative dependent variable to be predicted based on various qualitative explanatory variables. Dependent variables are the desired result of analyses. Explanatory variables items affect dependent variables.

A coefficient is calculated by the quantification theory. The coefficient correlates to the contribution of the item, and it influences the dependent variable directly. The landslide hazard is large when the category score is high, and conversely is small when the category score is low.

Category range and partial correlation coefficient on each item are also calculated by the quantification theory. Range is the difference between maximum and minimum values of category score, and indicates the contribution of the dependent variable. That is, an item with a large range has a greater effect when predicting the dependent variable. Partial correlation coefficient is the index that shows the contribution of each item on the dependent variable, and can be considered to be a correlation coefficient that does not influence other items. The contribution becomes larger the closer the value comes to 1.

Thus, hazard on landslides is able to be discussed with the results of the quantification theory. This hazard evaluation method has applied on landslides in the JICA projects, which are introduced on next sections.

Landslide on roads in Ethiopia

Main road 3, a major arterial road in Ethiopia, steeply climbs nearly 1,500 meters over 40 kilometres through the Abay Gorge. It is plagued by landslides in the rainy season. Some of these are up to two kilometres wide, jeopardizing this vital link.

The road disaster inspection was carried out for 90 landslides in the Abay Gorge to identify the priority for countermeasures (Kuwano et al. 2012A). The inspected items are topographic features, geological condition and history of landslide. The results are compared with the hazard score of landslides determined by geotechnical experts with more than 20 years' experience. The hazard score by the experts is 0 to 20, that the high score means high hazard site.

Category score is indicated in Tab. 1. Category range and partial correlation coefficient on each item are indicated in Tab. 2 (Kuwano et al. 2012B).

Table 1 Category scores of the items in national road 3 in Ethiopia

Item	Category	Score
Photo interpretation	Exist clearly	2.567
	Exist but partial and not clear	-0.945
	Exist but not clear	-2.189
Surface anomalies	Large and new cracks, steps	0.958
	Small and old cracks, steps	0.603
	Slight deformation	-0.381
	No anomalies	-1.625
Geological structure	Fault, fracture zone, dip slope	0.017
	Undip slope	-0.013
Main rock formation of landslide body	Colluvial deposit	0.100
	Pyroclastic materials	2.060
	Basalt	-0.673
	Limestone	0.007
	Gypsum	-2.562
	Siltstone	2.323
	Sandstone	-2.565
Hydrological feature	Much springs / seepage	-1.318
	Little springs /little seepage	0.995
	Surface water /trace of water	0.039
	No water observed	-0.163
Existing record	Obvious	-0.199
	Slight	3.617
	None	-0.549
Damage on road facilities	Obvious	1.569
	Slight	0.632
	None	-1.418

Table 2 Category range and partial correlation coefficient in national road 3 in Ethiopia

Item	Category Range	Partial Correlation Coefficient
Photo interpretation	4.756	0.675
Surface anomalies	2.583	0.307
Geological structure	0.030	0.006
Main rock formation	4.888	0.526
Hydrological feature	2.313	0.313
Existing record	4.166	0.490
Damage on road/ house	2.987	0.406

These analysis results lead to the conclusion that "main rock formation of landslide body" and "result of photo interpretation" affected the hazard of a landslide greatly, and the "geological structure" seldom affected it. Coefficient of determination on the hazard of landslide is 0.74, utilizing significant items and categories. These coefficients indicate that it is good accuracy for the prediction.

Slope failure on roads in Bhutan

Roads are major means of travel and transportation in Bhutan, and development of an efficient and safe road network is essential for Bhutan's social and economic development. However, because large parts of the country consist of steep mountainous areas there are significant geological and topographic constraints to the construction of the majority of roads. There are few roads with sufficient road slope disaster management in place. Consequently, slope failures and landslides frequently occur, disrupting travel and the transport of agricultural crops.

Table 3 Category scores of the items in national road 1 in Bhutan

Item	Category	Score
Topography (Collapsed factor)	2 or more	2.059
	1 or less	-0.433
Soil (Susceptible to erosion, less strength with water)	Marked	6.884
	A little marked or none	-1.617
Structure (Dip slope of bedding plane)	It corresponds.	13.874
	None	-1.055
Unstable rock/soil (Topsoil, detached rock and unsteady rock)	Instability	3.280
	A little unstable	0.232
	Stability	-2.643
Spring water	Notable spring waster or seepage	3.726
	None	-0.845
Surface condition	Bare land with minor vegetation	0.239
	Mainly structure, mainly tree	-2.347
Height	H≧50m	3.098
	30≦H＜50m	0.027
	15≦H＜30m	-3.146
	H＜15m	-7.329
Dip	i≧70°	13.251
	45°≦i＜70°	0.424
	i＜45°	-1.605
Collapse, small fallen rock, gully, erosion, piping, subsidence	2 or more / clarity	6.872
	Certain/unclarity	-0.864
	None	-2.636

The hazard in road slope disaster in Bhutan was analysed by the quantification theory based on evaluation sheets created by JICA Consultant Team (JICA 2016). JICA Consultant Team implemented the slope inspection for more than 450 sites on the national roads and divided the sites into three ranks based on the hazard for slope disasters. The three ranks of the evaluation were used for analysis as dependent variables. The results of the evaluation were used for the analysis of the explanatory variables.

Category score is indicated in Tab. 3. Category range and partial correlation coefficient on each item are indicated in Tab. 4.

Table 4 Category range and partial correlation coefficient in national road 1 in Bhutan

Item	Category Range	Partial Correlation Coefficient
Topography	2.493	0.063
Soil	8.501	0.219
Structure	14.929	0.244
Unstable rock/soil	5.924	0.097
Spring water	4.571	0.114
Surface condition	2.586	0.052
Height	10.427	0.228
Dip	14.855	0.236
Anomaly	9.508	0.231

These analysis results lead to that which items affect the hazard of a slope disaster greatly, and which items seldom affected it. Based on the degree of the affection, new evaluation sheet for the inspection of slope failure had been developed, which are suitable to the conditions of geology and topography in Bhutan, by using a category score that directly affects the dependent variables. The scoring of the new evaluation sheet was based on the relative difference of the category score and was adjusted as 100 points at a maximum (Fig. 2).

Strengthening and capacity building

In the current Project in Honduras, JICA has implemented technical transfer about the control and mitigation on landslides to UNAH and AMDC, and created a landslide inventory and susceptibility maps in the 2 pilot sites. However there are still several dozen landslides in Tegucigalpa area. Hazard evaluation and subsequent countermeasures for the landslides are urgently needed by using the technologies transferred in the JICA projects.

The Committee for the Risk Analysis on Slope Disaster in Honduras was established in the Project. We suggest that the Committee should be expanded to ex-

Item		factor	category of score	Point	score
topography	Collaps ed factor	talus slope, clear convex break of slope, eroded toe of slope , overhang, w ater catchment slope	3 or more correspondences	6	
			2 correspondences	5	
			1 correspondences	3	
			no correspondence	2	
Geological conditions	Soil	susceptible to erosion less strength w ith w ater	marked	12	
			a little marked	1	
			None	0	
	Rock	high density of cracks and a w eak layers, susceptible to erosion, fast w eathering	marked	-	*
			a little marked	-	
			None	-	
	Structure	dip slope of bedding plane	It corresponds.	22	
			None	2	
		debris on impermeability bedrock, the upper part is a hard /the toe of slope is w eak.	marked	-	*
			a little marked	-	
			None	-	
Surface codition		Topsoil, detached rock and unsteady rock	instability	8	
			a little unstable	3	
			stability	0	
		Spring w ater	notable spring w ater	8	
			seepage	7	
			none	2	
		Surface condition	bare land with minor vagetation	3	
			intermediate (bare·grass·tree)	2	
			mainly structure, mainly tree	0	
Profile		Height (H), dip (i)	height	H≧50m	7	
				30≦H<50m	3	
				15≦H<30m	-1	
				H<15m	-7	
			dip	i≧70°	21	
				45°≦i<70°	4	
				i<45°	1	
Anomaly		Surface collapse, small fallen rock, gully, erosion, piping hole, subsidence, heaving, bending of tree root, fallen tree, crack, open crack, anomaly of countermeasure	2 or more correspondences·clarity	12	
			certain·unclarity	2	
			none	0	
			sum total	(A)	0

* : No score

Fig. 2 New evaluation sheet for slope failure in national road in Bhutan.

change the technologies, knowledges and experiences among engineer, government officer and researcher, so that they will be able to tackle with the landslide problems.

In order to strengthen the technology on landslides, the experience is necessary. Investigation, analysis, evaluation, design, construction of countermeasure, management and maintenance should be continuously conducted, since landslides have various mechanism, shape, cause and trigger.

References

Hirota K. (2015) Landslide and geology education in Honduras, as activities of Japan International Cooperation Agency senior volunteer, Journal of the Japan Landslide Society. Vol.52, No.4, pp.36-42.

Japan International Cooperation Agency (2016) Final Report, The Project for Master Plan Study on Road Slope Management in Bhutan.

Kuwano T., Enokida M., Tsukamoto S., Ichikawa K., Yokoo F., Hara T., Nakagawa A., Takeuchi T. (2012A) Hazard evaluation with multivariate statistical analysis for landslide disaster in the Abay Gorge in Ethiopia, 34th International Geological Congress (IGC): AUSTRALIA 2012.

Kuwano T., Enokida M., Tsukamoto S., Ichikawa K., Nakagawa A., Takeuchi T. (2012B) Assessment of hazard and contributing factors of landslides in Abay Gorge in Ethiopia, International Symposium on Earthquake-induced Landslides.

Sato G., Kamiya S., and Hirota K. (2015) Investigation and mitigation of landslides in Republic of Honduras as Japan's International cooperation program, Journal of the Japan Landslide Society. Vol.52, No.4, pp.1-7.

Yamagishi H. (2014) Integrated disaster prevention maps and landslide hazard maps using GIS −Examples of Shikoku and Central America Honduras-, Journal of the Japan Landslide Society. Vol.51, No.2, pp.24-29.

Yagi H., Higaki D. and Japan Landslide Society Research Committee for Detection of Landslide Hazardous Sites in Tersiary Distributed Area (2009) Methodological study on landslide hazard assessment by interpretation of aerial photographs combined with AHP in the middle course area of Agano River, central Japan, Journal of the Japan Landslide Society. Vol.45, No.5, pp.358-366.

Takeshi Kuwano (✉)
Kokusai Kogyo Co., Ltd, Disaster and Water Resources Management Division, Tokyo, Japan, +81-3-6361-2452
e-mail: takeshi_kuwano@kk-grp.jp

Takashi Hara
OYO International Corporation, Geotechnical and Geology Division, Tokyo, Japan, +81-3-5840-5155

Satoru Tsukamoto
Kokusai Kogyo Co., Ltd, Disaster and Water Resources Management Division, Tokyo, Japan, +81-3-6361-2452

Miki Inaoka
Japan International Cooperation Agency, Global Environment Department, Tokyo, Japan, +81-3-5226-9521

Hisashi Suzuki
Japan International Cooperation Agency, Honduras Office, Tegucigalpa, Honduras, +504-2232-6727

Landslide susceptibility analysis in urban environments: a case study in Tegucigalpa, Honduras

Javier García, Kiyoharu Hirota, Satoru Tsukamoto, Marco Funes, Vera Véliz, Alex Cardona

Abstract The Project "Strengthening Landslides Control and Mitigation Capacities in the Metropolitan area of Tegucigalpa" was started in 2013 in order to strengthen the capacity of academia and the Local Government of the Central District of Honduras in taking measures against landslides and contribute to the mitigation of its damages.

The project was carried out with the support and technical assistance of Japan International Cooperation Agency (JICA), the coordination of the National Autonomous University of Honduras (UNAH) and the Municipality of the Central District of Honduras (AMDC) as main executors, the project had also the participation of the National Pedagogical University "Francisco Morazán" (UPNFM), the Polytechnic University of Engineering (UPI) and the Permanent Commission of Contingencies (COPECO).

As a part of this project, a susceptibility map for the area of El Eden, in the Metropolitan area of the Central District of Honduras was built from the interpretation of aerial photographs, field work, geo-referencing of relevant points for the characterization of landslide bodies and the evaluation of the variables: micro - topography, slope profile, geological conditions, land use and water condition.

Fourteen main landslide bodies were identified, out of which 36 % showed a high susceptibility to landslides; 50% showed a medium susceptibility to landslides and 14% showed allow susceptibility to landslides.

Keywords landslides, susceptibility maps, stereoscopy

Introduction

Over the past three decades, massive population explosion combined with the lack of urban planning and weak enforcement of urban policies have contributed to the fragility of Tegucigalpa to natural disasters. Rainfall thresholds studies in which the minimum values of rain triggering landslides have been defined, have suggested that human intervention has significantly predisposed in Tegucigalpa's slopes fault. (Garcia-Urquia & Axelsson, 2015).

Studies made by the Kokusai Kogyo Co. (2015), have pointed out the importance of improving institutional collaboration to promote the use and maintenance of works against landslides and monitoring facilities built following the subsequent mudslides in hurricane Mitch; and highlights the lack of research institutions to conduct the study and control of landslides nationwide.

Considering the context above, a technical cooperation project aimed at strengthening internal capacities in academia, local governments and natural disasters attention agencies was designed and coordinated by JICA and the Honduran government. This article presents some of the results of the project, focusing on the landslide susceptibility analysis carried out in the zone of El Eden of the metropolitan area of Tegucigalpa, as the main input for the construction of a susceptibility map for the study area.

Materials and methods

Identification of sites of interest in the study area

In order to make a preliminary description of the study area, high resolution images were used to carry out aerial photo interpretation to identify scarps, landslide bodies, surface runoff and steep slopes.

The images, which showed an overlap of 40% of the visual field covered on each, were observed with Sokkia MS27 mirror stereoscopes, consistent with Spencer's (2000) guidelines, by two teams who interpreted the field topography, consolidating priority points maps (Fig. 1) for observation that would form the basis for its confirmation on the field.

Landslide bodies that did not clearly show defined borders through the photo interpretation constituted points to be verified on the field through the presence of fissures, ground movements, cracks and damage and inclinations on infrastructure (poles, houses, streets, etc.).

The differentiation between bodies, distinction between old and recent scarps, debris flows, geology of the zone, and other relevant observations to the current state of the study area were supplemented by direct observation on the field and further discussion by multi- disciplinary teams.

Determining Susceptibility in the Site of Study

About 12 visits were scheduled to the zone of El Eden between April 2015 and May 2016 for the gathering of primary information in order to generate a map of susceptibility of the study area. During the field observation visits, Garmin E-Trex GPS units were used to geo-reference the major sites of surface water flow, water springs and other water sources and infrastructure disturbances associated with soil movements.

A S82T South Surveying differential GPS unit was used for the delimitation of the main body and the limits of the upper scarps of the landslide bodies in the study area.

The geo-referenced polygons and points were subsequently treated in geographic information processing software. The intergroup consensus resulted in the definition of 14 landslide bodies to be interpreted according to the degree of susceptibility they represented.

The "Table for the evaluation of susceptibility of landslide bodies" (Yagi, 2013) was used as a primary susceptibility evaluation tool, which allocates scores to each identified body based on their topographical, geological and socio-environmental characteristics, generating a quantitative rating which is translated to three possible qualitative outcomes: high, medium and low susceptibility.

The variables analyzed for the assessment of landslide bodies are detailed below.

Micro-topography

The variable of Micro-topography, which describes the variations in soil within a range of about one centimeter to a maximum of one meter (Moser et al, 2007) consisted in four possible indicators for the assessment of susceptibility.

Tilting poles, trees, walls or any other prominent vertical structure, when observed, assigned a score of
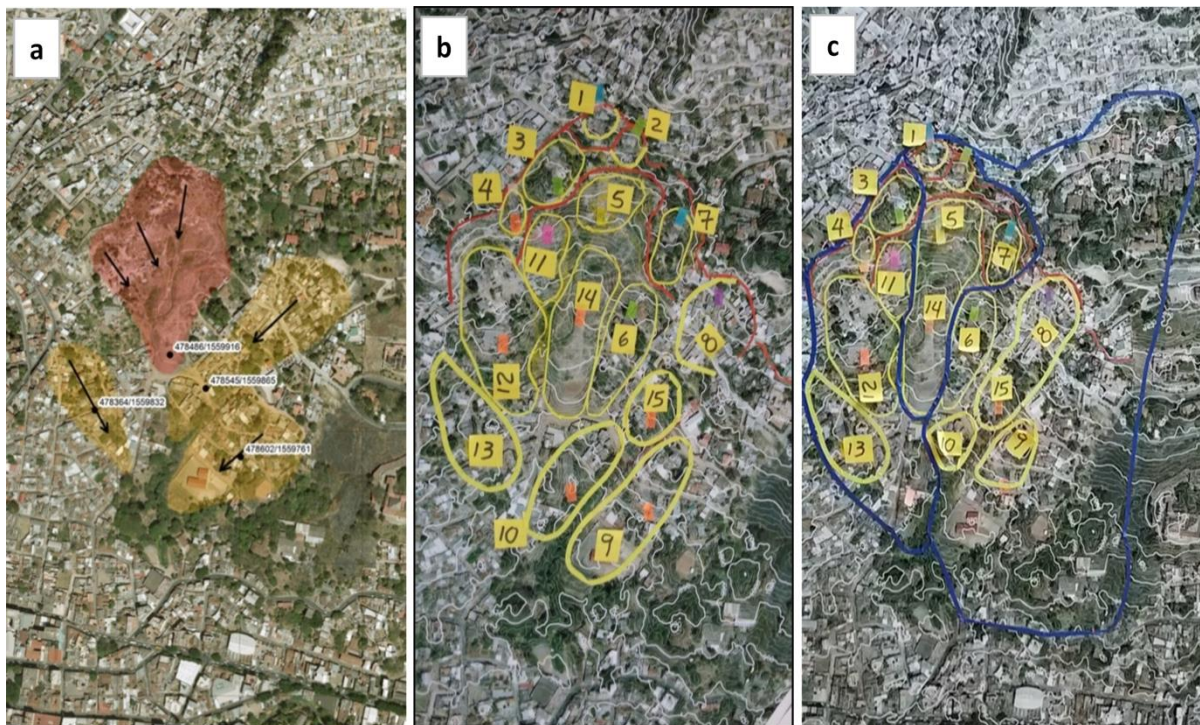
Fig 1 Earlier versions of the preliminary description of the study area. The team's consensus resulted in priority-points maps for the zone of El Edén. Image "A", generated prior to field visits via photo interpretation of stereoscopic images, shows the first approach to landslide bodies, with the black arrows indicating the direction of the slope. Image "B", generated after the first field visit shows the limits of the suggested landslide bodies outlined in yellow and the main scarp as red lines. Image "C", showing bodies and main scarps, also presents outlined in blue, three main blocks of landslides bodies, based on their possible antiquity, being the far right block the oldest and the far left one the newest block.

20 points; fragmentation stands would assign the landslide body 15 points; cracks would assign 10 points and fissures 5 points. Zero points were assigned to the bodies that did not present any of the above characteristics.

Slope Profile

The analysis of the profile of the slope for the assigning of susceptibility scores evaluated the presence of slope faults, understood for the purposes of this study as prominent cracks in the surface layer of soil, and assigned the body a score of 20 points; break points, understood as angular direction changes in the slope, assigned a valuation of 15 points; convex slopes were worth 7 points; linear slope inclination was worth 3 points and concave slopes, with less potential slip, were assessed with zero points.

Geological Conditions

The variable of Geological Conditions evaluated the nature of topsoil in the landslide bodies. Colluvial soil, understood as sedimentary deposit comprising surface mantle accumulated at the base of a slope as a result of gravitational transport and unchannelized flows (Millar, 2014), was rated with a score of 20. Tertiary sediments, i.e., sand, silt and clay in unconsolidated discontinuous patches (USGS, n.d), were assessed with a score of 15 and the solid rock, with much less slide potential, was rated with zero points.

Water Condition

Four possible indicators for the variable Water Condition were taken into account for the assessment of the susceptibility of the bodies. The variable was included in the Table for the evaluation of susceptibility of landslide bodies proposed by Yagi, considering the particular context of Honduras, in which the lacking of 32% of sanitary sewerage coverage (McLean, 2009), causes the recurrent feature of discharging waste water on soil surface, which is especially noticeable in rural and marginal urban areas.

More importantly, the annual rainfall of Honduras, with average values of 1976 mm (The World Bank, 2016) is significantly higher than those of non-tropical regions, which directly affects the presence of surface and underground water, making necessary its incorporation into the original instrument.

The indicators evaluated in the variable Water Condition were the presence of springs on the slope's foot, valued with 20 points; water filtration on the slope's foot, valued with 15 points; filtration, spring or presence of sewage on the sliding body, valued with 12 points; and natural or winter runoffs, valued with 10 points.

Land Use

The variable Land Use was assessed based on the presence or absence of 3 possible indicators: dense urbanization, which naturally presents greater risk potential to the effects of landslides, was assessed with 20 points; scattered presence of houses in the landslide body was valued with 10 points, and presence of vegetation or forest with 5 points.

Seeking of Additional Attributes

Intending to complement the field data and the assessment of susceptibility in the 14landslide bodies, the history of sliding events in the region studied was collected from written sources, mainly using printed and digital local newspapers.

The concentration of schools and other public agencies in the areas of health and human services, as well as the facilities of a religious nature, given their cultural value, was also diagnosed, representing all key inputs for the qualitative assessment of the susceptibility of the bodies.

Results

Following the assessment of individual indicators, it was determined that out of 14 identified bodies, 36% (5 bodies) had a high susceptibility to landslides, 50% (7 bodies) presented a medium susceptibility and 14% (2 bodies) showed a low susceptibility.

Public and socially relevant infrastructure data, indicators of soil movements (cracks, fissures inclinations, etc.) and the level of susceptibility of each of the sliding bodies were consolidated into a map of susceptibility of the area.

Discussion

Regarding the values presented in the "Max scores" column of Tab. 1, it is to be noted that the selected methodology for determining susceptibility in the study area, given that arbitrary units for the weighting of indicators are used for the generation of scores, is more of a bodies' susceptibility relative sizing tool with respect to other bodies within a common area of study, rather than a quantitative methodology to describe with mathematical precision the magnitude of individual susceptibilities.

From the analysis of the susceptibility map shown in Fig 2, it is relevant to mention that about 50% of the landslide bodies show overlapping events. Blocks 2, 3, 4 and 8, for example, have pronounced scarps on its bodies, while the blocks 7 and 13, on the other hand, which have been suggested to have an earlier origin

show minor scarps near the boundaries of the landslide body. Both kinds of overlaps could be considered an indicator of intense and prolonged activity in this sector of Honduras' Central District.

The generation of data to strengthen the understanding of the potential impacts of natural phenomena and human alteration of the environment as well as its location and previous magnitudes should lay the foundation for a technical oriented and detailed risk management, for which the involvement of various actors is essential. This becomes vitally important considering that throughout the field work, it became evident a relatively rapid growth of local domestic infrastructure, which means a greater potential risk in the high and medium susceptibility bodies identified.

Table 1 Table for the evaluation of susceptibility of landslide bodies implemented in El Edén community, Central District, Honduras

Variable	Indicator	Max Score	Landslide bodies score													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
Micro-topography	Tilting structures	20		20	20	20		20								
	Fragmentation stands	15					15			15	15		15	15		
	Cracks	10	10									10			10	
	Fissures	5														
	No	0							0							
Slope profile	Slope faults	20			20	20	20	20					20			
	Break Point	15								15				15		
	Convex slope	7		7												
	Linear slope inclination	3	3								3				3	
	Concave slopes	0							0			0				0
Geological conditions	Colluvial	20				20	20	20		20	20	20				
	Tertiary Sediments	15	15	15	15				15				15	15	15	15
	Solid Rock	0														
Water condition	Spring on slope's foot	20														
	Water filtration on slope's foot	15														
	Filtration, spring or sewage on landslide body	12					12				12					
	Natural or winter runoffs	10	10	10	10	10		10	10	10		10	10	10	10	10
Land Use	Dense urbanization	20	20	20					20				20	20	20	20
	Scattered houses	10			10	10		10		10	10	10				
	Vegetation or forest	5					5									
Total Score		100	58	72	75	80	72	80	45	70	60	50	80	75	58	45
Susceptibility to landslide			M	M	H	H	M	H	L	M	M	M	H	H	M	L
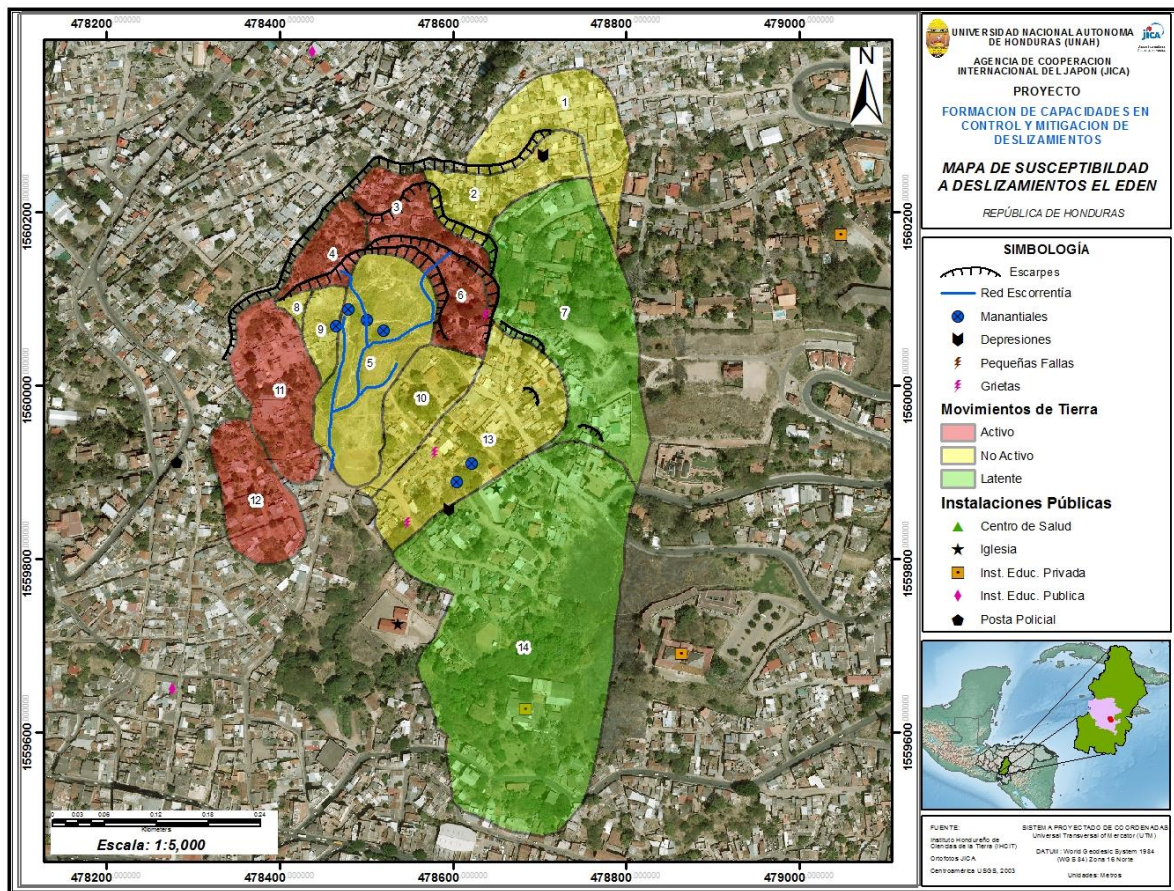
Fig 2. Susceptibility map of the zone of El Edén. Systematic analysis of aerial images, field observation and the assessment of the variables: micro - topography, slope profile, geological conditions, land use and water condition resulted in a map in a 1:5000 scale showing the landslide bodies, its level of activity, relevant public and private infrastructure and runoff courses .Surfaces outlined in blue represent the different antiquities of each block, being the A block the newest block of landslides, the B block, a less recent block of landslides, and C block the oldest block of landslides.

It is also noteworthy, regarding the objectives on capacity building for control and mitigation of landslides, that the results of the process described in this article have reinforced at the level of academia, local government and risk managing institutions, a practical methodology for susceptibility comparison according to topographic, hydrological and social characteristics observable in the field; and has strengthened in the participating team their competence in photo interpretation and use of geographic information systems for determining susceptibility characteristics. The replication potential of the conceptual and procedural contents developed in the course of the project represents one of the most significant gains in the process.

The susceptibility map generated as a result of project capacity building represents a relevant input to the initiative of generating inventories of landslides and risk factors for the Metropolitan area of Tegucigalpa, and is consistent with the mitigation and monitoring efforts of the recent past, representing an important aid for future initiatives of this nature.

Acknowledgments

References

García-Urquia, E; Axelsson, A. (2015). Rainfall thresholds for the occurrence of urban landslides in Tegucigalpa, Honduras: an application of the critical rainfall intensity. Geografiska Annaler Series A: Physical Geography. 97 (1): 61-83.

Kokusai Kogyo Co. (2015). Proyecto de Apoyo para el Fortalecimiento y Formación de Capacidades Profesionales en Control y Mitigación Frente a Deslizamientos de Tierra en la Zona Metropolitana de Tegucigalpa. OYO International Corp.

McLean, R. (2009). Honduras Wastewater Treatment: Chemically Enhanced Primary Treatment and Sustainable Secondary Treatment Technologies for Use with Imhoff Tanks. Masters degree thesis for engineering in civil and environmental engineering. Massachusetts Institute of Technology. USA.

Millar, S. (2014). Encyclopedia of Planetary Landforms. Springer Science + Business Media. New York. USA. (ISBN 9781461431336). 2460p.

Moser, K; Ahn, C; Noe, G. (2007). Characterization of Microtopography and its Influence on Vegetation Patterns in Created Wetlands. Wetlands. 27 (4): 1081-1097.

Spencer, W.(2000). Geologic Maps. A Practical Guide to the Preparation and Interpretation of Geologic Maps. Prentice Hall. New Jersey. USA. (ISBN 0-13-011583-5). 49p

The World Bank. (2016). Average precipitation in depth. http://data.worldbank.org/indicator/AG.LND.PRCP.MM /countries/1W-HN?display=graph (Last accessed: June 26 2016).

USGS (n.d.). Tertiary Sediments. http://mrdata.usgs.gov/geology/state/sgmc-unit.php?unit=MAT%3B0 (Last accessed: June 26 2016).

Yagi, H. (2013). Landslide susceptibility assessment by AHP. First Central American and Caribbean Landslide Congress. Tegucigalpa, Honduras. pp 1-5.

Javier García Reynaud (✉)
National Pedagogical University "Francisco Morazán", Department of Natural Sciences, Tegucigalpa 11101, Honduras.
e-mail: ccnn@upnfm.edu.hn

Kiyoharu Hirota
Ehime University, Department of Infrastructure Development, Center for Disaster Management Informatics Research, Matsuyama790-8571, Japan
e-mail: sbhirota@gmail.com

Satoru Tsukamoto
Kokusai Kogyo Co. LTD, Disaster and Water Resources Management Division, Overseas Operations Department, Kamaishi 026-8686, Japan
e-mail: satoru_tsukamoto@jcom.home.ne.jp

Marco Funes
Municipality of the Central District of Honduras. Integral Management of Risk Municipal Unit, Tegucigalpa 11101, Honduras.
e-mail: marco48122004@yahoo.com

Vera Veliz
Municipal Mayoralty of the Central District, Tegucigalpa 11101, Honduras.
e-mail: vsveliz@yahoo.es

Alex Cardona
National Autonomous University of Honduras. Honduran Institute of Earth Sciences, Risk and Disaster Management Unit. Tegucigalpa 11101, Honduras.
e-mail: aljaca70@yahoo.com

Preliminary report: relationship between geology and landform for landslides of Tegucigalpa, Honduras

Kiyoharu Hirota

Abstract This paper is a report regarding landslides and the relationship between geology and landform in the Tegucigalpa Basin of Honduras. Tegucigalpa is located in an almost rotund basin which is 10 kilometers across with a somewhat elongated east-west axis.

In 1998 when hurricane Mitch made landfall in Latin America, there was an increase in landslides occurring in the Tegucigalpa basin. There are two major types of landslides; the first is a small-scale landslide that rotates near the nick line, and the second is characterized by debris flow removed from the boundary of the slide and has the consistency of somewhere between detritus and tuff.

The landslides are concentrated at the northern to northwestern slopes around the Tegucigalpa basin. In this area, there are Mesozoic sediments belonging to the Valle de Ángeles Group. The sediments consist of dark red silt and sandstone which are the basement rocks in the basin. Pumice tuff, rhyolitic tuff, and ignimbrite overlie the Valle de Ángeles Group. Ignimbrite located in the uppermost stratum of the mountain ridge is flattened and is almost the same level across the entire ridgeline. Ignimbrite flows are broken and tilted by the faults and only partially join. At the slope facing south to southwest, there are some concave forms which gradually decline in the same direction as the slope where the stratum decline. The distribution of ignimbrite forms separated vertical joints and the weathered pumice tuff was deposited at the foot of mountain slope. The northern landform of the Tegucigalpa basin is made by landslides. There are two main factors for these landslides: internal causes and external causes. Internal causes control the geological structure of the landform such as faults, joints, and strata. The external causes are earthquakes, heavy rain, surface runoff, and slope cutting.

Keywords landslide, geology, landform, Tegucigalpa basin, Honduras,

Introduction

The purpose of this study is to monitor geological structures, specifically faults and joints for potential landslides.

We investigated two areas, El Edén and Nueva Santa Rosa in Tegucigalpa as part of the JICA project "Assistance for Strengthening and Capacity Building of Professional Techniques for the Control and Mitigation of Landslides in the Tegucigalpa Metropolitan Area".

Geology and Landform

Geology

Honduras has an area of 112,492 km² and about 70 percent of the area is mountainous. The geology of Honduras is composed of Quaternary deposits (Alluvium), metamorphic rocks, sedimentary rocks, and volcanic rocks, respectively, from the north to the south (Fig. 1).
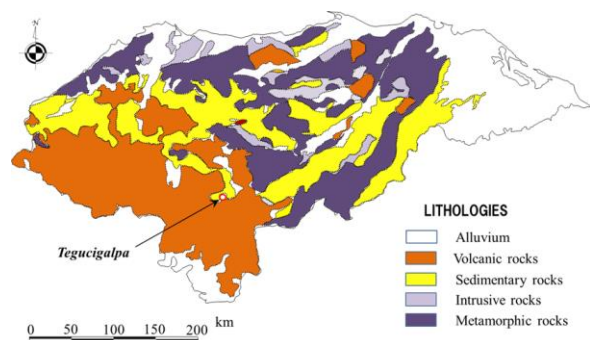
Fig. 1 Geology of Honduras (simplified from Rodgers et al., 2007).

Further geology information about Tegucigalpa, is that hard tuff lies over the Mesozoic sandstone, and ignimbrite that forms the ridge called Cerro El Picacho, along the northern margins of the basin (Fig. 2).
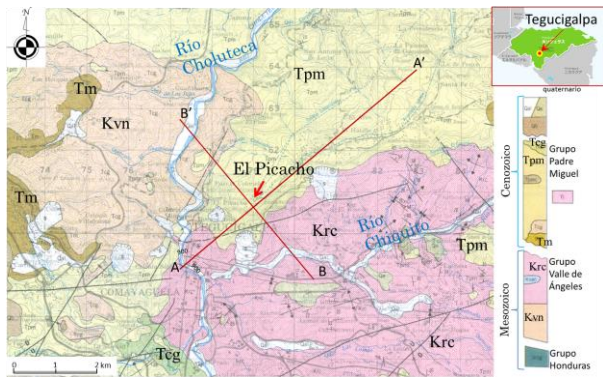
Fig. 2 Geologic Map of TEGUCIGALPA (partial area after Rogers, 1990): **Tpm**, **Tcg**, and **Tm** (the Cenozoic *Padre Miguel* Group), **Krc** as *Río Chiquito* Formation and **Kvn** as the *Villa Nueva* Formation (the Mesozoic *Valle de Ángeles* Group).

Landform

Two cross sections of the ridge of El Picacho, between a longitudinal section (A-A') and a traverse section (B-B', Fig. 2).

The longitudinal section is almost flat on the top of ridge (see Fig.3 and Fig. 4). In the traverse section, the ridge does not show a symmetrical formation, it has a tendency to steeply slope on the south side. There is a thick talus which shifts debris flow deposits and boulder sized rocks from top of the ridge that are composed ignimbrite.
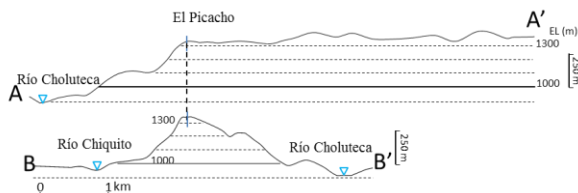
Fig. 3 Cross sections in Fig.2, A-A' and B-B'

Fig. 4 South side slope of *El Picacho* with landslides *Bambú* and *Reparto*.

Landslide

JICA (2002) studied seventeen landslides in Tegucigalpa after Hurricane Mitch, and selected 3 landslide sites, *Berrinche*, *Bumbú*, and *Reparto*, for countermeasures taken against landslides (Fig. 5). Re-evaluating seventeen landslides, the typology is divided mainly into two types, flow-type and slide-type (Hirota and Kamiya, 2014).
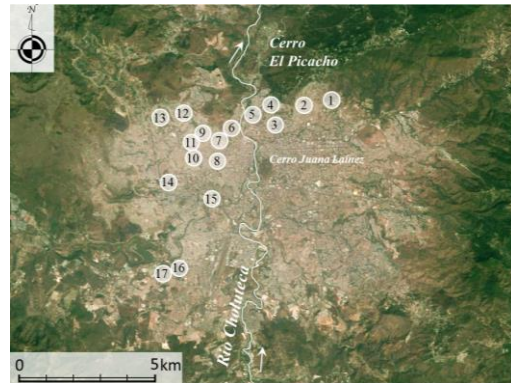
Fig. 5 Landslides in Tegucigalpa: 17 landslides affected by Hurricane Mitch in 1998 (after Hirota, 2015), A Google Earth image is used as the base map: 1. Canaán, 2. Reparto, 3. Bambú, 4. Bosque, 5. Buena Vista, 6. Berrinche, 7. Campo Cielo, 8. San Martín, 9. Flor 1, 10. Zapote Centro, 11. Zapote norte, 12. Villa Union, 13. Brasilia, 14. Centroamerica, 15. Nueva Esperanza, 16. Las Torres Este, 17. Las Torres Oeste.

During the landslide study JICA project the cause of these slides was identified (Yamagishi, 2014; Yamagishi et al.,2014; Hirota,2015; Sato et al.,2015) According to UPI-JICA (2014), we can identify the distribution of landslides in Tegucigalpa. There are many landslides on the north to northwestern slope of the basin (Fig. 6).
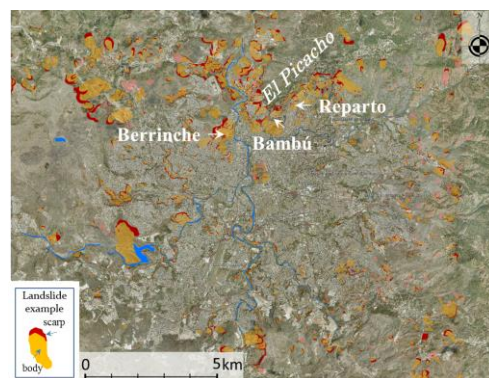
Fig. 6 Landslide Inventry Map of the Tegucigalpa Basin (arranged by UPI-JICA, 2014)).

Results and discussions

The study area is characterized by sedimentary rock which is divided into sandstone, tuff (pumice tuff, rhyolitic tuff), and ignimbrite. Sandstone is the basement rock in this basin. The Valle de Ángeles Group is characterized by reddish fine grained sandstone which partially degrades into siltstone. Tuff is characterized various facies, pumice tuff, rhyolitic tuff, which includes andesitic rock and dacitic rock. The rock is partially weathered at the boundary between the sandstone and ignimbrite.

Ignimbrite is usually vertically jointed. The ignimbrite flows are widely broken and tilted by the joints and faults. It is easy for rainfall to penetrate through the vertical joints.

In the geological structure there are significant faults at NE-SW and NNW-SSE. The fault with the directions of NE-SW is concordant with the longitudinal axis of the El Picacho ridge. There are probably convex breaks in the slope with ignimbrite joints at the El Picacho ridge. El Picacho's detailed geological structure remains unknown, but the data indicates a fault line (red broken lines on the right side of the geologic map in Fig. 7). This area should be studied further.
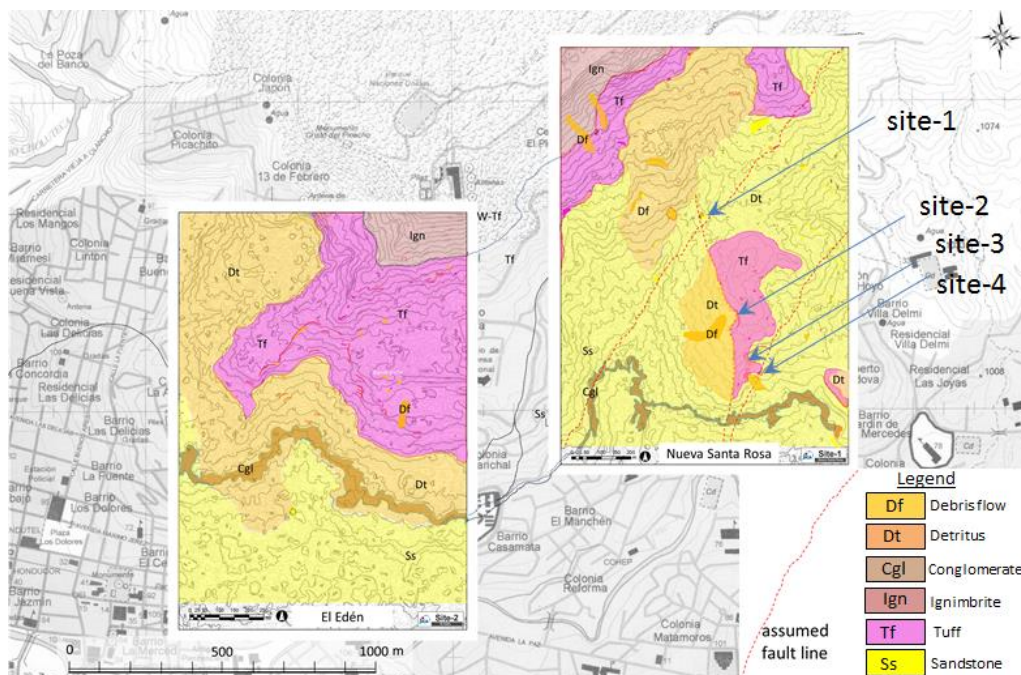
Fig. 7 Geological Map of two sites El Edén and Nueva Santa Rosa

Site-1 has two faults (Fig. 8). The first fault strikes at N14°W and dips 62°S in detritus (Fig. 8B). The second fault strikes at N30°E and dips 42°N in sandstone (Fig. 8C). Site-2 is composed crushed pumice tuff due to the fault's movement (Fig. 9A). Site-3 is composed of pumice tuff (Fig. 9B, 9B'). Site-4 is composed of sandstone and pumice tuff, in which two of the faces are in contact with fault (Fig. 9C). The fault strikes at N32°E and dips 57°S. The pumice tuff is crushed into fine particles and composed of massive broken tuff blocks.
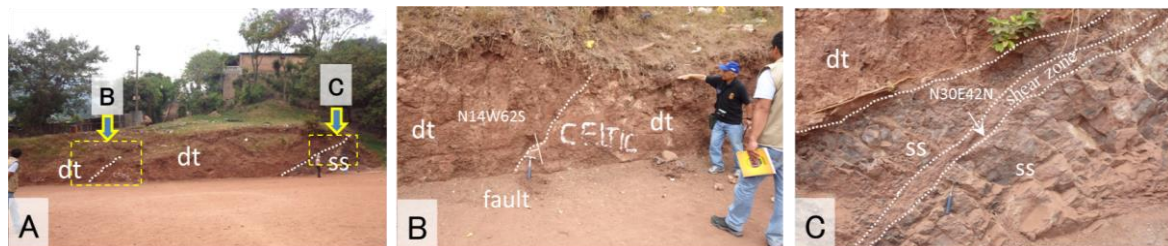
Fig. 8 Site-1 as listed on Figure 7: outcrop with faults at Nueva Santa Rosa. A: Outcrop, B: fault with strike/dip of N14°W62°S in detritus (dt), C: fault with strike/dip of N30°E42°N in sandstone (ss).

21
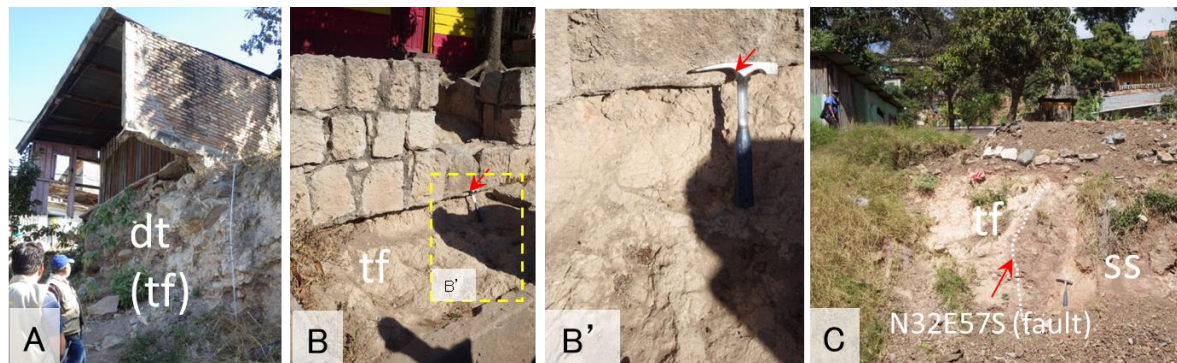
Fig. 9 Outcrop Site-2 (A), Site-3 (B, B'), and Site-4 (C) in Figure 7. A: Scarp of landslide with detritus (dt) that originated from tuff, B: Outcrop of tuff (tf), C: Fault with strike/dip of N32°E57°S.

Conclusions

1. Topographic features of El Picacho include a steep slope on the south side.
2. The formation of landforms with steep slopes is dependent upon underlying geological structures; such as faults.
3. In this study area, landforms are directly related to geologic structure, internally caused by faults and joints and externally caused by precipitation.
4. Micro-landforms are most likely caused by weakened bedding planes of tuff and faults. It makes horseshoe shape in the fault and bedding plane.

Acknowledgments

References

Hirota, K. (2015): Landslide and geology education in Honduras, as activities of Japan International Cooperation Agency senior volunteer. Journal of the Japanese Landslide Society, Vol. 52, No. 4, pp. 36-42.

Hirota, K. and Kamiya, S. (2014): Re-evaluation of landslide caused by Hurricane Mitch 1998, Tegucigalpa Honduras. In: K. Sassa (ed.) landslide Science for a Safer Geo-Environment, Vol. 3, pp.393-400.

JICA (2002): The study on flood control and landslide prevention in Tegucigalpa metropolitan area of the republic of Honduras (official document). Final Report in English version.

Sato, G., Kamiya, S., and Hirota, K. (2015): Investigation and Mitigation of Landslide in Republic of Honduras as Japan´s International Cooperation Program. Journal of the Japanese Landslide Society, Vol. 52, No. 4, pp. 1-7.

Rogers, R. D. (1990): Geologia del Cuadrandulo de Tegucigalpa, Francisco Morazan. "TEGUCIGALPA" de Mapa Geológico de Honduras, Geología Honduras 1:50,000, Secretaria de Comunicaciones, Obras Públicas y Transporte, Instituto Geográfico Nacional.

Rogers, R. D., Mann, P. and Emmet, P.A. (2007): Tectonic terranes of the Chortis block based on integration of regional aeromagnetic and geologic data. Geological Society of America Special papers, 428, pp.65-88.

UPI-JICA, (2014): Manual Para Elaboración de Inventario de Deslizamientos de Tierra. Caso de aplicación: Ciudad de Tegucigalpa. Agencia de Cooperación Internacional del Japón (JICA). Tegucigalpa. ISBN: 978-99926-701-1-8

Yamagishi, H. (2014): Integrated Disaster Prevention Maps and Landslide Hazard Maps using GIS –Examples of Shikoku and Central America Honduras-. Journal of the Japanese Landslide Society, Vol. 51, No. 2, pp. 24-29.

Yamagishi, H., Yagi, H. and Sato, G. (2014): Landslide Hazard Mapping of Tegucigalpa, Honduras-Capacity Building by JICA-JSPS Project of 2012-2014. Proceedings of World Landslide Forum 3, 2-6 June 2014, Beijing, 712-715.

Kiyoharu Hirota (✉)

JICA (Hirota PE office): 1-28, Minami-machi 2 chome, Matsuyama, Ehime Prefecture, 790-0856 Japan

e-mail: sbhirota@gmail.com

Landslide mapping using a 2 m DEM based on AW3D digital topographic data in Tegucigalpa, Honduras

Go Sato, Hiroshi Yagi, Elias Garcia-Urquia, Mark Mullings,

Takeshi Kuwano, Kazuo Isono

Abstract Detailed landslide distribution maps are necessary for planning structural and non-structural measures in Tegucigalpa, Honduras. We constructed landslide maps for two sites using a 2 m DEM based on AW3D digital topographic data and aerial photography. Our results demonstrate the effectiveness of high-resolution DEMs for making detailed landslide maps and for slip surface estimation, even for landslides with depths at the meter scale.

Keywords Landslide mapping, AW3D, DEM, landslide topography, Tegucigalpa

Introduction

In 1998, Tegucigalpa, the capital of the Republic of Honduras, suffered heavy damage caused by massive landslides that were induced by Hurricane Mitch (Harp et al., 2002; JICA, 2002). In response, the Japan

Table 1 Projects for landslide prevention in Honduras supported by the Japanese government (after Sato et al., 2015)

Program Title	Period	Scheme	Counterpart
Metropolitan landslide prevention plan in the Republic of Honduras	2000-2002	Development survey	Secretariat of Public Works, Transportation and Housing (SOPTRAVI) Technical Secretariat and International Cooperation (SETCO) Permanent Committee of Contingencies (COPECO) National Autonomous Survey of Aqueducts and Sewage (SANAA) Secretariat of Natural Resources and Environment of Honduras (SERNA) Municipal Council of the Central District (AMDC)
Project on landslide prevention in the Tegucigalpa Metropolitan Area	2011-2013	Grant aid	Municipal Council of the Central District (AMDC)
Project on capacity development for disaster risk management in Central America "BOSAI" (Phase 1)	2007-2012	Technical cooperation project	Permanent Committee of Contingencies (COPECO) Municipal Council of the Central District (AMDC) Municipality of Namasigüe Municipality of El Triunfo Municipality of Marcovia
Hazard geology focusing on the landslides in Tegucigalpa	2011-2013	Dispatch of science and technology researchers (JSPS-JICA)	Geoscience Institute of Honduras (IGH) Engineering Polytechnical University of Honduras (UPI) National Autonomous University of Honduras
JICA's volunteer program	2011-2013	Senior volunteers	Engineering Polytechnical University of Honduras (UPI) Panamerican Agricultural School
Assistance for strengthening and capacity building of professional techniques for the control and mitigation of landslides in Tegucigalpa Metropolitan Area	2015-2016	Dispatch of Expert	National Autonomous University of Honduras (UNAH) Municipal Council of the Central District (AMDC)

A: Landslide distribution map. The landslide distribution that was shown by the project of "Hazard geology focusing on the landslides in Tegucigalpa" was used. The hill shade image was developed using 5 m DEM was provided by UNDP. B: El Berrinche landslide. C: El Bambu landslide, D: El Reparto landslide. The pictures of Fig. B, C and D were taken on September, 11, 2012. The broken line shows the area of countermeasure.

Fig. 1 Landslide distribution and landslide topographies in Tegucigalpa (Sato et al. 2015)

International Cooperation Agency (JICA) undertook six projects (see Tab. 1) using Japanese scientific methods and technologies to reduce landslide hazards in the region. Through the projects "Metropolitan landslide prevention plan in the Republic of Honduras" and "Project on landslide prevention in the Tegucigalpa metropolitan area", structural measures such as catchment wells and water collection drains were constructed at landslide sites. These landslide sites have not undergone any subsequent movement, owing to the effectiveness of these countermeasures (El Heraldo, 2013). On the other hand, such construction projects are costly, and it is difficult to address all landslide-prone sites in Tegucigalpa. Therefore, non-structural measures, for example hazard mapping, education in disaster prevention, and land-use regulation, are also important methods for decreasing landslide disasters (Orrego, 2013). In planning Tegucigalpa's structural and non-structural measures,

detailed landslide distribution maps are needed. In this paper, we introduce the landslide mapping results and outline advantages of using high-resolution AW3D for the construction of a 2 m DEM.

Study Area

Tegucigalpa is located in central Honduras. To date, it occupies an area of approximately 200 km² and is inhabited by nearly 1.5 million people. The city is surrounded by mountains, and its residential area has not only developed in the valley bottom, but also on hillslopes. Unfortunately, the lack of a proper urban plan and the rural migration to the city driven by the search for a better life has aggravated the housing deficit in the city in the last decades (Angel et al., 2004). Due to the existence of an illegal parallel land market that promotes housing in unstable areas (Pearce-Oroz, 2005), several thousand inhabitants live
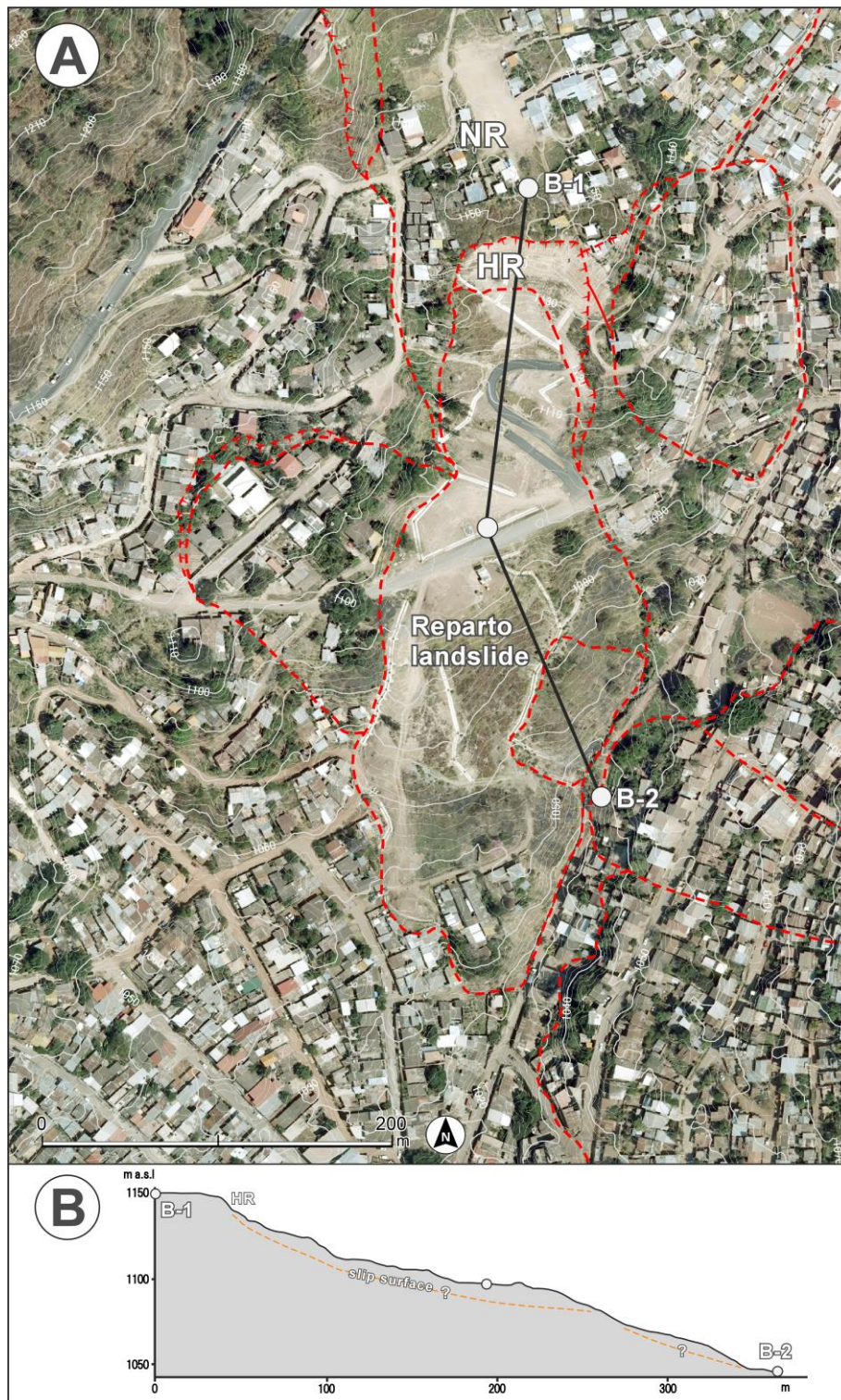
Fig. 2   A: Landslide mapping in and around Reparto. Contours were created from the 2 m resolution AW3D DSM. JICA installed drainage wells and surface water drainages in the area. The red dashed lines indicate the landslide extent. B: Profile of the Reparto landslide, from B-1 to B-2 in Fig. 2A
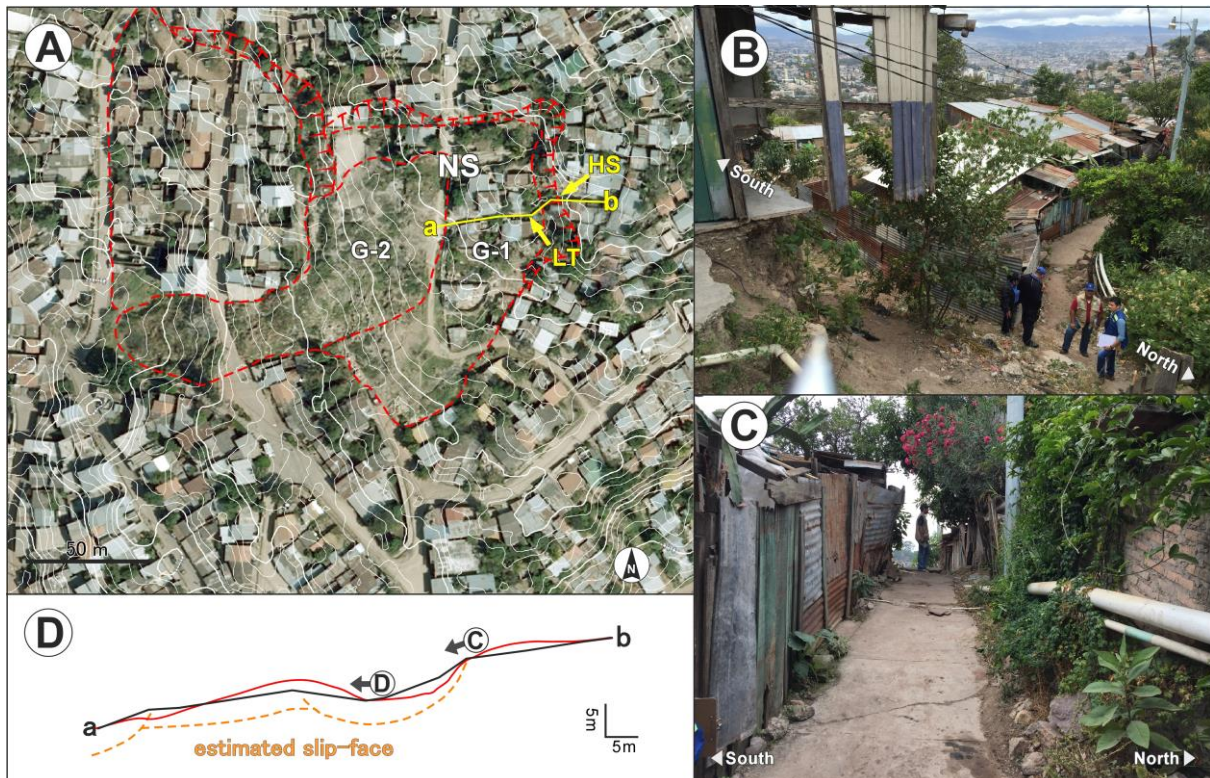
Fig. 3 A: Landslide map of Nueva Santa Rosa. Contours were created from the 2 m resolution AW3D DSM. B and C: Site photographs taken in February 2016 at locations B and C, as marked in Fig. 3-D A. D: Longitudinal profile (a–b) constructed from location surveying (black line) and AW3D 2m DEM (red line).

at risk of losing their lives and belongings every year due to floods and landslides during the rainy season (May to October). Deforestation, uncontrolled loading and cutting of slopes and the lack of appropriate drainage of sewage and rainwater have all contributed to the occurrence of urban landslides. These anthropogenic actions have made the relationship between the triggers and the different kinds of landslides in the study area difficult to analyse (Garcia-Urquia, 2015).

Landside topographies are well developed, especially in the northern part of the basin (Fig. 1). The landslide study done by Garcia-Urquia and Axelsson (2014) has revealed that landslide activity is very frequent in this part of the city due to the rugged topography and a high population density. Landslide sites at Berrinche (Fig. 1B), Bambú (Fig. 1C), and Reparto (Fig. 1D) were affected by Hurricane Mitch. Structural measures were constructed for these landslides under JICA projects (JICA, 2002). In this paper, we present two detailed landslide maps, one for the Reparto landslide and the other for an active landslide site at Nueva Santa Rosa (see Fig. 1 for location).

Method

We have conducted landslide mapping and susceptibility evaluation since 2015, as part of one of the projects carried out by JICA. In this project, we used digital aerial photography taken by JICA (Yamagishi et al., 2014), and a high-resolution digital elevation model (DEM) generated by NTT DATA and the Remote Sensing Technology Center of Japan (RESTEC) using Digital Globe imagery. These data have enabled us to create a detailed landslide distribution map. In addition, we have constructed profiles and estimated slip surfaces for two landslide sites.

Results and Discussion

The Reparto landslide distribution map

The Reparto landslide map is shown in Figure 2A. Contours at 2 m intervals were created from the AW3D 2 m DEM, using satellite images observed in 2013. The aerial photograph of the site was taken by JICA in 2013. Topography interpreted from aerial photography and from DEM contour intervals is consistent; surface features in the body of the Reparto landslide are well

expressed. Because the DEM is actually a Digital Surface Model (DSM), contour lines of areas without trees and houses represent the surface topography well. Using the map, we identified landslide areas and delineated them with red dashed lines in Fig. 2A. These show that the Reparto landslide occurred on the site of a previous event, because the landslide body (NR) was dissected by the Reparto landslide head-scarp (HR). Figure 2B shows the profile between B-1 and B-2, which provides a good representation of landslide topography. The AW3D 2 m DEM provides us with very important data for the initial stage of countermeasure planning as we can estimate landslide slip surfaces from it.

The Nueva Santa Rosa landslide distribution map

Figure 3A is a map of the Nueva Santa Rosa landslide (GY), which has moved intermittently since 2008, and is divided into two parts, G-1 and G-2. Figure 3B is a photograph of the G-1 head-scarp (taken at HS on Fig. 3A), which shows house foundations destroyed by the landslide. Figure 3C, which was taken from LT looking westward (opposite direction to head-scarp), shows a walkway tilted to the head-scarp side. We conducted a summary survey using the laser rangefinder "TruPulse 200" between locations A and B, and the micro topography produced is shown by the black line in Fig 3D. From its characteristic shape, it is clear that the eastern-side of landslide body G-1 has moved as a rotational slide. The estimated slip surface is shown with orange dashed lines. The red line is the profile created from the AW3D 2 m DEM using Arc GIS 3D analyst. The profile shape is a good reflection of the real ground, closely matching the laser survey line.

Conclusion

Our results demonstrate the applicability of using AW3D data to generate a 2 m DEM for mapping both large scale landslides like Reparto, and small scale landslides with only several meters depth, like Nueva Santa Rosa. The use of high resolution topographical data enables the estimation of slip surfaces, making it ideal for the establishment of structural measures for the reduction of landslide risk.

Acknowledgments

Reference

Angel, S., Bartley, K., & Derr, M. (2004). Rapid Urbanization in Tegucigalpa, Honduras: Preparing for the Doubling of the City's Population in the Next Twenty-Five Years.

El Heraldo. (2013). Mas de 81 años de pánico finalizan en El Berrinche. El Heraldo. Published on August 14th, 2013. Retrieved from http://www.elheraldo.hn/Secciones-Principales/Metro/Mas-de-81-anos-de-panico-finalizan-en-El-Berrinche

Garcia-Urquia, E., & Axelsson, K. (2014). The Use of Press Data in the Development of a Database for Rainfall-Induced Landslides in Tegucigalpa, Honduras, 1980-2005. Nat Hazards, 73(2), 237-258. doi:10.1007/s11069-014-1043-5

Garcia-Urquia, E. (2015). The Use of Press Archives in the Temporal and Spatial Analysis of Rainfall-Induced Landslides in Tegucigalpa, Honduras, 1980-2005. (Doctoral Degree), Uppsala University, Uppsala, Sweden.

Harp, E. L., Castañeda, M., & Held, M. D. (2002). Landslides triggered by Hurricane Mitch in Tegucigalpa, Honduras: U.S. Geologic Survey Open File Report 02-0033.

JICA (2002). The Study on Flood Control and Landslide Prevention in Tegucigalpa Metropolitan Area of the Republic of Honduras.

Pearce-Oroz, G. (2005). Causes and consequences of rapid urban spatial segregation. In D. Varady (Ed.), Desegragating The City: Ghettos, Enclaves and Inequality (pp. 108-124): Suny Press.

Orrego, J. C. (2013). En busca del orden perdido: PNUD Honduras.

Sato, G., Kamiya, S., K., Hirota (2015) Investigation and mitigation of landslides in Republic of Honduras as Japan's International cooperation program. Journal of Japan Landslide Society. 52 (4) 161-167.

Yamagishi, H., Yagi, H., & Sato, G. (2014). Landslide hazard mapping of Tegucigalpa, Honduras - capacity building by JICA-JSPS Project (2012 to 2014). Proceedings of World Landslide Forum 3, 2-6 June 2014, Bejing, 712-715.

Go Sato （✉）

Teikyo Heisei University, Graduate School of Information Science, 4-21-2 Nakano, Tokyo, 164-8530, Japan
e-mail: gsato@thu.ac.jp

Hiroshi Yagi

Yamagata University, Faculty of Education, Art and Science, Japan
e-mail: yagi@e.yamagata-u.ac.jp

Elias Garcia-Urquia

National Autonomous University of Honduras, Civil Engineering Department, Tegucigalpa, Honduras

e-mail: elias.urquia82@gmail.com

Mark Reilly Mullings Najera

National Autonomous University of Honduras, Earth Sciences Honduran Institute, Tegucigalpa, Honduras

e-mail: markunah@hotmail.com

Takeshi Kuwano

Kokusai Kogyo Co., Ltd, Tokyo, Japan

e-mail: takeshi_kuwano@kk-grp.jp

Kazuo Isono

Remote Sensing Technology Center of Japan, Tokyo, Japan

e-mail: isono@restec.or.jp

How to make a database of landslides in Tegucigalpa, Honduras

Lidia Torres, Nelson Sevilla, Kyoharu Hirota, Hiromitsu Yamagishi, Satoru Tsukamoto

Abstract This article aims first to highlight the importance of integrating new divulgation systems for the application of analytical tools in evaluating landslides, also it aims to inform the reader interested; the basic process for creating a map of susceptibility to landslides through photo interpretation in conjunction with basic elements such as geological field surveys and use of Geographic Information Systems (GIS). A Landslide Interactive Teaching Tool is presented trough this article and it is also one of the most relevant results of the Project: Assistance for Strengthening and Building of Professional Techniques for the Control and Mitigation of Landslide Capacity in Tegucigalpa-Honduras Metropolitan Area; which it was conducted with the support of the Japan International Cooperation Agency (JICA) to strengthen National Autonomous University of Honduras (UNAH) researchers and to strengthen action framework between academia and decision makers at the local level (Municipality of Central District; AMDC)

Keywords Landslides, aerial photographs, photointerpretation, Geographic Information Systems, susceptibility maps, database, layers, Analytical Hierarchy Process (AHP).

Introduction

Honduras, a country located in the central part of Central America, with coastlines open to both the Atlantic Ocean and the Pacific; it is geographically located in a region that increases the level of risk to be affected by natural hazards, as it is positioned in the forced route of tropical storms and hurricanes; it has also been listed as one of the 20 countries with the highest risk of damage from flooding and landslides caused by hydro-meteorological threat, and also the degree of exposure and vulnerability of communities living in risk areas. In Honduras are also seen, different factors that increase the level of risk such as indiscriminate development, land and agro-ecological condition of the country, as well as mismanagement and destruction of watersheds, uncontrolled population growth and migration from the rural areas to the city, etc.

Hurricane Mitch in 1998, let see not only the high level of country's exposure to natural hazards stemming from its geographical position, but also its high degree of vulnerability, resulting from the interaction of natural hazards with inadequate systems of the environmental/land resources and a number of human factors causing alarming risk conditions.

The Republic of Honduras has a population of 8.6 million people of which 54% live in the major cities; it has an area of 112,000km². In Honduras the population is unevenly distributed; migration from the countryside to major cities increases poverty in them, forcing residents to settle in high risk areas in precarious conditions. During the second half of the twentieth century, there was an accelerated process of urbanization in Honduras. The population living in cities increased from 30.3% of the total in 1950 to 46% in 2001. Between 1988 and 2001, the urban population grew at an average annual rate of 3.4%, higher than the population growth of the country a whole, which was 2.6%. According to the National Institute of Statistics (INE, 2015) estimates this trend has continued in the period 2001- 2008, with a growth rate of urban population of 3.6% compared to 2.4% of the total population, increasing urban population to 50% of the total. (INE, 2007)

Tegucigalpa is a city with an area of 150 Km² approximately; and hosts about 14% of the country total population, and according to the Municipal Emergency Committee of the Central District (CODEM-DC) in 2010, about 150 neighbourhoods has some problem with landslides.

All the above, reveals the urgent need to study landslide risk in Tegucigalpa, promote joint actions among relevant institutions such as UNAH, local government offices, the Municipal Emergency Committee (CODEM) supported by the Honduran Permanent Commission of Contingencies (COPECO); these institutions should be kept permanently researching for vulnerability and risk reduction, control and mitigation of landslides. That is why the focus of the JICA suggested and urged capacity building for the UNAH through the Honduran Institute of Earth

Sciences (IHCIT) to jointly with the Local Government in the developing of landslide evaluation projects to promote the control and mitigation from landslide. For this reason, pilot intervention projects were carried out in two critical sites in the city of Tegucigalpa, and as a result, landslide susceptibility maps were created. The results of the process to create the landslide susceptibility maps generated the creation of a Landslide Interactive Teaching Tool, seeking to promote an interactive and dynamic way to socialize results through a database or web tool based on our experiences from landslide interpretation by aerial photographs to landslide mapping using GIS.

The history of landslides in Honduras and specifically in the metropolitan area of Tegucigalpa

Throughout history, Honduras has been hit by severe hurricanes and tropical storms, which have caused huge economic losses but even more importantly loss of life. Among the hurricanes that more damage caused can mention Hurricane Alma in 1966, Hurricane Marco occurred in 1969, Edith in September 1971, Hurricane Fifi in 1974, Mitch in October 1998, Katrina in 1999, most recently we have Michelle and Beta in 2001, Hurricane Wilma in 2005 and Felix in 2007. The most devastating of all were the Fifi and Mitch, as we can see in the Tab 1.

Landslide disasters by Hurricane Mitch in 1998

The intense rainfall caused by Hurricane Mitch from 27 to 31 October 1998 in parts of Honduras came to exceed 900 mm and caused more than 500,000 landslides throughout the country. Based on calculations of the US Army Corps of Engineers, it is estimated that landslides damaged 70% of the road network in Honduras. The number of deaths caused by landslide is not known precisely because in many of the Honduran communities, the number of people missing as a result of landslides was not recorded. More than 95% of landslides consisted debris flows. These thicknesses ranged from 1 to 15 m; path length of the flow was from several meters to 7.5 km. The highest concentration of debris flows occurred in the mountains near the town of Choluteca at the south part of the country. Landslides several deep earth that occurred in the city of Tegucigalpa seriously affected people and property in this city. The collapse of the rotational landslide (Berrinche landslide), followed with a volume of approximately six million cubic, completely destroyed the neighbourhood of Colonia Soto, near the downtown. The landslide caused the damming of the Rio Choluteca, which resulted in the formation of a lake; brought about a serious health problem for the

city, due to the discharge of untreated sewage in the Choluteca River. (Harp et al., 2002)

Table 1 The Hurricane that damaged the most in the past 35 years in Honduras. Translated from the Report: En Tierra Segura. Desastres Naturales y Tenencia de la Tierra-Honduras: La Amenaza Hidrometereológica en Honduras. (FAO-UNHABITAT, 2010.)

Year	Hurricane	Caused Impact
1974	Fifi	Approximately 8,000 deaths, 80% of the road network destroyed, total damages around 900 million USD in 1974
1998	Mitch	1.5 million victims, around 5,657 dead, 8,058 missing, 12,272 injured, 285,000 houses affected or destroyed, 60% of road damaged, 189 bridges destroyed, 81 uncommunicated cities, damage around of 3,800 million USD.
2001	Michelle	6 deaths, 14 missing, 27,719 victims
2001	Beta	60,483 victims, 237 homes destroyed and 954 damaged, 11,000 people without home, 41 bridges destroyed or damaged, 30 unutilized roads

Due to the slow movement of the earth it was possible to evacuate residents who lived in the mass of the landslide however the rapid displacement of slide began and culminating in the damming of the river. The river was blocked at approximately 12:30 am of October 31, about an hour after the maximum flood flow occurs in Choluteca River; Fig. 1 shows the mechanism of this landslide.

Historically, there have been emergencies every year due to floods and landslides in Tegucigalpa, especially during the rainy season. That is why we consider the importance of analysing which has been the factors that have led the city to deal with this problematic. The characteristics of the risks in Tegucigalpa can be summarized as follows: (a) a high rate of pollution of rivers, (b) invasion of land on the banks of rivers, (c) insufficient solid waste collection system, (d) soil erosion, including the reduction of the natural riverbeds generating floods in the lower basin, (e) the city of Tegucigalpa is surrounded by sedimentary and volcanic rocks, highly susceptible to failure in the presence of water, (f) lack of urban water channelling, (g) inadequate management of surface water and lack of sewerage system in some sectors, (h)

there are approximately 54 critical sectors, the risk conditions are exacerbated by steep terrain, or the road constructions in inadequate forms.

Fig. 1 Aerial view of the land called the Berrinche, followed by subsidence / rotational flow. The arrow indicates the direction of displacement of the whole landslide body. "T" denotes the sliding to the river; the "L" indicates the lake dammed by landslide. (Harp et al., 2002)

Landslide susceptibility map development in Tegucigalpa. (Basics Processes)

In this section we try to summarize the most important points during the construction of landslide susceptibility maps. This requires the generation of an inventory maps of landslides in the study sites (Nueva Santa Rosa and El Eden, in Tegucigalpa). In this project landslide susceptibility mapping is analysed through the methodology known as Analytic Hierarchical Process (AHP) method (Yagi et al., 2009); managing to give a quantitative value to each slide block; this allows classified interpretation through the use of GIS. Many different activities were taken place during this evaluation to finally obtain the two susceptibility maps and also the database through the Project Cloud System. Main activities are summarized as: (1) seminar and workshops on Geology, Geophysics, usage of the GIS software namely ArcGIS and aerial photo-interpretation, (2) design and application of a hazard perception survey, (3) photo-interpretation practices using aerial photographs of the study sites, (4) recognition and verification field surveys, (5) ArcGIS digitalization works, (6) unification of photo-interpretation and field observation criteria, (7) survey data analysis for geology recognition and GPS topography survey, (8) installation of a GIS laboratory, (9) installation and strengthening management tolls for control and monitoring of landslides, (10) creation and feeding of the cloud system and project database. Fig. 2

summarize the basic sequential process to create the landslides susceptibility maps before the ArcGIS digitalization data and Fig. 3 shows some of the field recognition data collection process.
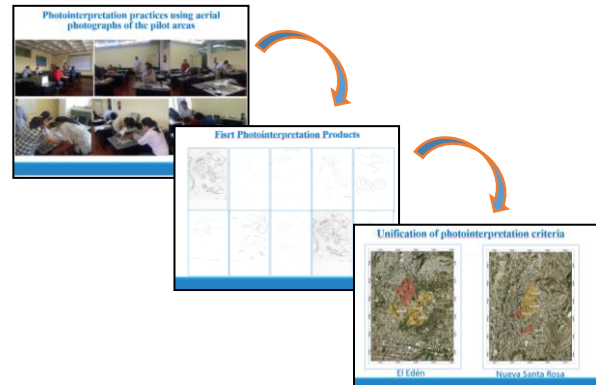
Fig. 2 Basic sequential process for photo interpretation and field verification. Finally getting a map verified and improved through the field recognition

Fig. 3 Photographic overview of the different field activities done for obtaining susceptibility maps

Landslide susceptibility map for Nueva Santa Rosa

The susceptibility map is the final product by all the above activities. Field work, laboratory, data processing work and multi-criteria analysis are summarized in a single product. Finally this is the product that can be use by the decisions makers to prioritize areas of intervention, monitoring work, evacuation, control and mitigation; as well as community education. Fig. 4 shows the preliminary results for one of the pilot cases operated during this project.
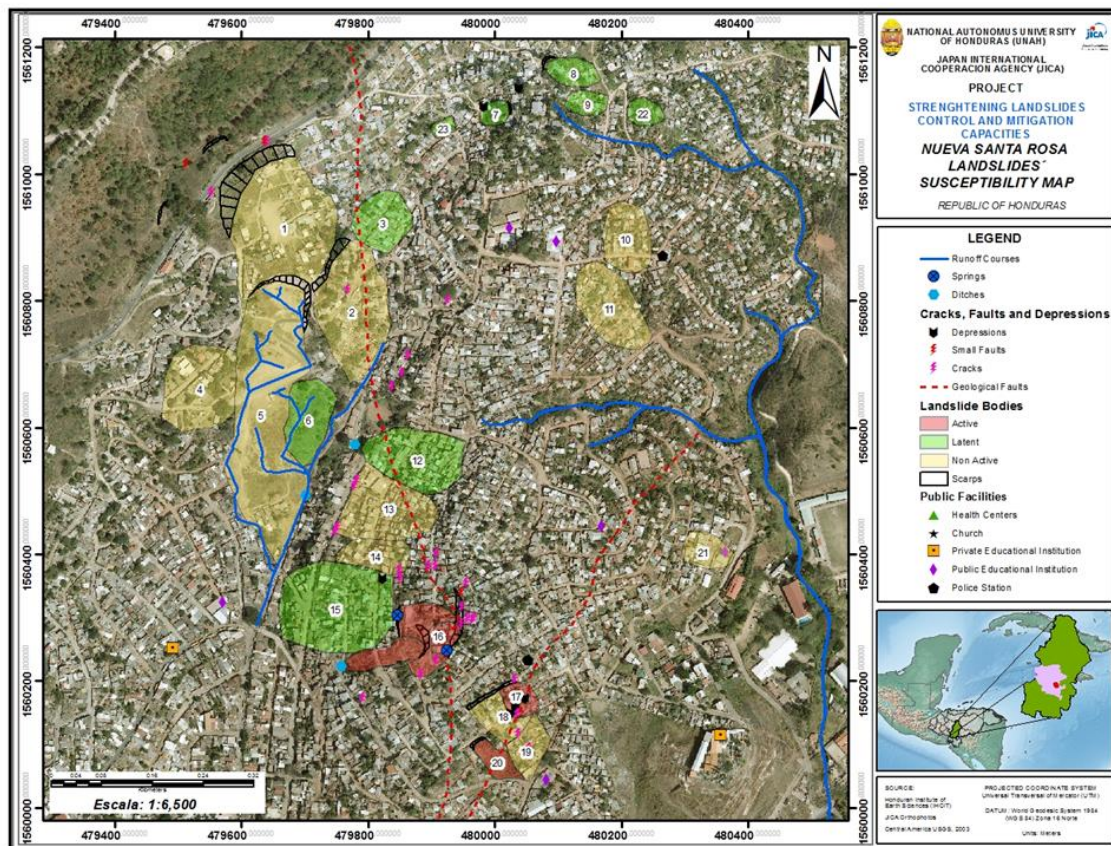
Fig 4 Susceptibility map of the zone of Nueva Santa Rosa. Systematic analysis of aerial images, field observation and the assessment of the variables: micro-topography, slope profile, geological conditions, land use and water condition resulted in a map in a 1:5000 scale showing the landslide bodies, its level of activity, relevant public and private infrastructure and runoff courses.

Technical development of the database for landslide in Tegucigalpa

This process is discussed among a group of specialists on the systems, data management, GISs and networks; trying to find a friendly way to integrate, store and view reports, data, surveys and landslides characterization maps for each of the two pilots sites: Nueva Santa Rosa and El Eden, both colonies of the Metropolitan area of Honduras, formed by the cities of Tegucigalpa and Comayagüela. Technical requirements for its creation can be summarized as follows: (1) Server Open Source operating system, database manager MSQL, (2) GIS Server and (3) Server/ Application Image Viewer.

New web system: designing, creating and feeding the database

The operation of this tool is based on client – server; where the administration of the layers and information is stored and processed on a network server with restricted access, but the publication are free access to specialized users, academics and the general public. Fig. 5 shows the structure of the system, which is explained in detail by component as below: (a) data server layers: will store finished products like layers, images, reports, documents and others; (b) data server: stores, manages data in tables for easy reference and access; (c) GIS server: server where final landslides mapping is generated and converter into publishable images; (d) work station: are the equipment's where specialists and other developed or researchers made its own calculations, studies, topographic maps, documents, etc; (e) system security: access control system to provide access to products according to the permissions granted to each user; (f) viewer: public access server images, layers, documents, etc. the user will access to all published information located on the server. But, through the viewer we do not allow that consultations

access directly to the server for security reasons; (g) network: network system that enables communication between process equipment, storage and display of information, (h) general user: group of users who can access information in their computers, mobile devices such as iPad, smartphones, PDAs, etc.
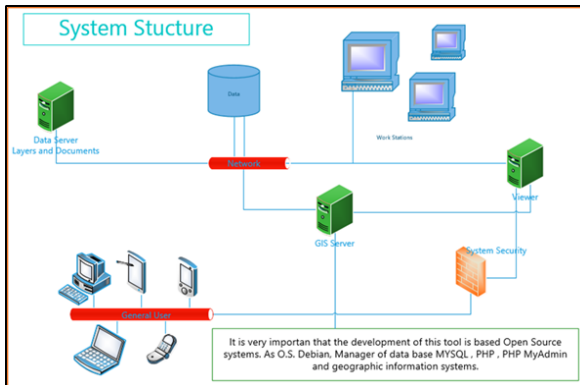
Fig. 5 Shows the Informatics System Structure containing and displays the database through the Project Cloud System.

How and who can access the database

Management services, consultation and feeding the database are performed via web through the HTTPS protocol, this according to the roles assigned to each user created for different authors. User roles are defined as follows: (a) level 1: users and the general public, (b) level 2: users, with editing faculty, (c) system administrators.

On the basis that user's level 1 could be students, teachers and the general public, and they will access only to layers in image format and to documents and reports in txt or pdf etc. Clarifying that at any time they need data for non-profit purposes, through formal request they will be able to offer the raw data.

In the case of level 2 users; these will have editor faculties, this means that they can upload information, which will be reviewed by specialists in charge; who grant permission to publish any new information that has been charged by these users and can also generate a change in layers, adding or removing relevant information.

Managers are responsible for reviewing each of the information (surveys, data, images, etc.) received by level 2 users, for analysis and subsequent publication or removal from the system.

A tool for social contribution. (point of view of the creators)

The UNAH, through IHCIT who were in charge of design, development and implementation of this Landslide Interactive Teaching Tool, believes that this toll is an innovative proposal for communication with the general public regarding to the issue of landslides. This teaching tool is intended to publicize the results of the pilot project in the colonies El Eden and Nueva Santa Rosa with support and funding from the JICA through Kokusai Kogyo Co. LTD, in collaboration with the AMDC and the CODEM; but at the same time, this teaching tool seeks to integrate other actions, to create a database that offers quality information and serve to document the efforts of the academy, the local government, NGOs, international cooperation and any other interested party. It is noteworthy that the development of this action marks an starting point for multi-sectoral integration; since it involved the participation and collaboration of other universities in the public sector such as the National Pedagogical University Francisco Morazán (UPNFM) and the Polytechnic University of Engineering (UPI) from the private sector; also managed to establish joint collaboration agreements with AMDC, CODEM, Secretary of Infrastructure and Public Services (INSEP) among others; therefore, we believe that the tool has a social value to improve knowledge of risk and disaster risk reduction and is offering a significant contribution to the Honduran society.

Discussion

One of the main factors of weakness in Honduras to cope with risk and vulnerability is the lack of knowledge of our hazards and the risk situation, lack of socialization and awareness to communities at risk; as well as the lack of economic resources permanently assigned to disaster risk reduction with a focus on prevention and mitigation. Therefore certain considerations must be taken into account, especially social education in terms of the threats we face; it is necessary to promote the analysis and scientific research of natural hazards over the country so that these studies become an instrument for the decision makers and also can be used as tools for teaching/learning to the public and private sectors; but specially for communities at risk.

For these reasons, we believe that this Teaching Tool provides useful information, certified by international and national experts; technically supported by the local government and supported by other relevant institutions inside and outside the country. It also offers a new proposal for mass communication of understanding of the threats against landslides through the virtual accessibility.

This teaching tool aims at a significant contribution to the Honduran society in promoting Risk

Management and Disaster Reduction caused by landslides especially in the Metropolitan Area of AMDC.

References

FAO-UNHABITAT (2010) En Tierra Segura. Desastres Naturales y tenencia de la Tierra. Honduras; La Amenaza Hidrometeorológica en Honduras. http://www.fao.org/docrep/013/i1255b/i1255b00.htm

Harp, E.L., Hagaman K.W., Held, M.D., McKenna J.P., (2002) Inventario digital de deslizamientos de tierra y los depósitos provocados por éstos que causó el paso del huracán Mitch en Honduras, Science for a Changing World. USGS.

Hirota, K. (2015) Landslide and geology education in Honduras, as activities of Japan International Cooperation Agency senior volunteer, Journal of the Japan Landslide Society. Vol.52, No.4, pp.36-42.

INE (2007) Honduras: Proyecciones de Población 2001-2050. Tegucigalpa 2007. Instituto Nacional de Estadística.

INE (2015). Honduras-XVII Censo de Población y VI de Vivienda 2013. Instituto Nacional de Estadística.

Kawas, N., Elvir, O., Torres, L., Rodríguez, M., Cardona, A., Wiesse , K., Canales, C., Gómez G., Mejía, J. and Sevilla.N. (2012). Atlas Climático y de Gestión de Riesgo de Honduras. pp. 57-63.

UPI-JICA, (2014). Manual para elaboración de mapa de inventario de deslizamientos de tierra. Caso de aplicación ciudad de Tegucigalpa. Agencia de Cooperación Internacional del Japón. (JICA). ISBN: 978-99926-701-1-8

Yagi H., Higaki D. and Japan Landslide Society Research Committee for Detection of Landslide Hazardous Sites in Tersiary Distributed Area (2009) Methodological study on landslide hazard assessment by interpretation of aerial photographs combined with AHP in the middle course area of Agano River, central Japan, Journal of the Japan Landslide Society. Vol.45.

Lidia Torres (✉)

National Autonomous University of Honduras. Honduras Earth Science Institute. Ciudad Universitaria E-1, Blvd. Suyapa.
e-mail: torres.lidia@unah.hn, le_torresb@yahoo.com

Nelson Sevilla

National Autonomous University of Honduras. Honduras Earth Science Institute. Ciudad Universitaria E-1, Boulevard Suyapa, Tegucigalpa. Honduras.
e-mail: nelson.sevilla@unah.edu.hn

Kiyoharu Hirota

NIPPON KOEI CO., Geosphere Engineering & Management Office, International Consulting Operations. LDT., 1-14-6 Kudan-kita Chiyoda-Ku, Tokyo, Japan
e-mail: sbhirota@gmail.com

Hiromitsu Yamagishi

SHIN ENGINEERING CONSULTANT CO. LTD
e-mail: hiromitsuyamagishi88@gmail.com

Satoru Tsukamoto

KOKUSAI KOGYO CO., LTD.
e-mail: satoru_tsukamoto@jcom.home.ne.jp

Landslide susceptibility in the Ulloa Sector in Tegucigalpa, Honduras

Jorge Tejeda, Bernard McCaul, Maynor Ruiz, Dorian Espinoza

Abstract Landslides are defined as the movement of rock, debris or mud down a slope triggered by a change in the level of stability due to the failure of materials that make up the slope. They are the result of various factors, including the geotechnical configuration and the evolution of slopes. Landslides frequently cause disasters and these have increased due to human settlement expansion on insecure slopes as a result of uncontrolled and rapid urban growth. Various methods and techniques have been proposed to analyze the factors that increase landslide occurrence, including the design of susceptibility maps, which define the spatial probability of landslides in an area. The purpose of this study is to create an inventory of data and a comprehensive detailed technical analysis of landslides, including susceptibility mapping in the José Angel Ulloa and Jose Arturo Duarte neighborhoods of the La Ulloa sector in Tegucigalpa, Honduras. There has been a strong emphasis on the relationship between the geology and the geomorphology present in the area in order to create a landslide susceptibility analysis. Analysis was carried out through an aerial photo-interpretation, LIDAR images, geological surveys, site inspections and other existing information of the area. As part of this study, two boreholes were drilled, each one with 30 m of depth. The preliminary results of this study are presented in a compilation of thematic maps including landslide tracking, geology, geomorphology, hydrogeology and a slope and landslide susceptibility map.

Keywords landslide, hazard analysis, urban planning, LIDAR, hazard map, Tegucigalpa

Introduction

The José Ángel Ulloa and José Arturo Duarte neighborhoods are located to the northeast of Tegucigalpa, Honduras (see Fig. 1). These neighborhoods are located on the hillsides of the inactive El Pedregal Volcano, adjacent to a sunken mass surrounded by faults with preferential direction N-S and NW-SW, on the east edge of the volcano. The established area for the present study is a quadrangle of 1.43 km². The study area is close to the Ring Road (Anillo Periférico), which is a high-traffic route leading to the eastern and northern region of the country. The neighborhoods in the Ulloa sector are situated on a historical landslide, inside of which more recent landslide movements have taken place.
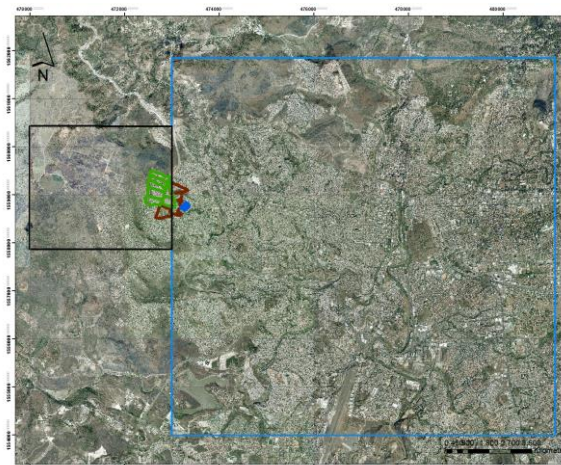
Fig. 1 Terrain map. The blue square shows Tegucigalpa and Comayaguela. The black square shows the study area. The green area shows the Ulloa sector

From the geological point of view, the study area is composed of weathered rock that has given rise to soils with a clay-like composition and poor mechanical properties. These soils are susceptible to movements when there is a high level of precipitation, especially on sites with steep slopes.

According to the analysis for the Sustainable and Emerging Cities Initiative (BID-NDF, 2015), the plateau of the El Pedregal Lagoon is one of the most important potential zones for future expansion of the city. If this possibility is to be explored, it is necessary to make a stability analysis and to determine the degree of landslide threat for the area.

Landslide susceptibility in the surrounding areas

The present state of the El Pedregal Volcano

El Pedregal is a shield volcano located at an elevation of 1,500 masl. It occupies an area of approximately 22 km², with a 4.4 km-long orientation in the E-W direction and a 5.0 km-long orientation in the N-S direction (see Fig. 2). It is set on the western edge of the cauldron of Tegucigalpa. Inside the crater of the volcano, there is a small lagoon of 0.5 km in diameter and a small dome. The volcanic activity came to a halt during the last phase of the magmatic activity which led to the formation of the Cauldron of Distrito Central in Honduras. In general, the volcano and its origin have a monogenetic nature. It is known for having a short but intense eruption in the past. It is considered an extinct volcano because the magmatic chamber was emptied. (Martinez Bermudez, 2002)
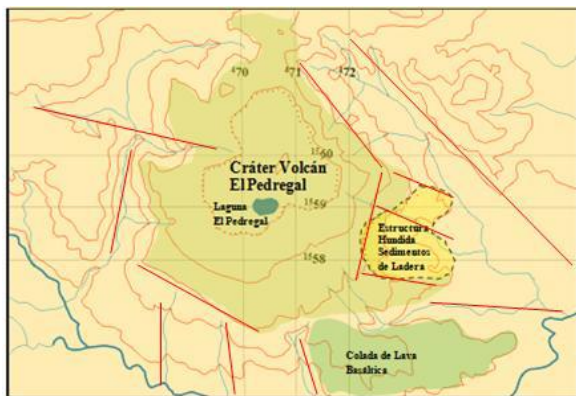
Fig. 2 Map and digital image interpretation of the extinct El Pedregal Volcano and its surroundings. Note the sunken structure located on the slope to the south east of the quaternary volcanic structure. The red lines in the map represent the guidelines of the main faults and ground fractures present in the area

The current status of the El Pedregal Volcano

The development of the topography corresponds to an unstable slope that is part of the sunken tectonic block that falls between 1,100 and 1,500 masl and is surrounded by active geological faults. This adds intense geodynamics to the terrain, both internally and externally, which create a high degree of energy due to the physical conditions of the faults (Martinez Bermudez, 2002)

The landslide vulnerability of the area is increased by anthropic factors. The excessive unplanned construction and the rapid development expansion in areas bordering natural water channels and slopes greater than 50% increase the vulnerability at the structural and social level. The integration of risk reduction to the policies of land-use planning in high settlement areas is necessary for the future urban development of Tegucigalpa.

Methodology

The methodology for the landslide analysis required the collection of information of past landslide events, the generation of high-resolution images (i.e. 10 cm x 10 cm orthophoto), LIDAR (Light Detection and Ranging) surveys to generate high-resolution elevation and terrain models, and geotechnical explorations in strategic areas within the landslide mass and at depths further than the estimated landslide surface. The LIDAR study was carried out in January 2016 and covered an area of 8.5 km². This included the entire study area and nearby sectors considered possible areas for the future expansion of the city.

For the geological classification, information from previous studies was collected. In addition, two geological surveys were carried out on the active landslide mass. The stratigraphic profile was generated to find out the possible depth of the failure surface. Additionally, in order to improve the geological and geophysical information collected, electrical resistivity tests were performed by the Honduran Institute of Earth Sciences of the National Autonomous University of Honduras. The susceptibility analysis required the generation of landslide data collection, as well as geomorphological interpretation and hydrogeological analysis of the area.

A historical landslide inventory was completed through consultations with the local population, review of previous studies, site visits, aerial photo interpretation and LIDAR image analyses. The work consisted in identifying the landslide deposits and available escarpment according to the scale of photographs and verifying them in the field. The resulting map is shown in Fig. 3.
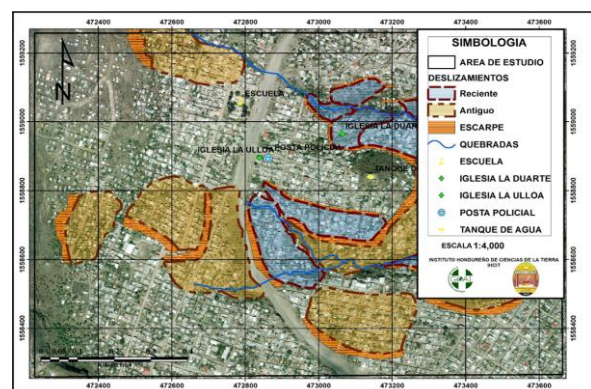
Fig. 3 Landslide inventory map

The scale and the geomorphological complexity as well as the insecurity of the area were the main factors that made it difficult to delimit the escarpment of some identified landslides and some landslide deposits. This limited the accuracy of the inventory map. A total of 19 landslides were identified, nine of which are considered longstanding landslides because these occurred prior to Hurricane Mitch (October 1998), and the majority of the local population does not remember them. The remaining ten landslides are considered recent because they were triggered during or after Hurricane Mitch due to extreme meteorological phenomenon (e.g. hurricanes and tropical depressions) or the construction of the Ring Road (i.e. the neighbors claim that the main problem has been the lack of a good drainage system during and after its construction).

Results and Discussion

Geomorphological map

The geomorphological map allows the visual conception of the dynamic and complex morphology for the particular area of interest (see Fig. 4). Unlike a landslide inventory map, where landslides are considered independent units, the geomorphological map allows landslides to be represented inside areas marked as affected by land mass movements. Representing landslides as complex natural processes comes closer to the essence of a susceptibility map.

The geomorphological units are classified according to their morphogenesis, as proposed by Van Zuidam (1985). In some cases, it was necessary to subdivide these units into specific morphological features. Therefore, the study area was divided in two main units: the predominant volcanic landforms and the denudation landforms, which only cover 5% of the study area. Based on the slope resulting from the DEM (Digital Elevation Model), the landforms present in the study area can be preliminarily classified as: foothills (3%-12%), alluvial fans (12%-30%), fine colluvium deposits (30%-45%) and thick colluvium deposits (>45%). Thus, the study area was divided in four units. The volcanic landforms dominate and cover 95% of the study target area, while the rest are denudation landforms and specifically cover areas affected by mass movements.

Geological map

Within the study area, the lithological composition consists mainly of volcanic matter, both effusive and pyroclastic (see Fig. 5). Four informal lithostratigraphic units were adopted. No radiometric data was available to date the age of these rocks; however, these units have been characterized based on the similarity of petrographic features of the formations. Rock units are described from the base to the top of the local lithological column:
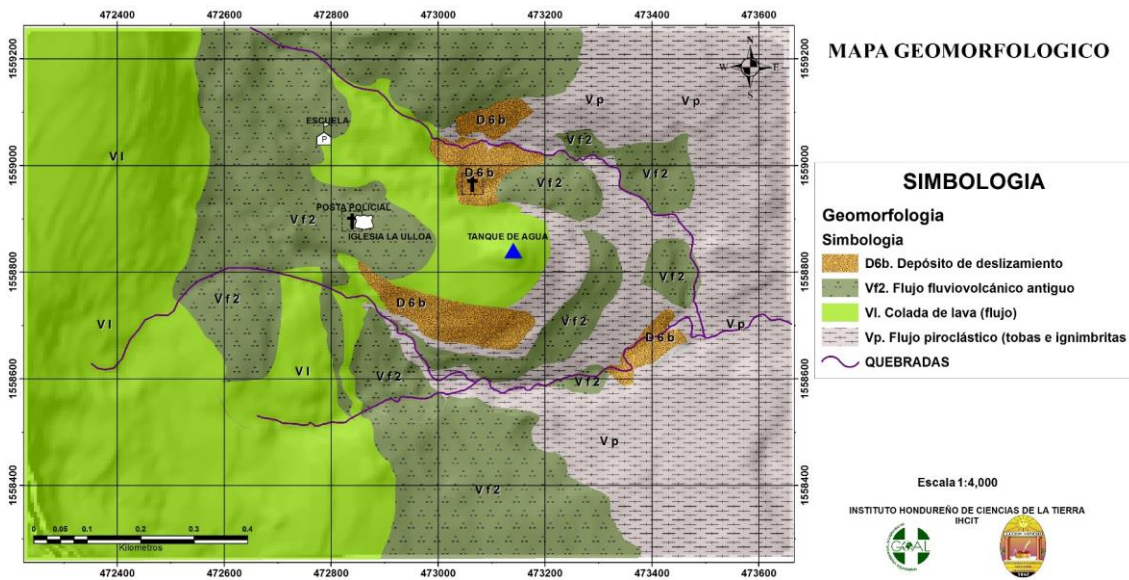
Fig. 4 Geomorphological map
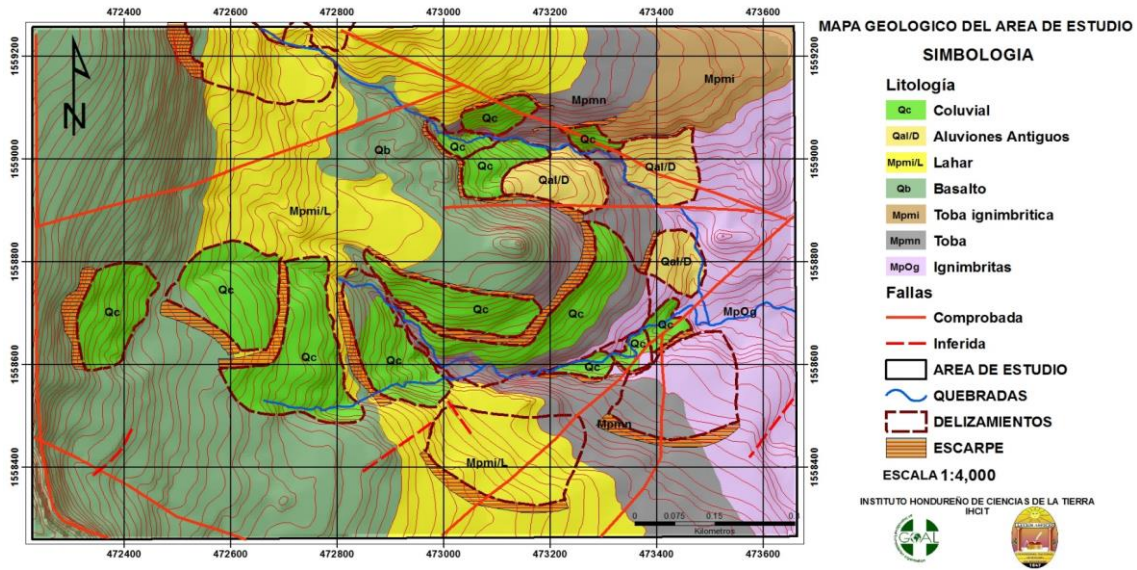
Fig. 5 Geologic map

- Ignimbrites Unit (MpOg): it is characterized as being a compact rock of white color with presence of biotitie and quartz minerals. It shows lateral and heterogeneous variations in its texture as much as its composition. No significant spatial variations were initially observed.
- Tuffs Ignimbrite Unit (Mpmi): this unit outcrops to the northeast of the study area. It corresponds to a pink to red tuff ignimbrite, compacted and unconsolidated with presence of silica.
- Tuffs Unit (Mpmn): This unit outcrops in the central zone of the study area, forming a strip and showing a pseudo lamination (pseudo stratification). It has a dark gray color with reddish tones. It presents fractures in the NE-SW and SE-NW directions.
- Basalt Unit (Qb): This is the largest unit of the study area and is found in the east hillside of the ancient El Pedregal Volcano. Generally, it is present as columnar basalts (Barber Vargas, 2011). To the west, pseudostratified lava flows, with an average thickness of 120 m, have been identified. To the south, a contact with a paleo soil and some faults with an approximate thickness of 3 m has been observed.

Geological risk map

To prevent or mitigate geological risks while having a positive influence in the planning and occupation of the territory, the assessment of the hazard and risk is necessary. The hazard refers to the geological process, while the risk refers to losses and damage. For the risk analysis, knowledge of the vulnerability is needed. For the study area, multiple types of analysis were used to determine the structural vulnerability level of the houses and the hazard level of the site, especially inside the delimited area considered to be active.

Parts of the La Ulloa and Jose A. Duarte neighborhoods are constructed upon faults that were created from the constant movements of the upper material strata (e.g. soil creep, landslides, rock falls, subsidence, etc.). These movements and their causes are complex, since usually the hillside and slopes find their own state of equilibrium. This stability is decreased due to the following:

- changes in the surface materials
- geotechnical, geological and geomorphological characteristics
- climate change that has occurred in recent years
- anthropic actions in the unregulated land occupation of these zones

All these factors have contributed to the generation of risk in the area, both for residents and the existing structures, which have been built without following the recommended technical criteria.

The main causes of the vulnerability in the study area are:

- development of human settlements with little or no planning. There are no previous studies of land-use planning. There are built houses on borders and channels of riverbeds, even though the Agreement 554 of the Metropolitan Council (created in January 1997 and currently valid) prohibits any kind of construction within an area located at 7.5 m on both sides of the riverbeds
- lack of surface drains

- deforestation
- construction of impermeable surfaces of large areas without any form of erosion control to adjacent water courses
- poor management and control of solid waste in areas leading to obstruction of water courses
- erosion related to cuts and fills with incorrect geometry and excavation for the housing construction.

Failure Mechanism

The failure mechanism corresponds to a translational or planar failure. There are various rupture surfaces, generally along the colluvium deposits with gray or yellow tuffs, which are the stable base of this stratigraphy. These slow moving masses are affecting the existing poor quality constructions in the La Ulloa and Jose A. Duarte neighborhoods. Fissures, dips, lifting and subsidence in some of these structures have also been observed. This situation is more critical in the La Ulloa neighborhood where the upper colluvial material has a high degree of organic contamination and a very low resistance to cutting. So far, these movements have been very slow, only perceptible through careful observation of changes on the structures, topography and some vegetation. However, the speeds of soil movements can vary, and under certain conditions, these can become very fast flows and move large volumes of soil.

Local, circular and composed failures (e.g. circular failures limited by a firmer stratum) have also been generated in the zone. To the west and northwest of the target study area, where basalt flows are present in the mountains, local failures are produced due to rock falls and basalt slumps. In some of these zones, rupture models with other typologies could occur if weaknesses or discontinuities are present. All these faults activate when the rise in the underground water level causes an increase in the pore water pressure that reduces the strength of the soils and favor the driving forces that induce failure.

In the case of the Ulloa sector, the most critical area is located next to the Ring Road. Under critical conditions, movements can occur along several tens of meters and may reach higher speeds than those recorded earlier, due to the saturation of soils in areas more susceptible to high slopes, which would cause the creation of flows. This may result in a mudslide, similar to the one that took place in the adjacent Ciudad del Angel. Initial slow movements developed into mudflows that dragged houses to the foot of slope along the Ring Road.

It is important to mention that the geological characteristics of the study area are the same as in Ciudad del Angel, located on the opposite side of the mountain to the north of La Ulloa neighborhood, with only some differences in topography, the thickness of the stratums and higher loads because of construction in the area. Another problem in this area is that a section of the Ring Road has been built upon colluvium deposits. For this reason, the road section has suffered vertical and horizontal displacements, which have required recent repair works.

According to the stratigraphy of the fault and the results of research and analysis, the layer of colluvial deposits aligns with the course of the creek that drains surface water and passes under the motorway (which coincides with the alignment of a fault). They are at a depth of about 35.0 meters below the surface, where these deposits come in contact with the foundation of stable rock.

Proposed future works

New data on the areas that are exposed to the highest landslide risk are needed based on photo-interpretation, geological surveys, and damage and structural assessment. For the improvement and safety of the neighborhood, the options are: the relocation of the residents living in the areas of highest risk, and avoiding soil saturation through the management of surface runoff caused by rainfall. The combination of interventions shown in the zoning map (Fig. 6) emphasizes the prioritization of relocation in the areas in deep red and other interventions that are presently being investigated for areas of orange and yellow hues.

To ensure the best results in proposed future works, there is a need for an analysis of the general stability of the sliding mass by means of numerical simulation modelling. Suárez Díaz (1998) claims that "the landslide stability methods that include water control, both surface and groundwater, are effective and in general more economical than huge countermeasure constructions, since the former tends to deactivate the pore water pressure which is considered to be the main sliding element on slopes". Therefore, the strategic construction of surface water structures and the protection of existing water courses are needed to increase the safety and stability of the sliding mass. These solutions are considered feasible and appropriate given the magnitude of the problem. However, based on previous research studies, the increase of the factor of safety and the landslide stability can also be achieved through the application of bioengineering techniques and an integrated watershed management. With this project, the integration of different techniques is sought for the integrated management of risk in the study areas. The implementation of feasible measures to reduce infiltration and drainage of surface water, in addition to the control of these throughout the main

channels of streams and natural water courses are also needed.
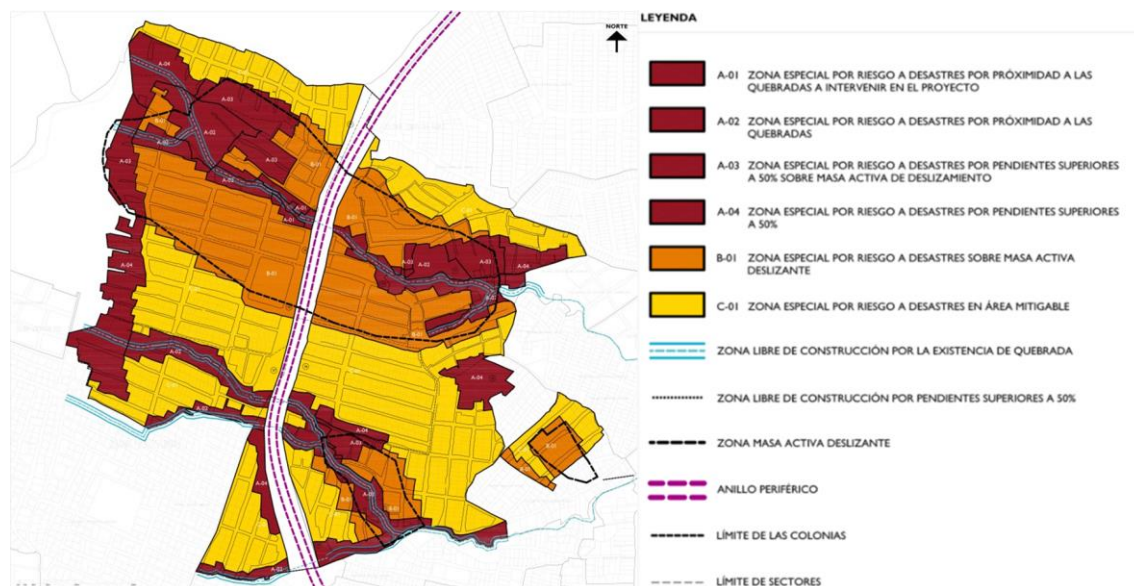
Fig. 6 Landslide hazard zoning map for the Jose Angel Ulloa, José Arturo Duarte and Nueva Providencia neighborhoods

References

Barber Vargas, A. M. (2011). Informe final Campana Geológica, Geological study of Colonia Jose Ángel Ulloa surroundings Universidad de Costa Rica 46.

BID-NDF (2015). Tegucigalpa y Comayaguela, Capital Sostenible, Segura y Abierta al Público. Banco Interamericano de Desarrollo y Fondo Nórdico de Desarrollo. Disponible en: http://www.observatoriodescentralizacion.org/download/informaci%C3%B3n_general_/Plan%20de%20Accion%20-%20Tegucigalpa.pdf

Martinez Bermudez (2002). Status of El Pedregal Volcano, Early Recovery UNDP - Honduras, Geological Assessment Five Colonias José Ángel Ulloa, Fuerzas Unidas, Nueva Dani, José Arturo Duarte and Nueva Providencia

Suárez Díaz (1998) Control de aguas Superficiales y Subterráneas, Deslizamientos y estabilidad de taludes en zonas tropicales (223). Colombia: Publicaciones UIS

Van Zuidam, R. A. (1985). Areal Photo Interpretation in Terrain Analysis and Geomorphological Mapping. The Hague: Smits Publisher

Jorge Tejeda
GOAL Honduras, Risk Reduction Unit, Tegucigalpa, Honduras
e-mail: jtejeda@hn.goal.ie

Bernard McCaul (✉)
GOAL Honduras, Country Director, Tegucigalpa, Honduras
e-mail: bmccaul@hn.goal.ie

Maynor Ruiz
National Autonomous University of Honduras, Earth Sciences Honduran Institute, Tegucigalpa, Honduras
e-mail: maynor.ruiz02@gmail.com

Dorian Espinoza
Geoconsult, Unit of Economic Development, Tegucigalpa, Honduras
e-mail: despinoza@geoconsult.hn

Barrio Resiliente: building resilient cities through resilient neighborhoods

Bernard McCaul, Ana Nuñez

Abstract GOAL recognizes that cities are made up of socio-economic systems that serve the needs of their residents. Addressing recurrent crises and effectively building urban resilience requires an integrated systems approach. Where these systems are fragile and large portions of the population are socially or economically marginalized, urban areas are highly susceptible to external shocks and stresses; coordination among stakeholders to strengthen these systems will ultimately improve urban resilience. Resilience can be understood as the ability of communities and households to anticipate and adapt to risks and to absorb, respond and recover from shocks and stresses in a timely and effective manner without compromising their long term prospects.

The ideal process for developing a new urbanization is to first establish land title, then service the land and finally build houses for families to move into. In informal settlements, this process occurs in reverse order in the sense that families first move into a plot of land and begin to build a shelter using their own unskilled labor and using whatever materials are available. The community then struggles to try to provide services to the land and finally, after 30 to 40 years, land ownership is usually resolved. This process puts families in these neighborhoods in a situation of extreme vulnerability to shocks and stresses. Barrio Resiliente (Resilient Neighborhood) or BR is an innovative program to build resilience in high risk informal urban settlements using a systems approach. BR targets the most critical socio-economic systems to increase resilience in urban communities. BR considers all the actors of targeted socio-economic systems and aims to improve the functionality of these systems for the benefit of the most vulnerable groups. Systemic interventions to build resilience are framed within eight development sectors: Education, Economic, Enviromental, Political/Governance, Social/Cultural, Infrastructure, Health and Disaster Risk Management.

Study Area

The BR model has been developed through a pilot project in landslide-prone marginal neighborhoods situated on the periphery of the Honduran capital of Tegucigalpa (in the Municipality of the Central District). These neighborhoods are José Angel Ulloa, José Arturo Duarte and Nueva Providencia. Together, these neighborhoods have a population of 16,500 inhabitants and aproximatly 2,200 houses. This pilot programme is being funded by the Office of U.S. Foreign Disaster Assitance (USAID/OFDA) and the Municipality of the Central District.

Steps in Applying a Systemic Approach

The principal steps of the systemic approach of BR are: (a) diagnostic of the root causes of disaster risk, (b) selection of the critical socio-economic systems considering which systems are most relevant to vulnerable families, their potential to increase resilience (GOAL, 2015) and feasibility for systemic change, (c) strategic design of intervention, (d) engagement with key actors, (e) participatory mapping and analysis of the system, (f) participative planning, (g) facilitating change and (h) feedback loops of monitoring, evaluation and learning. The sustainability of the systemic change is based on achieving a win win scenario for the participating actors of the system considering their respective capabilities and incentives. Designing for Behavior Change (DBC) and Community Led Development (CLD) are important strategies for interventions with actors at community level in particular.

BR applies an adopt, adapt, expand and respond framework in which the targeted stakeholders adopt pro-poor systemic changes and then adapt these changes as they become fully assimilated. GOAL aims to leverage additional support to expand these systemic changes to other actors and locations and advocate

with national and international agencies to respond by improving the supporting environment for broader take up of the systemic changes. GOAL performs a temporary role as facilitator for the targeted change in the selected socio-economic systems and will exit from the process when the selected systems are functioning more effectively for the target population. The application of BR in Tegucigalpa is targeting five socio-economic systems within four development sector as shown in Fig. 1.
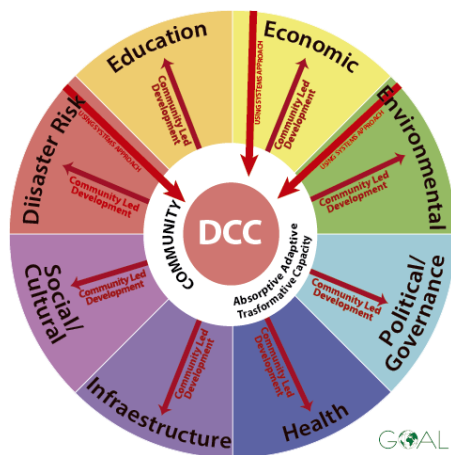
Fig. 1 Barrio Resiliente – resilience wheel showing intervention strategy

Description of Development of 5 Critical Systems under BR in Tegucigalpa

For the application of BR in the target neighborhoods in Tegucigalpa, the following 5 critical systems have been prioritized: 1. Neighborhood Landslide Early Warning System (EWS), 2. System for Provision and Maintenance of Neighborhood Drainage, 3. Social Housing Market System, 4. Market Systems for the provision of Basic Food Supply through Neighborhood Stores (Pulperías), and 5. "Succeeding Together" Campaign to increase Youth Participation in Improving Neighborhood Environment.

Neighborhood Landslide Early Warning System

For the vast majority of families living in high risk areas in Tegucigalpa, relocation to reduce their exposure to hazard is not a feasible option due to the lack of availability of suitable land for development, prohibitive costs and the emotional and economic investment that families have made in their current locations. Neighborhood or Community-based EWS are an important mechanism to reduce disaster risk for vulnerable communities who live with the threat of disaster. Best practice in disaster preparedness has

shown that EWS comprise of four components: 1. Disaster Risk Awareness, 2. Definition of Alert Thresholds and Hazard Monitoring, 3. Dissemination of alerts and 4. Response Capacity.

Neighborhood Landslide EWS in Tegucigalpa is administered by the Municipal Emergency Committee of the Central District (CODEM) with technical support from the Permanent Committee of Contingencies (COPECO) and other stakeholders such as the National Meteorological Service and the National Autonomous University of Honduras (UNAH) and requires close partnership with Local Emergency Committees (CODELs).

The CODEM operates the EWS through a dedicated SAT unit (where SAT stands for Sistema de Alerta Temprana or Early Warning System) which has been established. BR has supported the development of technical capacities within this unit in relation to their training program and engagement with the CODELs and training their staff and sectorial committees to operationalize the EWS in the target neighborhoods.

Disaster Risk Awareness
The municipality and the communities have developed a hazard zoning map (Fig. 2). A full census of families in risk has been completed and uploaded to a GIS database; contingency plans have been developed with the families deemed to be at most risk. A communication campaign has been facilitated using a number of different approaches including door-to-door visits and distribution of information pamphlets, "Pregoneros de Prevencion" (Prevention Preachers) have communicated messaging on public transport routes to the neighborhoods, public fairs on EWS and a wider communication effort through local and national media. GOAL is also working with the National Risk Management Agency to develop a proof of concept for an application for "dumb" phones which is also compatible with smartphones to reinforce the operation of the EWS and risk awareness.
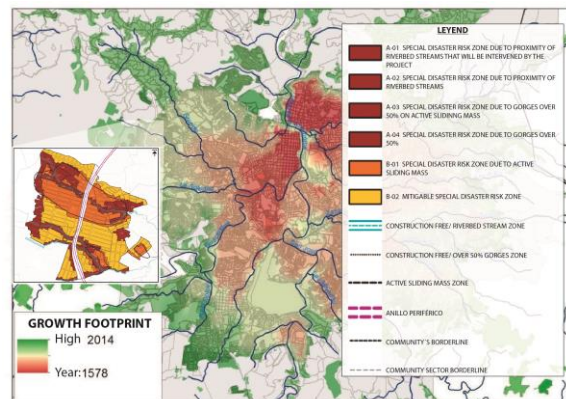
Fig. 2 Landslide hazard zoning map

Definition of Alert Thresholds and Hazard Monitoring
Landslide alert thresholds have been defined for Tegucigalpa based on a detailed analysis of the characteristics of landslides that have occured in Tegucigalpa and their statistical correlation with historical rainfall records over the past 30 years. Rainfall and corresponding soil saturation was deemed to be the primary trigger for landslide. A technical analysis has been completed in partnership with the United Nations Development Program (UNDP) and UNAH for the design of the Landslide EWS and a clear correlation was determined between rainfall and landslide probability. The data confirmed strong correlation between peaks in annual precipitation and the number of landslides. In relation to specific landslide events, it was clear that the accumulated rainfall over the period leading up to the landslide had a significant influence. Through detailed analysis and modelling, alert thresholds were determined based on accumulated rainfall over the preceding days and rainfall distribution during the period (UNDP-GOAL, 2012).

Tab. 1 shows the alert thresholds defined for the landslide EWS in Tegucigalpa which are based on an analysis of the 10-day accumulated rainfall (P_{10}) and the 90th percentile and 95th percentile rainfall probability distribution (E_{90} and E_{95}, respectively).

Table 1 Landslide alert thresholds for Tegucigalpa

Alert threshold	Green	Yellow	Red
E_{95} (mm)	130 to 160	160 to 200	>200
E_{90} (mm)	80 to 110	110 to 160	>160
P_{10} (mm)	90 to 120	120 to 160	>160

For the continuous monitoring of the landslide hazard, rainfall is monitored both using automated telemetry and manual rain gauges. Three telemetry stations transfer data through GPRS (General Packet Radio Service) to a central receptor located in the National Meteorological Service (SMN) offices in Toncontín International Airport to the south of the city. The information can be accessed in real time by staff from SMN, COPECO and CODEM over the internet. With respect to manual rainfall data collection, this is done by community volunteers using simplified rain gauges located in strategic sites; this information is registered daily in a format created for this purpose and transferred by telephone or radio to the SAT unit of CODEM. GOAL is developing a Digital Data Gathering system using CommCare software on mobile phones to improve the efficiency of this manual data collection. All this data is tabulated and analyzed in the SAT unit of the CODEM who make the final recommendation on declaring alerts within the municipal jurisdiction.

Dissemination of Alerts
This component includes the various communication protocols used for the dissemination of alert warnings and recommendations regarding potential occurrence of landslide to the relevant institutions, first responders and to the public particularly those in at risk areas. The dissemination is made at different levels: CODEM level (interinstitutional), CODEL level, family-at-risk level and the general population. Communication protocols have been agreed with stakeholders and documented in agreed Memorandum of Understanding (MoU). Alerts are communicated through diversity of means including email, mobile phone, VHF radios, social networks, television and radio and by community leaders using megaphones and home visits.

Response capacity
Response capacity is based on the capacities and available resources at institutional, municipal and local level to manage a response to an adverse event that may affect population, assets, livelihood etc. The CODEM staff are trained as trainers using a curriculum which includes evacuation, basic search and rescue, communication and monitoring, first aid, shelter management and humanitarian aid, damage evaluation and needs assessment and protection of vulnerable groups. The aim is to ensure that training provided to CODELs uses a behavior change approach and is relevant and practical with minimal time in classroom-type settings. Simulation drills and practical exercises are important elements of the training process at community level. For the CODEM, more specialized training is also provided on Incident Command Centers, Certified Professional Instructor and Managing Emergency Operation Centers. First responders, such as the fire brigade, are provided with certified training on Search and Rescue in Collapsed Buildings and Operating in Confined Spaces.

Four operational instruments are developed which set out the operation and maintenance of the Landslide EWS:
- EWS Operation and Maintenance Manual
- Municipal Preparedness and Response Plan
- Community Risk Management Plans
- Family Risk Management Plans

System for Provision and Maintenance of Drainage

In addition to the geological and hydrogeological characteristics of the three neighborhoods, which contribute to landslide susceptibility, other anthropic factors have a significant influence on landslide risk:

- unplanned urbanization and housing development (see Fig. 3)
- increased erosion due to removed vegetative layer and other excavations to the natural terrain
- increased impermeable surface and inadequate surface water management
- construction of major highways crossing landslide zones without assessment of the effects of the vibrations from heavy traffic volumes on landslide hazard.

Fig. 3 Neighborhood exposed to landslides in Tegucigalpa

Surface water drainage is the least regulated public service in Honduras in spite of its direct contribution to landslide, flooding and vector/water borne disease risks. There is no national institution mandated to oversee and regulate this service. The national water authority's (SANAA) responsibility is limited to potable water supply and foul water drainage. Also, due to the reversed process of development of informal urban settlements, drainage is the most difficult to construct retrospectively and hence the last to be obtained. Due to the poor standard and incompleteness of surface water drainage, which is characteristic of informal settlements, they have higher vulnerability to flood, landslide (due to increased soil saturation and erosion) and vector/water borne disease (due to presence of stagnant and contaminated water) hazards.

Thirty-five years after the target neighborhoods were first established in Tegucigalpa, they still lack a plan for a drainage network. As indicated above, the installation of surface water drainage is more complex because it is a gravity system and usually constructed after the houses have already been built. Unfortunately, the community water administration committees

(Juntas de Agua) only assume responsibility for the management of potable water, but not for surface water drainage. Municipalities and communities struggle to deal with these challenges without the support of any national institution or central government budget. Residents pay for water supply to their house but not for the drainage of the wastewater away from their homes.

BR aims to develop the system for provision and maintenance of surface water drainage and strengthen the relationship between the Municipality and community water committees. This also involves working closely with others key actors including COPECO, SANAA, UNAH, National Vocational Training Institute (INFOP), Honduran College of Civil Engineers (CICH) and Honduran College of Architects (CAH).

Fig. 4 provides an overview of the strategic design of the proposed system for provision and maintenance of drainage. This system proposes to develop a sustainable business plan for Juntas de Agua which includes key responsibilities for drainage maintenance. In order to develop new drainage infrastructure, it is proposed to use the Projects Executed by Communities model (PEC) which is a community-led development model through which communities are contracted to construct social infrastructure projects maximizing communities' contributions in labor and local materials. The PEC methodology was designed by GOAL in partnership with the German Development Bank (KfW) and has been hugely successful in improving the efficiency, quality and transparency of social infrastructure projects. The PEC model includes a strong component of social accountability which has
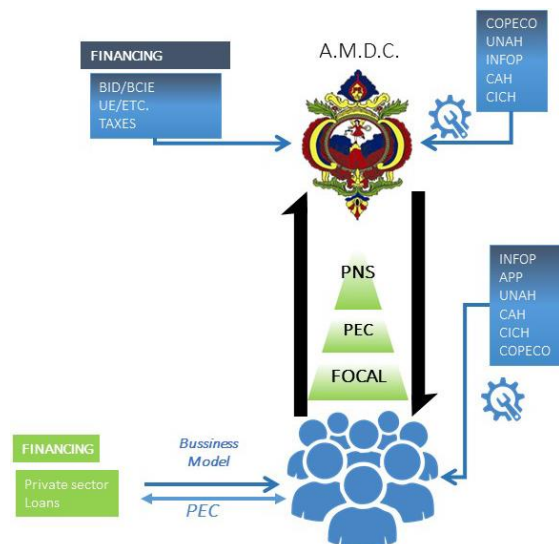
Fig. 4 System for provision and maintenance of neighborhood drainage

been a key component of its success. Within the PEC model, technical support is provided by certified technicians in the municipality. PEC has been successfully adapted by the Honduran Social Investment Fund to set out specifically its application for water services projects and is known as PEC Agua.

Social Housing Market System

Approximately 80,000 families are currently living in poor quality housing in Tegucigalpa, the vast majority of which are located in areas prone to disaster risk. It is estimated that over 70% of these houses are self-constructed and, in almost all cases, this is done without any form of technical assistance and using poor quality materials. As a result, these families are even more vulnerable as the quality of housing is extremely poor with no measures to reduce disaster risk such as controlling surface water, weather proofing, vector control, small scale mitigation works, erosion protection, etc. As mentioned, relocation to alternative sites is not a feasible option for many families. Improving access to technical and financial services to support the self-construction housing market system is an area which offers significant opportunity to reduce disaster risk for the poorest and most vulnerable families (see Fig. 5).
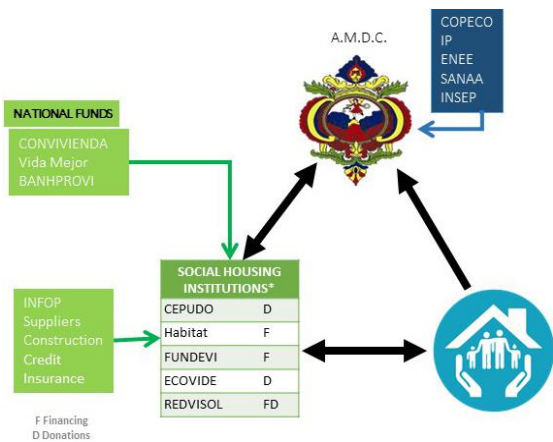
Fig. 5 Social housing market system in Tegucigalpa

BR's proposed intervention to the social housing market system is centered on strengthening the relationship between three key stakeholder groups, namely the Municipality of the Central District, the social housing agencies such as Habitat for Humanity, Housing Development Fund (FUNDEVI), etc. and the families at risk. BR aims to:

- Support the Municipality to develop a census of the families living at risk to prioritize families for access to technical and financial support to improve their housing.

- Support the development of extensionist services to provide technical assistance to the self-construction segment of the housing market.
- Support the development of financial products in partnership with financial institutions and construction material suppliers to increase access to better quality materials.
- Support the development of a social housing strategy for the city that addresses the needs of self-construction segments of the market.
- Support the creation of a social housing commission bringing together key actors within the social housing market system.

BR aims to address barriers affecting the relationships between the stakeholders such as institutional instability, weak capacities in urban planning, uncertainty in relation to land title, lack of information and communication, distrust and political bias, insecurity and lack of financial products for housing adapted to the needs of poor families.

Market Systems for the provision of Basic Food Supply through Neighborhood Stores (Pulperías)

GOAL partnered with UNAH's Department of Social Science to investigate solutions to job creation and economic opportunity in marginal urban neighborhoods and found that 60% of people are employed in the informal sector made up entirely of microbusinesses and sole traders. Since then, GOAL has focused on developing the ecosystem for small businesses including neighborhood stores or pulperías. Following a detailed diagnostic in the three neighborhoods, pulperías were found to play a key role in building the resilience of critical market systems, particularly in relation to ensuring the supply of basic food to the poorest and most vulnerable families. Pulperías also act as an important focal point for the dissemination of information and commercializing other critical products (medicine, clothing, gas, and firewood among others). BR aims to develop the role of pulperías in community resilience and strengthen their operation to ensure the continuity of their services during emergencies.

In 2015, GOAL partnered with the University of Cambridge Business School to analyze the business model for pulperías and develop strategies for intervention. Under BR's program "Pulpería a Pulpería" a full package of technical support has been developed and implemented using Participatory Market System Development (PMSD), which has been proven to significantly strengthen the business operation of pulperías and also have a direct impact on the surrounding neighborhood including connecting other small businesses, increasing market access to products and services to the bottom of the pyramid, increasing

access to credit and savings as well strengthening communication processes within the neighborhood. BR has facilitated the creation of networks of small businesses, provided technical assistance and training in businesses management, increased access to mobile technology, developed market alliances with suppliers and support services, increased access to formal credit services, strengthened relations with local government to obtain necessary licensing and support and supported businesses to address disaster risks and challenges such as insecurity.

BR also supports the recently-established Enterprise Development Center (CDE) in Tegucigalpa, which is funded by the Honduran government and private sector agencies. This CDE is a key actor to provide ongoing support for the strengthening of pulperías into the future and replicate the success of this intervention to other vulnerable neighborhoods and cities.

Through BR, pulperías also play an important role in the operation of the landslide EWS. Pulpería owners are trained on the EWS so that they can effectively communicate the operation of this system to their clients. Also, pulperías are used as a focal point for communicating hazard mapping and display alert warnings on their shop walls.

"Succeeding Together" Campaign to increase youth participation to improve neighborhood environment

Social cohesion is a key ingredient of a community's resilience to disaster. In order to strengthen social cohesion in informal settlements affected by high levels of youth violence, it is critical to engage with youths so that they can make a positive contribution to and have pride in their communities. The target areas for the intervention under BR are gang-controlled neighborhoods. While there are many factors contributing to youth violence, there is strong evidence that increased participation of at-risk youth in socio-economic systems and improving neighborhood environments has a strong impact on strengthening social cohesion. Under BR, GOAL supports a campaign, entitled "Succeeding Together", which aims to bring together various stakeholders from both the public and private sectors to facilitate youth participation in transforming public spaces and streetscapes in their neighborhoods, based on CPTED (Crime Prevention through Environmental Design). CPTED was originally developed in marginal neighborhoods in US cities and has been very effective in reducing crime rates, engaging youths and cultivating community self-esteem. In recent years, the CPTED model has been successfully adapted by USAID to the urban context in Honduras in an effort to reduce gang violence and migration. The Succeeding Together campaign works with partners to transform at-risk areas in target neighborhoods into positive public spaces using public furniture, art, planting and lighting through a process of training and engagement with youths. The emphasis of the messaging is on building resilience of the target barrios.

Conclusions

BR is an innovative model for building disaster resilience in high-risk informal urban settlements. The models approach has demonstrated significant results over three years of implementation in vulnerable neighborhoods in Tegucigalpa.

Applying a systemic approach is an essential requirement if interventions to reduce urban risk are to be sustainable and relevant to stakeholders.

GOAL works in partnership with the International Strategy for "Making Cities Resilient". An important contribution of BR is that factors such as volunteerism, community leadership and protection of vulnerable groups in urban communities are essential characteristics of resilient cities and that building resilient cities requires building resilient neighborhoods.

References

UNDP-GOAL (2012). Project DIPECHO VII, Description of the Landslide Early Warning Monitoring System in Tegucigalpa and Comayaguela, Central District Municipality, Honduras.

GOAL (2015). Analysis of Resilience in Communities (ARC-D) Toolkit.

Bernard McCaul (✉)
GOAL Honduras, Country Director, Tegucigalpa, Honduras.
    e-mail: bmccaul@hn.goal.ie

Ana Luisa Nuñez
GOAL Honduras, Urban Risk Reduction Unit, Tegucigalpa, Honduras.
 e-mail: anunez@hn.goal.ie

Geophysical prospection and layering analysis of a landslide susceptible area

Luis Vargas

Abstract The present work shows the results of a research conducted in a zone with high risk to suffer a landslide, located in the neighbourhood of Campo Cielo in the city of Comayagüela in Francisco Morazán, Honduras in February 2013. The research was developed using the geophysical prospection methods of Seismic Refraction, and Electrical Resistivity Tomography. The primary method used for the research was Seismic Refraction, since the purpose of the study was to analyze the layers of the zones that might be susceptible to have a landslide. The results obtained from Seismic Refraction in comparison with the results of Electrical Resistivity Tomography allow us to identify the zones that are susceptible to have landslides, and at the time to estimate the thickness of the loosed sediment layer, which were estimated to be six meters of thickness around the crown of the landslide and 10 meters in the base of the landslide.

Keywords Layer, Sediments, Refraction, Seismic, Kriging, Landslide

Introduction

The risk of a zone to suffer a type of landslide had been of great importance for the world ever since the moment in which society have started to develop urbanizations. Having in mind the majestic power of nature in consideration for any event that can occur and detonate a landslide, lead us to think in forms to prevent the damages produced by such events. In this case it is considered that the landslides or mass movements can be generated by different factors natural and unnatural. This study have as base the analysis of the amount of mass that is susceptible to be in movement in a zone of landslides, where previously had occur one.

The presented study was realized on February, 2013 at the neighbourhood of Campo Cielo in the city of Comayagüela in Francisco Morazán, Honduras (see Fig. 1).

Fig. 1 Location of the study area. The red square locates the zone in the city of Comayagüela. (Source for basemap: www.google.com/maps)

The suffered damage in this zone is presented with different characteristics (e.g. mass movement, soil instability, loss of structural support) and these lead to the land to be loose and fail (see Fig. 2 and 3) another damage suffered is in the structures of the water service and waste water systems, where the mass movement had taken the pipes to fracture and this limits the services and the fluids can contaminate the area.

The finality of the research was to determine what areas within the zone are still susceptible to a landslide, considering the amount of loose sediments in it. The study have as a base the use of geophysical methods of prospection such as seismic refraction to determine the sediments layers of the zone, and electricalresistivity tomography to reassure the results of refraction and to validate the hypothesis.

Methodology

Seismic refraction prospection

The seismic refraction method is a method that consists on the propagation of an artificial wave that must be related to a P wave, in the medium the wave will propagate to be studied. This method is considered

an active seismic prospection method due the great amount of energy that is necessary for the wave to propagate al through the medium or mediums, and collect the information of the same, (Rodriguez 2013).

The method consist in align on a straight line with the sensors known as geophones at an equidistant separation between them on the surface. These geophones will record the earth movement that is produced by the artificial wave, creating a signal of the size of a small window of 0.25 seconds. It will be recorded the signal from each geophone showing them together to observe the phenomena (see Fig. 4).

Fig.2 Illustration of the impact of a previous landslide that occurred in the area. The higher the number of damage level according to the legend, the higher the severity of the impact in a specific zone

The generated mechanic wave it is transmitted from the surface in all the directions of the space until it finds a transition surface between two mediums in which the wave will change its mechanical properties such as propagation velocity.

Fig.3 Location of a damage level 4 (see Fig. 2), presenting the structural damage of the road (Photography by Xiomara Robleda, 2013).
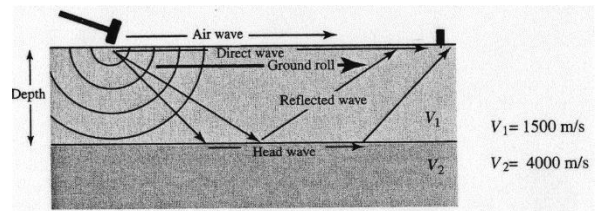
Fig.4 Illustration of the geophones arraigns and how they perceive the artificial wave that bounced at the lower layer (Rodriguez 2013).

At the moment the properties of the wave change the direction of the same will do it as well, depending on the properties of the mediums and the incident angle of the wave will reach a critical value that will bounce the wave to the surface with a higher propagation velocity (the respective propagation velocity for the lower medium) this new wave will be known as head wave. The records will show that the arrivals of the wave will get faster and the records will show a variation (see Fig. 5).

The variation on the recorded signals will provide the information related to the order and mechanical characteristics of the layers below the surface (the two surfaces showed as example). The noted variation is related to the change in the propagation velocity of the wave according to the given phenomena during the waves contact with the transition surface.
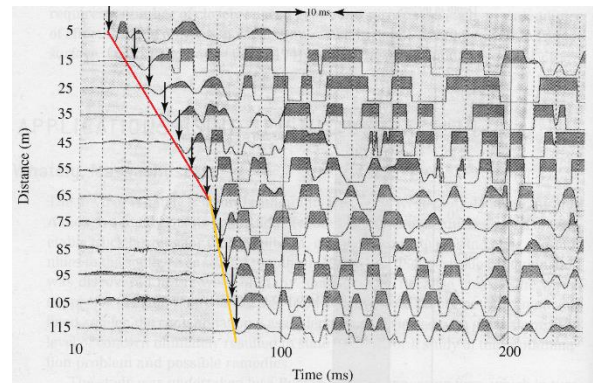
Fig.5 Illustration of the recorded signals from the geophones arraign and variation that appears on the record from the phenomena of the Head wave. (Rodriguez 2013)

For this phenomena, there are two equations that quantify the model that can be created to represent the situation under surface. The equations are:

$$t = \frac{x}{v_2} + \frac{2h_1\sqrt{v_2^2 - v_1^2}}{v_1 v_2}$$

[1]

$$h_1 = \frac{x_{co}}{2}\sqrt{\frac{v_2 - v_1}{v_2 + v_1}} \qquad [2]$$

Where t is the time of the first arrival for each recorded signal in mili-seconds, x is the separation between geophones in meters, h_1 is the thickness of the first layer from the surface down in meters, v_1 and v_2 are the propagation velocities for the first and second layer of soils from the surface down respectively in meters per second, and the distance x_{co} is the cross distance in which the variation on the records appear, in meters.

Kriging's method

The Kriging's method or process of Gaussian regression is a method of statistical interpolation commonly used in geosciences. It is based on the regression of the observed values of the z coordinate of the surrounding points. Weight values are given according to the spatial variations.

Kriging assign weight values according to the managed information of the weight functions on the contraire of an arbitrary function but continuous being an interpolation method. If the location of the information is dense and uniformly distribute all over the area of study it will be obtained good results. (See Eq. 1)

Some advantages of Kriging's Method:

1. Helps to compensate the effect of the conglomerate information assigning weight values individually to each point with a lower weight.
2. Gives an estimated error (Kriging's variance) with the estimated values of each variable.

Kriging's basic equation:

$$Z^*(\vec{u}) - m(\vec{u}) = \sum_{\alpha=1}^{n(\vec{u})} \lambda_\alpha (Z(\vec{u}_\alpha) - m(\vec{u}_\alpha)) \qquad [3]$$

Where u is the position vector, and the alpha sub index represent the estimated point, n is the number of points to be determine, m are the expected values (measures) of the heights Z and $[Z(\vec{u})_\alpha]$. λ_α are the weight values that are estimated by iteration when the position is estimated as function of the height, making used of the equation:

$$\sigma_E^2(\vec{u}) = VarZ^*(\vec{u}) - Z(\vec{u}) \qquad [4]$$

Where σ_E is the standard deviation for the Error (E)

Selected data

Exploration and observations

The selection of the profiles that were studied it was based on the observations of the surrounding, considering the damages that were made due the previous landslides that created the loss of structural support, which created the damages shown on Fig. 2 and Fig. 3.

The profiles were established according the observations and they try to cover the upper side of the previous landslide surrounding the crown (see Fig. 6) in which there was selected a total of six profiles to cover the zone.

Fig.6 Illustration of the seismic refraction profiles that were made to study the layering of the zone (Source for basemap: www.google.com/maps)

The observations of the zone during the period of the study are:

1. Many of the streets had fail, for that it was possible to analyse the consistence and texture of the soil under them, which was proven to be the product of eroded siltstone.
2. Most of the areas were found under weathering, and that can decrease the cohesion of the soil.
3. On the area that covers the previous landslide it was found a great amount of vegetation that was not corresponding in size to the season at the time (dry season – summer).

These are many other observations of the zone gave us a better understanding of it to develop the models of the layers.

Results

Seismic refraction

The seismic refraction profiles were made according to the distribution above mentioned. These were

49

modelled in a software and the results are shown in Fig. 7. In the profile, the different layers below the surface were modelled into two layers considering the continuity of the material and the fact that the upper layer will represent the loose sediments of the soil. The points on top of the graph represent the tendency of the data to be aligned with the measurements and their correlativity. Each layer will possess a different value for the propagation velocity where the upper layer will present a lower value according to the theory presented and the fact that the wave will propagate slower in that layer for their physical and mechanical conditions
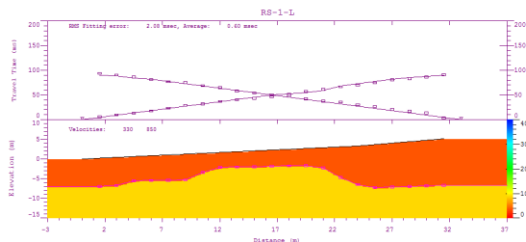
Fig. 7 Seismic refraction model profile made on the profile RS-1-L

From all the seismic refraction profiles it was obtained a set of data for each one a pair of values of propagation velocity (see Tab. 1).

Table 1 Results obtained from the seismic refraction models that belong to each profile, where their characteristic is the representation of the values of propagation velocity

Profile's name	V1 [m/s]	V2 [m/s]	Error [ms]
RS-1-L	330	850	2.08
RS-1-D	344	979	2.97
RS-2-D	250	974	1.60
RS-3-U	317	682	8.26
RS-4-U	323	659	7.64
RS-5-L	344	786	1.65
RS-5-D	309	619	4.26
RS-6-L	360	924	3.79

These results show the low level of error between the measurements and the proposed model for the profiles in which can be observed that the values between them are close to each other and base on this can be related that the layers are the same for all the models by the continuity of the materials.

All the profiles were plotted into on a three dimensional (3D) diagram were can be use the Kriging's method of linear regression to line up all the values and create a 3D model of the surface of the lower layer, the one that represent the consolidate sediments within the soil under the surface.

3D model of the lower layer

The results that were obtained from the profiles were used to create a 3D representation of the lower layer of sediments (see Fig. 8), the one that possess the consolidate sediments within the soil and can be considered the amount of soil mass that will not move during an event. It will be considered that the thickness of the upper layer is the loose sediment and the one that create the susceptibility in the area.

This 3D representation can provide us with an idea of the behaviour of the area and which zones can or might be possible be more susceptible to present a mass movement during an event that can detonate the loss of structural support or cohesion within the soil and provoke a landslide.
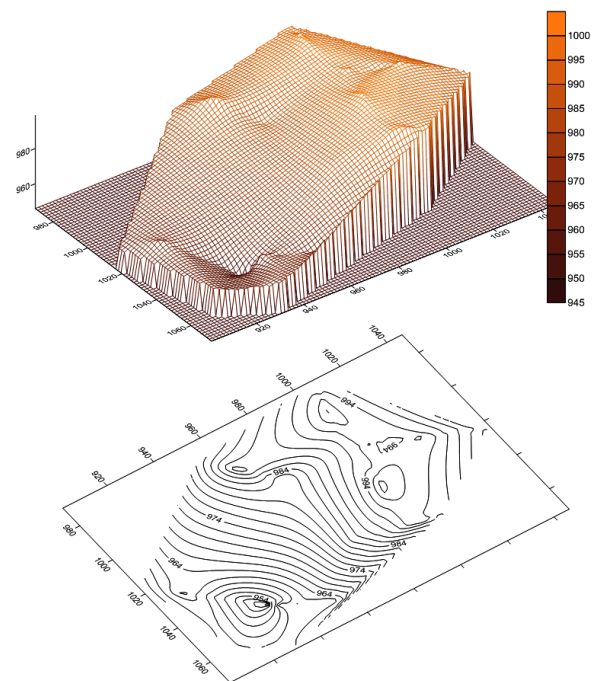
Fig. 8 3D model made from the seismic refraction profiles considering only the information for the lower layer of the model and the continuity of the medium, the model show the form of the lower layer respective to its elevation as shown the values in the colour bar legend

Electrical resistivity tomography

Using geophysical methods of prospection can lead to the uncertainty of the results and these ones need to be
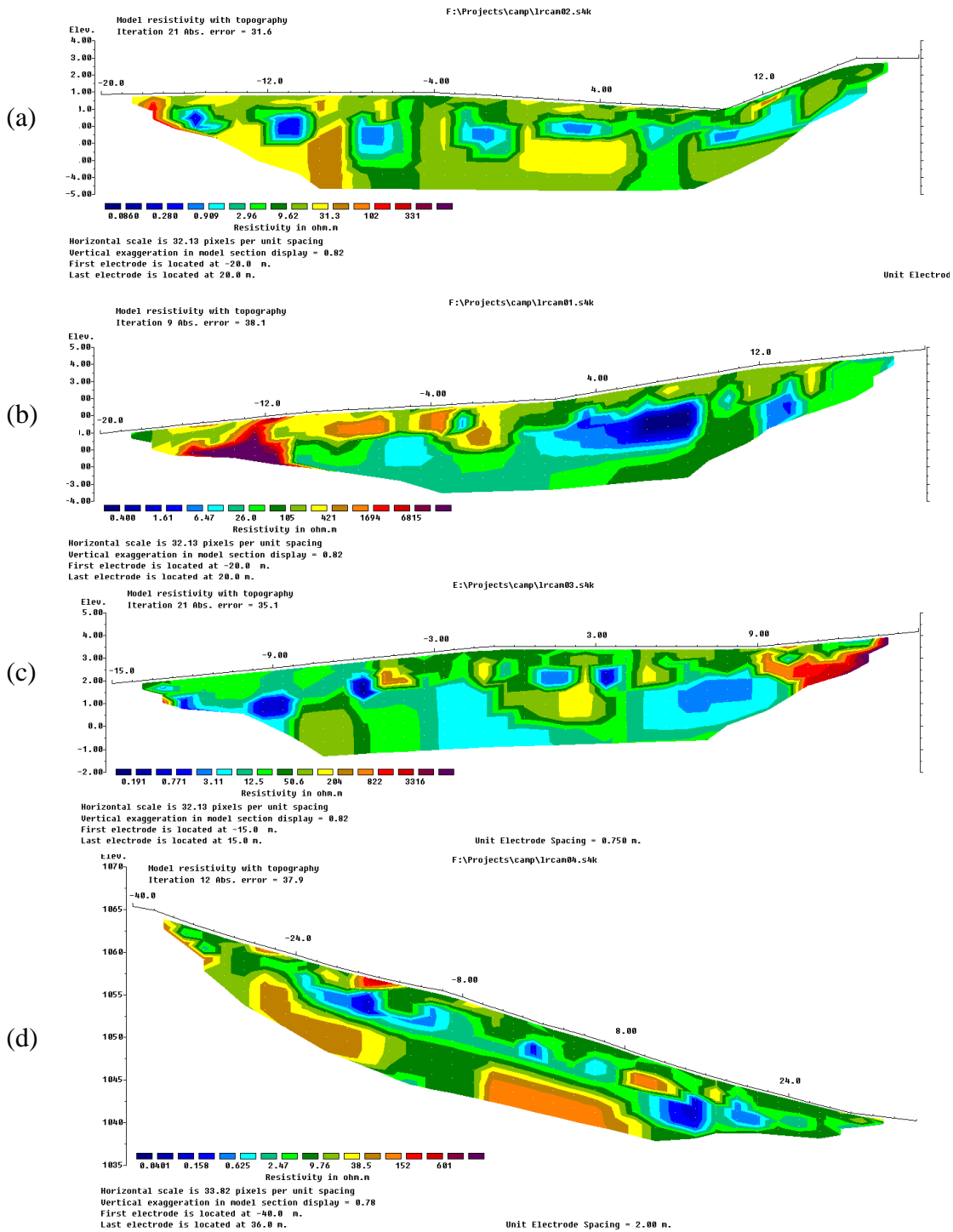
Fig. 9 Electrical resistivity tomography (a) Parallel and over the seismic refraction profile named RS-2-D, (b) Parallel and over the seismic refraction profile named RS-3-U, (c) Parallel and over the seismic refraction profile named RS-5-L, and (d) All over and in the middle of the line of the landslide.

validated by another media or methodology because they are indirect measurements for the properties of a body. It was selected the use of Electrical resistivity tomography to prove that the results and the assumptions taken to use the seismic refraction results for the model were right. It was determine the electrical resistivity for some of the profiles that were made with seismic refraction, the results from these electrical resistivity tomography will provide a validation or comparison for all the seismic refraction profiles where the thickness of the layer and many other factors can be estimated by this method (Schechan et al., 2006). The electrical resistivity tomography for those profiles can be observed in the Fig.9.

Discussion

Comparing the results from both methods it appears to be resembles between then concerning to the thickness of the layers, it may be mentioned that the assumption of considering only two types of layers was not far from the truth, taking into account that the loose sediment would have a higher electrical resistivity value.When considering the soil model where is compose by water, air, and sediment, where a greater number of gaps in the medium provides a higher value of electrical resistivity because of the presence of air, although not only material difference was found, so it appears within the tomography points that demonstrate the presence of water or points of low electrical resistivity which taking into account the observations made about the area ("High in vegetation in the surrounding of the landslide zone, something not concordant with the dry season") that they were actually water tributaries points due an aquifer in the area. These points of influent water can be considered as points where there under pressure increases because the amount of water flowing through the gaps of the loose sediments. Consideringthe points of influent water can betaken as a future detonator for another landslidewhen approaching the rainy season in the region where once recharged the aquifer it would increase the underpressure efforts thus decreasing the capacity of the soil of cohesion and internal friction of the material (i.e. structural support of the soil), which would lead to activate a future landslide in the area again, provoking that the loose sediment layer will be a mass movement.

In particular it should consider the efforts that are in the direction of the slide (see Fig.9d), where these efforts of underpressure to be located in the slide area could cause less recharge a new detonation glide.

Taking into account the model obtained by the method of Kriging using the results of the seismic refraction of the area where a dimension of the layer of loose sediment of about six meters surrounding territories was determined to crown glide and ten meters in the lower area of the slide. These results are validated by comparing the results obtained from the study of electrical resistivity tomography, which provided similar patterns of soil types, depending on the electrical resistivity of the soil.

Conclusion

The identification of the locations in which the area is more susceptible to suffer another landslides, is determine by the closeness of the elevation curves on the model generated with the results of seismic refraction profiles using the Kriging's method (see Fig. 8). Analyzingthe results of electrical resistivity tomo-graphy that provided the location of points where it's greater the under pressure due the presence of water concentrate the locations in the upper middle part of the area. The location was determined using the profile RS-5 which locates most of the locations in its surrounding.Likewise I was able to determine an average thickness for loose sediment of about six meters in the area near the landslide crown, and 10 meters at the base of the landslide zone, which leads to give an idea of the subsurface stratigraphic structure in the area at high risk slip.

References

Bohling, G. (2005). Kriging. Kansas Geological Survey, 864-2093.

Rodriguez M. (2013). Report: Electrical Resistivity at Campo Cielo, Comayaguela. IHCIT, UNAH.

Schechan A. F., Jones C. H., and Burguer, H. R. (2006). Introduction to applied Geophysics, Chapter 2, 3, and 4.

LuisVargas (✉)

Universidad Nacional Autónoma de Honduras, Science Faculty, Blvd. Suyapa, Tegucigalpa, Honduras
e-mail: luisfisicaunah@gmail.com

The project for landslide prevention in Berrinche and Reparto in Tegucigalpa

Alejandra Muñoz

Abstract This article describes the landslide prevention projects carried out in El Berrinche and El Reparto in Tegucigalpa, Honduras between the years 2011 and 2013. Both of these locations suffered landslides during hurricane Mitch in the year 1998, which caused devastating human, economic and structural losses. After these events the government of Honduras kindly requested Japan to help with their expertise in landslide topics and give a solution to these vulnerable areas.

After several hydrological, topographical and geological studies, Japanese experts finalized both project designs, which consist of five basic elements: drainage wells with horizontal perforations, superficial canals, safety devices, soil counterweight and access roads.

The main purpose of the works in both sites is to evacuate underground and superficial water through the wells and canals to keep the soil from saturating which increases the hazard of a landslide. With the help of the safety devices, data was taken at the start of the project to measure underground water levels. Once the wells and horizontal perforations were finished, there was a decrease in these levels, which confirmed the mission to reduce and keep evacuating water was accomplished. The project was handed over to CODEM (Comité de Emergencia Municipal), the entity now in charge of the maintenance works. Since then, several winter seasons have passed and the works have functioned as expected.

Keywords landslide, drainage well, horizontal perforation, safety devices, Berrinche, Reparto

Background

In the year 1998 Honduras was heavily affected by Hurricane Mitch, which caused severe damages in several parts of the country. The capital city, Teguci-galpa, received approximately 281 mm of rain in three days, which caused several landslides, including Berrinche and Reparto (Harp et al, 2002). The landslide in Berrinche had approximately 6 million cubic meters of soil that fell and destroyed the Colonia Soto as well as other surrounding neighborhoods (Harp et al, 2002).

Aside from the destruction of these houses, the soil from the landslide was deposited at the bottom of the mountain where the Choluteca River crosses. This material blocked the water from following its natural course, causing a dam to form and consequently flooding the city as can be seen in Fig.1.

Fig. 1 Frontal view of the landslide in Berrinche (1). Landslide from the top and toe portion of the mountain (2). The dam formed in the Choluteca River due to the soil deposited from the landslide. (Harp et al, 2002).

The landslide in Reparto had approximately 400,000 cubic meters of soil that destroyed the houses in this area, as seen in Fig. 2 (Harp et al, 2002).

Fig. 2 Frontal view in Reparto. (Harp et al, 2002).

After these disasters, the Honduran government seeked Japan's help and they sent a group of engineers to study the different landslide locations. Finally, both projects were designed by Central Consultant Inc & Earth System Science Co. Ltd (CCI&ESS) and constructed by Hazama Ando Corporation.

Project description

Purpose of the projects

Due to Honduras' propensity to hurricanes and its mountainous topography it is of vital importance for the country to control the major landslides, in this case specifically Berrinche and Reparto since future landslides would mean more human and economic losses for the country.

According to CCI&ESS, the major expected goals with these projects are:

1. A reduction of landslide activity.
2. An alert and evacuation criteria by authorities.
3. Extended knowledge of landslides that can be applied to similar cases in Tegucigalpa.
4. Education of the population about the importance of maintenance and care of the works done. Universities will be able to study these cases of landslide control and therefore expand their classroom knowledge.

General details of the projects

The construction cost of both projects summed up to 870 million Japanese yens, approximately 8 million US dollars, financed by the Japanese Grant Aid (Hazama Ando Corporation, 2011). The construction period lasted from December 2011 to October 2013.

As seen in Fig.3, both projects consisted of 5 items:

1. Drainage wells with horizontal perforations that capture and drain the underground water
2. Canals to discharge superficial water
3. Soil removal from the top portion to reduce weight and placed in the toe part to act as a counterweight
4. Access roads for maintenance works
5. Safety devices to monitor the area

Drainage wells and horizontal perforations

Two drainage wells were constructed in Reparto and eight in Berrinche, with a diameter of 3.5 meters and depths varying between 13, 17 and 28 meters, depending on the underground water level and the surface of rupture, as seen in Fig.4 (CCI&ESS, 2011). The basic concept with this technology is that the ten intake pipes per level will allow underground water to enter

the well and be evacuated through the drainage pipe, preventing soil saturation as seen in Fig.5.

Fig. 3 General layout of countermeasure works in Berrinche. (CCI&ESS, 2011)

Fig. 4 Drainage well from the outside, with its protection cover and surrounding fence to avoid intruders. (Taken by Froilán Castro, 2013)

Construction works

First the topographic team marked the center of the well on the ground. Excavation works began and a crane was used to lift a bucket with the excavated material. Depending on the soil type, the daily excavation was generally between 1-2 meters in depth. As excavation occurred, the liner plates were installed.

Once the first liner plates were set, as seen in Fig.6, the top concrete base was casted. The process of excavation and liner plate setting continued. When the telescopic excavator was not able to reach any further, a mini excavator was placed inside to continue with the excavation until the design depth was reached.

Following the well excavation, the drilling team would enter the well as seen in Fig.7. First, the drainage pipe was drilled and installed with a declining angle to drain water by gravity. This allowed water from the

Fig. 5 Drainage well seen from above with its ladder for maintenance and at the bottom water is captured from the intake pipes. (Taken by Froilán Castro, 2013)

Fig. 6 Liner plate installation. (Taken by Froilán Castro, 2013)

Fig. 7 Drilling of intake pipes. (Taken by Froilán Castro, 2013)

drilling works to be evacuated as well as the water brought into the well when the intake pipes were installed. The drainage pipe was a steel pipe with a diameter of 90 mm. One well was connected to the next well through the drainage pipe, until finally one of the wells had the drainage pipe that reached a canal which would finally discharge the water to the river Choluteca in the case of Berrinche and to the residual waters canal in Reparto, as seen in Fig.8 and Fig. 9.

The team would then drill the intake pipes. These were PVC pipes with a diameter of 40 mm. Ten pipes were placed in each level, each one with 50 meters in length and with small perforations on the top portion to allow water to come inside the pipe. Some drainage wells had two levels of intake pipes if the underground water level was really high in the surrounding area.

Fig. 8 Drainage pipe from well No.6 in Berrinche connected to the canal to finally discharge to the river. (Taken by Froilán Castro, 2013)

Fig. 9 Drainage pipe from well No.2 in Reparto connected to the canal to finally discharge to the residual waters canal in this area. (Taken by Froilán Castro, 2013).

Canals

The canals were constructed along the roads and along the landslide area to evacuate rainwater and avoid the soil from saturating. These canals reach the bottom portion of the mountain to discharge the rainwater as well as the underground water coming from the drainage wells. To avoid soil erosion from blocking the canals some of them have concrete on the sides with rocks at certain intervals as seen in Fig.10, while others have gabions as seen in Fig.8.

Fig. 10 Canal with concrete sides (Taken by Froilán Castro, 2013)

Some of the canals were constructed in site, while others were prefabricated, which allowed a faster installation process.

Soil counterweight

Soil from the top portion of the mountain was excavated to reduce weight and transported to the bottom portion. Here it was compacted to act as a counterweight to the mountain allowing overall greater stability, as seen in Fig.11.

Access roads

Access roads were paved to facilitate the entrance of the people in charge of the maintenance works.

Safety devices

The safety devices installed in both sides have two main purposes:
1. They were installed at the beginning of the construction works to monitor the sites and in case any landslide was occurring the personnel would be able to evacuate.
2. Once the projects were finished, CODEM must continue to monitor them to evacuate the neighbors in case a landslide occurs

Fig. 11 In Berrinche, soil was removed from the top and compacted at the soccer field area, acting as a counterweight. (Taken by Froilán Castro, 2013)

The safety devices installed are:
1. Extensometers
2. Underground water level meters
3. Inclinometers
4. Rainfall gauge
5. Siren and alarm

The safety devices were installed in the landslide area and a central station was located in a neighbor's house in each site. The central station allows authorities to simply connect a laptop that has the Osasi Osnet Observer program installed and data from the devices is recorded. In Berrinche only extensometers, rainfall gauge, siren and alarm are connected to the central station so it's not necessary to take data for each of them in site. In Reparto all devices are connected to the central station except for inclinometers. Underground water level meters in Berrinche and inclinometers in both sites must be manually used to record data.

Extensometers

They measure displacements on the surface ground. The extensometer is placed in a protection box and from here a cable is extended protected by a PVC pipe with the end on a wooden stick, as seen in Fig.12.. If the ground between the extensometer box and the wooden stick moves, the cable will be pulled and data will be taken in mm/hr. An alarm is set in case a displacement of more than 2 mm/hr occurs (CCI&ESS, 2011). This does not mean a landslide is occurring but maintenance personnel must check the area and keep monitoring the site.

During the construction works no displacements were detected. Unusual readings occurred due to locals moving the cable.

Fig. 12 Extensometer. (Taken by F. Castro 2012, F., 2012).

Underground water level meters

These were inserted through a pipe drilled on the ground. Once the device reached water, an alarm would sound. The distance the cable went in, is used to determine the depth at which underground water is found. This data along with rainfall data is useful and can be correlated as most of the time when a heavy rain occurs, underground water level will also increase; but with the drainage wells properly working, this level should decrease again. In case the water level remains elevated, this would give us a hint that perhaps a drainage pipe is obstructed and must be cleaned.

There are two types of underground water level meters: automatic and manual. An automatic meter is installed in Reparto, its data can be seen directly on the laptop. Berrinche only has manual meters, as shown in Fig.13 since the automatic meters were damaged in a thunderstorm during the construction time. Therefore, data in Berrinche only obtained at the time authorities measure in site.

Fig. 13 Underground water level meter (Photo by author, 2013)

Inclinometers

Inclinometers, shown in Fig.14, are used to make a profile of the underground soil. A pipe must be vertically drilled up to a certain depth. The inclinometer is inserted and readings are taken every 50

cm to create the profile. Overtime, these profiles can be compared to see if movements have occurred.

Fig. 14 Inclinometer. (Photo by author, 2013).

Rainfall gauge

It's a device used to measure the amount of rainfall received over a certain period of time.

Siren and alarm

A siren and alarm were placed during the construction works in the sites to warn about possible movements in the mountain. The alarm would sound if certain values were reached, these don't indicate a landslide is occurring but give a warning to the people in charge to keep closely monitoring the site. Such values were indicated by Japanese experts, who given their knowledge in these cases have noticed these values are a good reference point (CCI&ESS, 2011). The values are:

1. For extensometers: if a value above 2mm/hr is recorded.
2. For rainfall gauge: if 99 mm of rain in a hour or 999 mm of rain in a day is recorded.

Once the projects were finished only a siren and alarm remain in the neighbor's house next to the central station to warn about movements and rainfall. In case the alarm is heard, the house owner must call CODEM who must go and check the situation.

Maintenance works

The success of the projects depends on the adequate maintenance given to each of the elements involved. Basic maintenance works include:

1. Cleaning of mud at the bottom of the drainage wells.
2. Cleaning of the intake and drainage pipes in the wells.
3. Grass cutting, soil and rock removal from the canals.
4. Monitoring of the safety devices, as well as a periodic battery change.
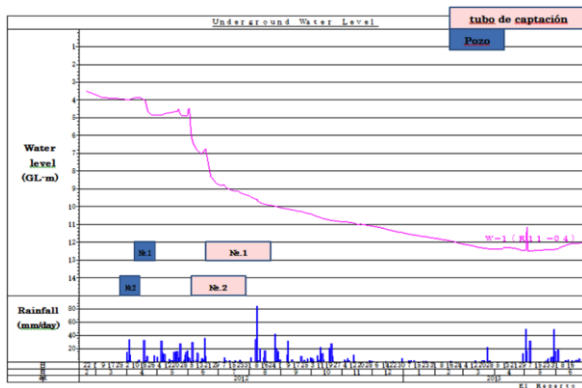
Fig. 15 The graph shows at the beginning of the projects, water was found 3 meters beneath the surface in Reparto. As the construction of the wells and pipes started, the water was discharged and at the end of the construction, water was found at 12 meters below the surface. (CCI&ESS, 2013)
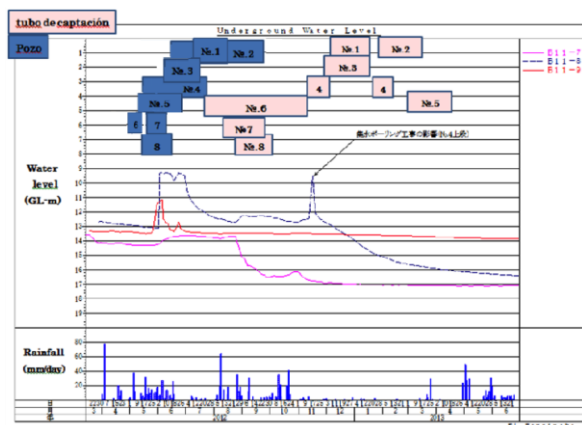
Fig. 16 Changes in underground water level can be seen from the three underground water level meters installed in Berrinche. (CCI&ESS, 2013).

Conclusions

At the end of the projects, after data was collected throughout the construction process, we saw how the initial underground water level lowered as the wells and horizontal perforations were finished and water was discharged, as seen in Fig. 15 and 16. This is the basic purpose of the works; therefore, the mission was accomplished.

CODEM continues to constantly monitor these devices and maintain the sites in optimal conditions. Special attention is given to the sites during winter seasons, to confirm water from the storms is evacuated properly. Since the construction finished, no abnormal values have been detected, some small repairs have been done in the canals and cleaning works are constantly performed to satisfy the project maintenance guidelines.

References

Harp, E., Castaneda, M., Held, M., (2002). Deslizamientos de tierra provocados por el Huracán Mitch en Tegucigalpa, Honduras, Open File Report 02-33, 12p.

Hazama Ando Corporation biding files for the Project for Landslide Prevention in Tegucigalpa Metropolitan Area

CCI&ESS, (2011) design documents for The Project for Landslide Prevention in Tegucigalpa Metropolitan Area.

Alejandra Muñoz (✉)
   Hazama Ando Corporation
e-mail: mm_ale@hotmail.com

What do we know of landslide hazard in Tegucigalpa, Honduras?

Ginés Suárez

Abstract Tegucigalpa, the capital city of Honduras, belongs to the Municipality of the Central District (MDC). This municipality has the highest number of landslide records at the national level (39% of total registrations). Currently, the MDC has data and information from several landslide hazard studies. Although these studies have limited accuracy, some important conclusions can be established for future studies and current development decisions. This paper addresses: i) the identification of two types of distinct landslides (large macro landslides and small shallow landslides), ii) the low capacity of the slope and geology factors to explain through a bivariate analysis the spatial distribution of the landslides and (iii) the identification of other factors related to the soil characteristics that better explain the spatial distribution of the landslides in the areas of El Picacho and La Laguna del Pedregal. The study states the relevance of soil mapping as an input for landslide susceptibility analysis in Tegucigalpa.

Keywords landslide hazard, susceptibility, Tegucigalpa

Introduction

The goal of landslide susceptibility analyses is to establish the propensity of an area to landslides based on the evaluation of factors that produce the movements (Suárez Díaz, 1998; Ayala Carcedo and Corominas, 2002). Susceptibility analysis is a spatial-statistical approach (Chica Olmo and Luque Espinar, 2002), which is a previous step for the application of deterministic methods that require significant investments in generating geotechnical information (Ayala Carcedo and Corominas, 2002).

The main landslide susceptibility models are (Ayala Carcedo and Corominas, 2002):

a) Models based on the analysis of distribution of landslides. These models require the development of an inventory of active landslides based on fieldwork, morphological analysis and aerial photograph interpretation (Suárez Díaz, 2001).

b) Models based on activity. These models are similar to those described in a) but also include the analysis of landslide activity through multi-temporal aerial photographs.

c) Density-based models. These models analyse the percentage of the area of a spatial variable affected by landslides (using the landslide inventory) and provide insight into the influence of each parameter generating movements.

d) Models based on geomorphological analysis. These models are based on expert analysis of terrain geometry and its relation with landslides. Not only do they identify areas with active movements, but also areas that may be prone to movements (SDC-INETER, 2005; Pérez, 2003).

e) Models based on qualitative analysis. In these models, weights are given based on expert judgment of the importance of the spatial variables in the generation of landslides. These variables are assigned a numerical value based on a method of multi-criteria analysis (Blandón Sandino, 2007).

f) Models based on bivariate statistical analysis. These methods are based on the identification of the spatial variables that concentrate the highest density of landslides and are then integrated into a multi-criteria analysis based on that density (van Westen, 2000, Eugster, 2002).

g) Models based on multivariate statistical analysis models. These models are based on the generation of discriminant functions from numerical combinations of the variables (Aldas and Aldás, 2005; Suárez, 2009).

h) Deterministic models. They use a physical basis. The two main types of models are based on the calculation of deformation and limit equilibrium. The most widely used method for regional analysis is the infinite slope (Dietrich and Montgomery, 1998; Harp et al., 2002b).

Study area

Tegucigalpa has an area of 200 km² and a population of 1,240,887 inhabitants (IDB, 2016). It belongs to the Municipality of the Central District, which has the highest number of landslide records at national level (39% of total registrations, according to the author's

analysis using the DESINVENTAR database (LA RED, 2016)). During the period 1966-2012, the municipality has been impacted by 239 landslides that affected 13,644 people, caused 49 victims, totally destroyed 460 homes and partially damaged 734 (IDB, 2016). In October 1998, Tegucigalpa was affected by extreme rainfall caused by hurricane Mitch. This precipitation, which caused flooding and triggered many landslides, was significantly higher than that of previous events, such as Gert and Fifi (Harp et al., 2002a).

Existing information has guided the implementation of major investments on stabilization of the larger landslides (e.g., the Berrinche and Reparto landslides cover a total area of 0.8 km^2). In addition, a municipal regulation that defines a zoning based on existing landslide susceptibility and hazard analysis and requires field inspections for granting building permits has been defined (IDB, 2016). The use of the existing hazard and susceptibility maps for land risk zoning has been a real challenge, because all studies have generated information having different resolution levels (IDB, 2016). Understanding the limitations of the methodologies is key in order to produce robust local legislation. This article tries to identify crucial aspects from existing information on susceptibility and hazard in order to guide an eventual update of the risk zoning.

The analysis is focused on an area of 140 km^2, where most of the urban neighbourhoods are located (Fig 1). Around this area, a grid of 384km^2 (16 km x 24 km) was generated.
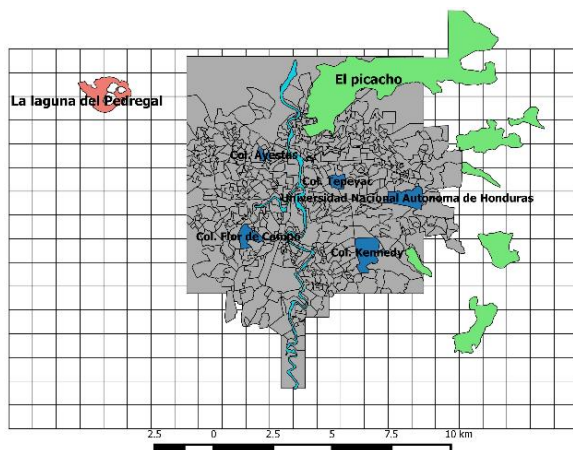
Fig. 1 Study area. The grey colour polygon represents Tegucigalpa's urban area. Dark blue polygons are specific neighbourhoods with their names. The Choluteca River is shown in light blue. Ignimbrite rocky outcrops are shown in green. The volcanic crater in La Laguna del Pedregal is shown in orange

Previous landslides studies

Currently, the MDC has data on the number of historical landslide events and their effects (IDB, 2016), inventories of landslides (Lotti, 1986; JICA, 2002; Harp et al., 2002a), various analyses of susceptibility to landslides (Eugster, 2002; Montoya Pineda, 2004; UNDP, 2011; IDB, 2016) and deterministic slope stability analysis (Harp et al., 2002b).

Comparative analysis of landslides inventories

The three most exhaustive inventories, which have combined photo analysis and field work, are the inventory from Lotti (1986), the inventory from the United States Geological Survey, USGS (Harp et al., 2002a) and the inventory from the Japan International Cooperation Agency, JICA (2002).

In order to compare those three inventories, two variables were considered: number of landslides and area of the landslides. Regarding the area of the landslides and based on the exponential scale for landslide classification defined by the Swiss Development Cooperation (SDC-INETER, 2005), four categories were defined: small landslides (0-1000 m^2), medium landslides (1,000-10,000 m^2), large landslides (10,000-100,000 m^2) and macro-landslides (>100,000 m^2).

The inventory from Lotti (1986) is integrated in a geological map of the city and was developed as part of a water supply master plan. The scale is approximately 1:25,000 and includes 43 landslides. Mapped polygons, on average, correspond to the category of macro-landslides (with an average area of 363,000 m^2); most of the polygons (28) have an area greater than 100,000 m^2.

The inventory of the USGS (Harp et al., 2002a) was made from aerial photo interpretation on a scale 1:40,000 and 1:20,000 taken immediately after Hurricane Mitch. The inventory has 487 landslides; most of the polygons (358 polygons, which represent 74%) have areas in the category of small landslides. Inventoried movements are mainly shallow debris flows and mostly mapped in areas where the soil or rock alteration was exposed after the hurricane.

The inventory of JICA (2002) was based on the inventory of the USGS and the geological map of Lotti (1986), and completed with fieldwork and photo interpretation (JICA, 2002). The inventory identified 61 landslides, with an average area that correspond to the category of large landslides (average 49,500 m^2), including 9 macro-landslides. Fig. 2 gives a summary of all identified landslides, based on the area and the inventory to which they belong.

The inventory of USGS (Harp et al., 2002a) was more oriented towards debris flows while Lotti (1986) and JICA (2002) focused on rotational and translational landslides (USGS, 2004). There is a 41% overlap

between the JICA (2002) and Lotti (1986) inventories, which is considered significant. However, several of the movements mapped by USGS (Harp et al., 2002a) were not integrated into the inventory of JICA (2002), maybe because they corresponded to debris flow instead of landslides.

For land use purposes, it is critical to identify the level of activity and probability of reactivation of the landslides and debris flow mapped in the inventories. JICA's inventory classified movements in A (active, 35 landslides, 57%), B (low activity, 21.5%) and C (inactive, 21.5%). A recent review of the inventory (IDB, 2016) identified 16 active landslides. This means there is a significant number of landslides in the inventory which should be inactive after Hurricane Mitch.
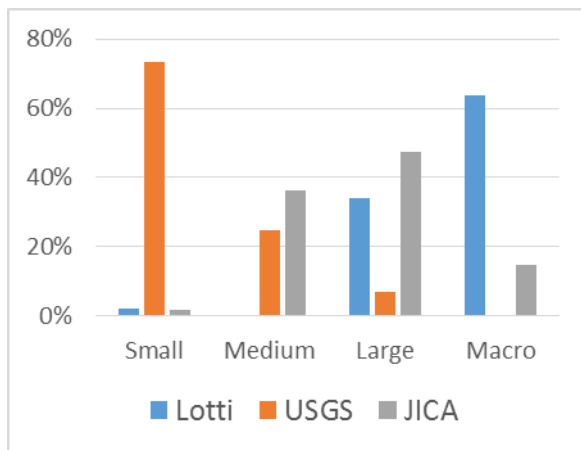
Fig. 2 Percentage of landslides per area and per inventory, according to the landslide classification criteria defined in SDC-INETER (2005)

Regarding the USGS inventory, it is relevant to identify which of those debris flows are still active in order to determine the level of hazard. There are no recent reports of activation for most of these debris flows, so it is assumed that the probability of reactivation for most of the inventory is low, associated with extreme events as Hurricane Mitch.

Method

Spatial Distribution Analysis

The point pattern analysis was applied to analyse the spatial distribution of the landslide inventories in order to verify if they follow: (i) a random distribution (i.e., any point is equally likely to occur at any location), (ii) uniform distribution (i.e., every point is as far from all of its neighbours as possible) or (iii) a clustered distribution (i.e., many points are concentrated close together) (see Fig. 3). The applied approach was the

variance/mean ratio (Lee and Wong, 2001). To carry out the analysis, the three landslide inventories were grouped in a single inventory. This single inventory was divided in two sub-inventories, according to the area of the landslides: sub-inventory A (small and medium landslides) and sub-inventory B (large and macro-landslides) (see Fig. 4). This division corresponds to the observed different typologies of landslides regarding their area: shallow debris flows for small and medium landslides (Harp et al., 2002b) and deep, rotational and translational landslides for the large and macro landslides (IDB, 2016).
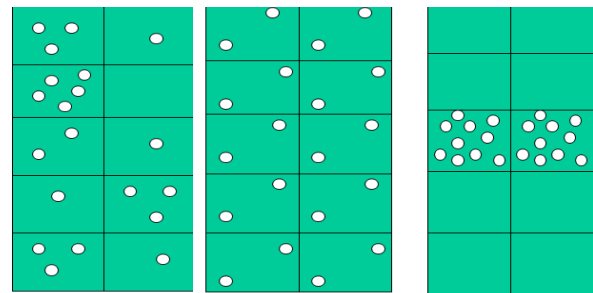
Fig. 3 Different scenarios for the point pattern analysis: random distribution (left), uniform distribution (center) and clustered distribution (right)

In order to carry out the analysis, a grid square around Tegucigalpa´s urban area was generated. Each grid square was sized at 1 km²; the cells covered an area of 16 km x 24 km. Following the variance/mean ratio approach, the variable X was generated as the number of centroids of landslides in each cell. In order to determine the type of spatial distribution (random, uniform or clustered), the variance/mean ratio for both sub-inventories was estimated. Both sub-inventories showed a variance/mean ratio above 1 (e.g., 6 for sub-inventory A and 2 for sub-inventory B), giving evidence that their spatial distributions correspond to a clustered model.

Analysis of Explanatory Variables

In order to map the areas susceptible to landslides, the explanatory variables of the spatial distribution of the landslides should be identified (Ayala Carcedo and Corominas, 2002).

Based on the results and methodologies of previous studies, the Interamerican Development Bank (IDB) carried out a recent susceptibility map (IDB, 2016). The susceptibility map was developed applying a bivariate analysis (van Westen, 2000). The final map is able to explain the distribution of the landslides with an acceptable accuracy, because 86% of the landslides of the inventory (which included landslides mapped by Lotti, USGS, JICA and the United Nations Development

Program (UNDP)) fell under the category of high and medium susceptibility. However, the area classified as high and medium susceptibility represents 80% of the urban footprint.
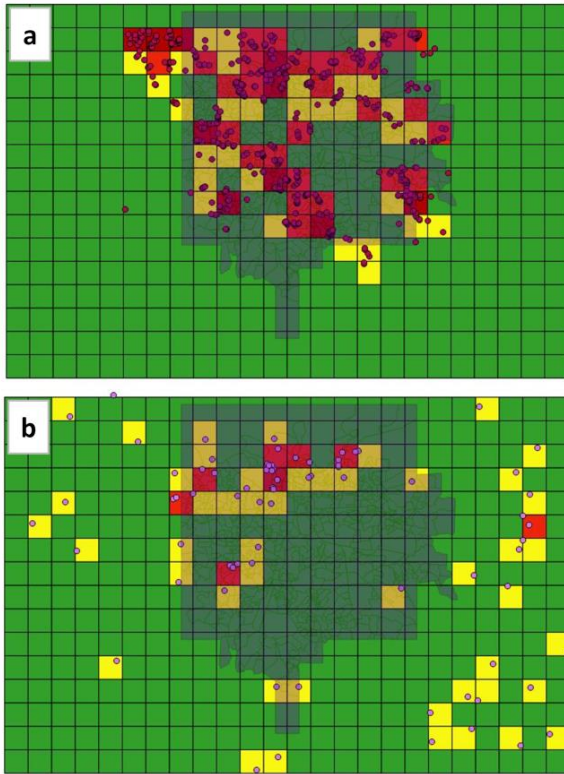
Fig. 4 Spatial distribution of landslides: a. small and medium landslides, b: large and macro-landslides. The points represent the centroids of the landslides. The dark green area shows the urban area of Tegucigalpa, as seen in Fig. 1. Green, yellow and red cells have low, medium and high concentration of centroids, respectively. The thresholds between low, medium and high concentrations were estimated applying the natural breaks method to each sub-inventory

In order to determine the explanatory capacity of each parameter class, the following expression for bivariate analysis was considered:

$$\ln W_i = \ln\left(\frac{Densclas}{Densmap}\right) = \ln\left(\frac{\dfrac{Npix(Si)}{Npix(Ni)}}{\dfrac{\sum Npix(Si)}{\sum Npix(Ni)}}\right) \quad [1]$$

where W_i = the weight given to certain parameter class (e.g. class slope), Densclas = the landslide density

within the parameter class, Densmap = the landslide density within the entire map, Npix (Si) = number of pixels which contain landslides in a certain parameter class and Npix (Ni) = total number of pixels in a certain parameter class.

A simplification of this expression allows the estimation of the landslide density (densclas) within the parameter class (i. e., higher densclas values imply higher explanatory capacity):

$$Densclas = \frac{Npix(Si)}{Npix(Ni)} \quad [2]$$

The formula was applied to estimate the explanatory power of two variables that have been considered in all existing susceptibility analysis for Tegucigalpa: geology and slope (Eugster, 2002; Montoya Pineda, 2004; UNDP, 2011; IDB, 2016).

Results and Discussion

Table 1 summarize the results. In order to simplify the analysis, three ranges were defined using the standard deviation (stdev) of the values: low explanatory capacity from 0.0-2.16% (1 stdev), medium explanatory capacity from 2.16-4.27% (2 stdev) and high explanatory capacity, >4.27%. Table 1 show that slope has low capacity to explain the spatial distribution of small and medium landslides. On the other hand, slope has better capacity to explain the spatial distribution of large and macro landslides, especially in ranges 0-15° and 15-30°. This may seem counterintuitive, but it is associated with the accumulation of residual soils prone to landslides in the medium to low slopes, while higher slopes indicate denuded rocky outcrops (Santacana et al., 2002).

Table 1 Class density for slope and geology

Variable	Subinventory A (small and medium)	Subinventory B (large and macro)
Slope ranges (degrees)		
0-15	0.12%	3.35%
15-30	0.18%	3.04%
30-45	0.14%	1.43%
>45	0.06%	1.38%
Geology		
Alluvium	0.50%	1.07%
PadreMiguel formation	0.17%	0.20%
Ignimbrites	0.65%	1.42%

Regarding the geology, the capacity to explain the spatial distribution of the landslides is very limited,

with low capacity for sub-inventory B and sub-inventory A. Considering the limited explanatory power of the traditional variables applied in the susceptibility models in Tegucigalpa, new variables should be considered in order to refine these models. For large and macro-landslides, the approach to identify variables that explain the spatial distribution of landslides should undertake a more comprehensive understanding of the geological and geomorphological dynamics associated with the landslides.

Most of the large and macro-landslides are located in two areas: the hills of "El Picacho" and "La Laguna del Pedregal" (see Fig. 1). In Lotti's geological map, these two hills are characterized as pertaining to the Valle de Angeles formation and Mafic flows, respectively. However, in recent field visits, it was observed that on top of these geological formations, there are colluvium soils, which is the material affected by the landslides (IDB, 2016). Therefore, the existing geological map, which is focused on the geological substrate, doesn't identify this type of colluvium soils that are particularly prone to major landslides.

In order to overcome the limitation of the geological map (i.e., it doesn't identify colluvium deposits), a proxy alternative was applied. In both areas, (Picacho and Laguna del Pedregal) there are rocky outcrops. The denudation of these rocky outcrops produced the colluvium which covers the hillsides. The Ignimbrite rocky outcrop of El Picacho Hill is well identified in Lotti's geological map and it was used to produce a buffer downhill. Additionally, other ignimbrite rocky outcrops were identified and similar buffers were generated (see Fig. 5).
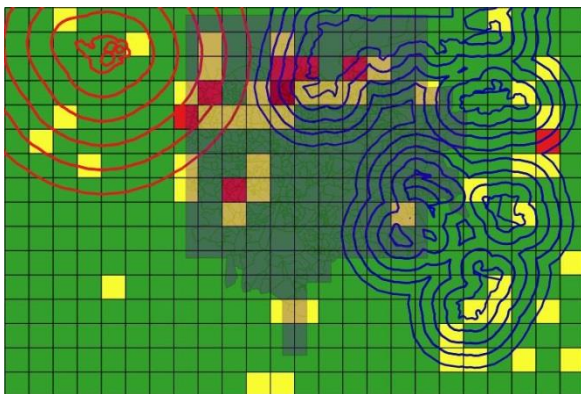
Fig. 5 Location of the buffers. Notice how they match with the cells that concentrate large and macro-landslides. The red lines are the buffers for "La Laguna del Pedregal" and blue lines are the buffers for El Picacho and other ignimbrite rocky outcrops

El Pedregal is a volcanic mafic structure, so the limits of the crater of the volcano were used to generate the buffer (see Fig. 5). This buffer approximately identifies the location of the colluvium (assuming that it covers the hill homogeneously).

The explanatory power of the buffers was calculated, obtaining a value of 2.3% for the buffers of El Picacho and other ignimbrite rocky outcrops and 15.72% for the buffer of La Laguna de El Pedregal. This correlation between spatial distribution of landslides and geological boundaries was identified by previous authors (Eugster, 2002; IDB, 2016).

Conclusions

The following conclusions can be drawn:
- Existing landslides inventories should be updated. Recent analyses of landslide activity provide evidence that many inventoried landslides show little activity.
- Additionally, the probability of debris flow mapped after Hurricane Mitch should be analysed, because it is very likely that they have low temporal probability of reactivation due to the low frequency of extreme events.
- The existing geological map has a limited capacity to explain the spatial distribution of landslides.
- The variable slope has good capacity to explain the spatial distribution of large and macro landslides, but very limited capacity to explain the spatial distribution of small and medium landslides.
- The location of colluvium soils is a good explanatory variable of spatial distribution of large and macro-landslides, especially in La Laguna del Pedregal hillside. A soil map should be elaborated as an input for landslide susceptibility analysis.

References

Aldas, U., Aldás, J. (2005), Análisis multivariante aplicado, Ed. Thomson, España.

Ayala Carcedo, F. J., Corominas J. (2002). Mapas de susceptibilidad a movimientos de ladera usando técnicas SIG, publicaciones del Instituto Geológico y Minero de España (ITGE), Madrid.

Blandón Sandino, D. Y. (2007). Evaluación de la susceptibilidad a movimientos del terreno en la zona núcleo de la reserva natural Tisey-La Estanzuela, Estelí, tesis de maestría en ciencias, no publicada, Nicaragua, Managua.

Chica Olmo, M., Luque Espinar, J. A. (2002) Interpolación espacial en la creación de cubiertas SIG, en Laín Huerta L. (ed.) Los Sistemas de Información Geográfica en la gestión de los riesgos geológicos y el medio ambiente (2002) Publicaciones del Instituto Geológico y Minero de

España, serie medio ambiente y riesgos geológicos, Madrid.

Dietrich, W., Montgomery, D. (1998) Shalstab a digital terrain model for mapping shallow landslide potential reporte técnico publicado por NCASI, USA

Eugster, S. (2002). Statistical landslide hazard analysis in Tegucigalpa, Honduras.

Harp E., Held M., Castañeda M. (2002a). Landslides Triggered by Hurricane Mitch in Tegucigalpa, Honduras. USGS.

Harp E., Held M., Castañeda M., McKenna J., Jibson, R. (2002b) Landslide Hazard Map of Tegucigalpa, Honduras. USGS.

IDB (2016). Plan de acción de Tegucigalpa. Interamerican Development Bank.

JICA (2002). El estudio sobre el control de inundaciones y prevención de deslizamientos de tierra en el área metropolitana de Tegucigalpa de la Republica de Honduras.

LA RED (2016). DesInventar Database (Disaster Inventory System). Corporación OSSO, Cali. Available at https://online.desinventar.org/

Lee, J., Wong, D. W. (2001). Statistical analysis with ArcView GIS. John Wiley & Sons.

Lotti (1986). Geological map for the underground water project and El Chile Mountain in Tegucigalpa. Tegucigalpa Master Plan. National Autonomous Survey of Aqueducts and Sewage (SANAA), Tegucigalpa, Honduras.

Montoya Pineda, M.A. (2004). Identificación y análisis de las áreas susceptibles a los procesos de remoción en masa, en la cuenca alta del río Grande o Choluteca, en Tegucigalpa, Honduras. C.A, tesis de maestro en ciencias, no publicada, San José, Costa Rica.

Pérez R. (2003). Propuesta de normalización para la representación cartográfica en Internet. Aplicación a mapas geomorfológicos, tesis doctoral, universidad politécnica de Madrid, escuela técnica superior de ingenieros de caminos, canales y puertos, sin publicar.

Santacana, N., Baeza, C., Corominas, J., De Paz, A., Marturia, J. (2002). Análisis de susceptibilidad del terreno a la formación de deslizamientos superficiales mediante el uso de un sistema de información geográfica. Aplicación de la Pobla de Lillet (Pirineo Oriental) en Ayala Carcedo, F. J et al (2002). Mapas de susceptibilidad a movimientos de ladera usando técnicas SIG, publicaciones del Instituto Geológico y Minero de España (ITGE), Madrid.

SDC-INETER (2005). Inestabilidad de Laderas, Mapas de Amenazas, Recomendaciones técnicas para su elaboración, COSUDE, Managua, Nicaragua.

Suárez Díaz, J. (2001). Control de erosión en zonas tropicales, instituto de investigaciones sobre erosión y deslizamientos, Bucamaranga, Colombia.

Suárez Díaz, J. (1998). Deslizamientos y estabilidad de taludes en zonas tropicales, Publicaciones UIS, Bucamaranga, Colombia.

Suárez, G. (2009). Relación entre las formas de alteración de las rocas ígneas en clima tropical, la geomorfología, la hidrogeología y los movimientos de ladera en la subcuenca del río Tocoa. Tesis de maestría sin publicar.

van Westen, C. J. (2000). The Modelling of Landslide Hazards Using GIS. Survey in Geophysics, 21, 2‑3, pp 241‑255

UNDP (2011). Evaluación geológica cinco colonias ladera ese extinto Volcán el pedregal, sector oeste distrito central. Programa de las Naciones Unidas para el Desarrollo. Sin publicar.

USGS (2004). Landslide types and processes. http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html

Ginés Suárez (✉)

Interamerican Development Bank, Disaster Risk Management Unit. Address: World Trade Center, San Salvador, El Salvador.

e-mail: giness@iadb.org

The use of the matrix method for the landslide susceptibility mapping of Tegucigalpa, Honduras

Elias Garcia-Urquia, Hiromitsu Yamagishi

Abstract A landslide inventory based on an aerial photograph interpretation carried out in 2013 has been used for the construction of a landslide susceptibility map for Tegucigalpa, Honduras. The matrix method has been employed due to its successful applicability in data-scarce regions. This method requires the creation of Unique Condition Units for the study area; these units represent a unique combination of classes for the selected variables associated with landslide occurrence. These variables are slope angle, geology and distance to drainage. Five susceptibility classes were established for the landslide susceptibility map using the natural breaks function built in ArcGIS. The success rate curve constructed to validate the analysis showed that the susceptibility map had 80% efficiency in depicting the landslides in the inventory. Meanwhile, the Degree of Fit measure also shows that 73% of the landslide cells are classified as having "very high" and "high" susceptibility while less than 10 % are in the "low" and "very low" susceptibility classes. Some limitations of landslide inventories based on aerial photograph interpretation are further discussed.

Keywords matrix method, aerial photograph interpretation, landslide susceptibility index, landslide susceptibility mapping, GIS, unique condition unit, Tegucigalpa

Introduction

Landslide susceptibility maps are constructed to indicate where landslides are more likely to occur in a given study area. Their reliability depends on the accuracy of the landslide inventory as well as the right selection of explanatory variables associated with landslide occurrence for the analysis. Several methods have been proposed in the scientific literature to produce landslide susceptibility maps (Pardeshi et al., 2013). These include logistic regression (Ayalew & Yamagishi, 2005), artificial neural network (Pradhan & Lee, 2010), frequency ratio (Lee & Sambath, 2006),

matrix method (Irigaray et al., 2007) and weights of evidence (Ayalew et al., 2005).

In this paper, the matrix method has been employed in the construction of a landslide susceptibility map for Tegucigalpa, Honduras. This method has the advantage of producing reliable maps in data scarce regions, since only three explanatory variables are needed in the analysis. Slope angle, geology and distance to drainage were employed to construct a susceptibility map capable of depicting the landslides contained in an inventory based on aerial photograph interpretation carried out in 2013. The high efficiency yielded by the success rate curve and the Degree of Fit indicates that the chosen variables have a strong connection with the landslides in the study area.

Study Area

Tegucigalpa is located in a mountainous basin in the central southern part of Honduras (see Fig. 1). To date, the city has an area of approximately 200 km² and a population of nearly 1.5 million inhabitants. Built on a

Fig. 1 Location of Tegucigalpa, Honduras

complex geological setting, the city's disorganized urban growth in the last 40 years has forced many inhabitants to build weak homes on unstable land along the rivers or on the steep slopes that surround the city (Angel et al., 2004). Tegucigalpa´s vulnerability to landslides was evident in October 1998, when Hurricane Mitch triggered a massive episode of landslides in the city (Harp et al., 2002; JICA, 2002). Although many inhabitants have become aware of the threat of landslides every year during the rainy season (which extends from May to October), the scarcity of job opportunities in nearby smaller but safer towns discourages these inhabitants to move away from Tegucigalpa (Pearce-Oroz, 2005). Fig. 2 shows a precarious neighbourhood in Tegucigalpa that experienced a recent landslide episode.

Fig. 2 The Izaguirre neighborhood suffered a landslide episode in 2014. Several houses were damaged and many inhabitants were affected. (This image is courtesy of El Heraldo newspaper.)

Methodology

For the construction of the landslide susceptibility map, a landslide inventory based on an aerial photograph interpretation carried out in 2013 was used. The compilation of the inventory began in 2011 when the Japanese Society for the Promotion of Science (JSPS) promoted a landslide hazard project in Tegucigalpa which led to the aerial photograph survey in March 2013. Experts from the Japan International Cooperation Agency (JICA) trained students and staff members of the Engineering Polytechnic University and the National Autonomous University of Honduras for the photograph interpretation (Yamagishi et al., 2014). Fig 3 shows the landslide inventory map presented to the municipal authorities in 2014.
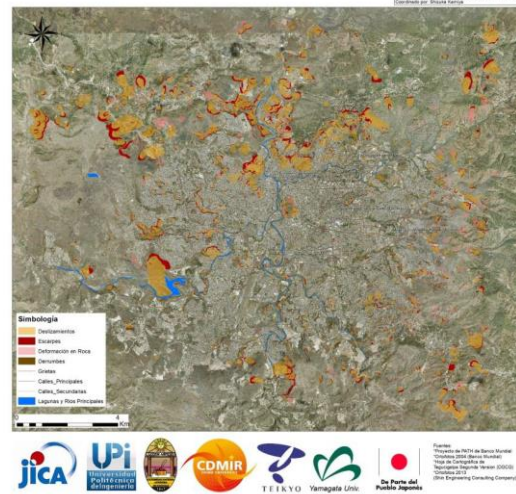
Fig. 3 Landslide inventory map based on an aerial photograph interpretation.

The explanatory variables have been derived from a thorough landslide study carried out in 2001 after the passage of Hurricane Mitch in 1998 (JICA, 2002). The variables, whose classes are shown in Tab. 1, are as follow:

a. Slope angle: six classes of 5 degrees in range were created. The seventh class encompasses all angles greater than 30 degrees.
b. Geology: the geological map developed by JICA at a scale of 1:10,000 was used as a base. This map shows 21 different geologic formations.
c. Distance to drainage: as part of the flood analysis, JICA carried out a detailed hydrological survey of the city. Buffers of 100, 200, 300 and 400 meters were created around the four major rivers.

Table 1 Explanatory variables for the landslide susceptibility analysis

Variable	Classes		Variable	Classes
Geology	Tcg	Qb	Slope Angle (°)	0 – 5
	Tm	Tpm1		5 - 10
	Qal	Qe2a		10 - 15
	Krc	Qe2b		15 – 20
	Qe3	Tpm2		20 - 25
	Qan1	Tpml		25 - 30
	Qan2	Tep		>30
	Tpm3	Kvn	Distance to Drainage (m)	0 - 100
	Qe1	Odt		100-200
	River bank	Reservoir		200-300
				300-400
	Ti			>400

The study area was divided into a grid composed of 50 m x 50 m cells and a total of 40,000 cells were created. Each cell stored information on the presence/absence of landslide as well as information concerning the explanatory variables. Unique Condition Units (UCUs) (Clerici et al., 2002) were then created to group those cells sharing exactly the same information regarding the explanatory variables. The Landslide Susceptibility Index for a specific UCU (LSI_{UCU}) was calculated as:

$$LSI_{UCU} = \frac{LC_{UCU}}{LC_{UCU} + NLC_{UCU}} \qquad [1]$$

where LC_{UCU} and NLC_{UCU} represent the number of landslide and non-landslide cells in the UCU, respectively. A higher value of LSI indicates a higher susceptibility to landslides. Five susceptibility classes were established using the natural breaks classification method built in ArcGIS.

To validate the analysis, two measures were determined. The first one was the area under the success rate curve. This curve is constructed by ordering the UCUs from highest to lowest LSI values and comparing the accumulation of both the number of landslide cells and the total number of cells that each UCU depicts. The second measure is the Degree of Fit (DoF) to evaluate the relative proportion of landslides cells to the total number of cells in each susceptibilty class (Irigaray, 2007). It is calculated as follows:

$$DoF = \frac{\dfrac{z_i}{s_i}}{\sum \dfrac{z_i}{s_i}} \qquad [2]$$

where z_i is the number of landslide cells in the ith susceptibility class and s_i is the total number of cells belonging to the ith class. A good susceptibility map would have low values of DoF for the low and very low susceptbility classes (considered as error) and high values of DoF for the high and very high susceptibility classes (considered as accuracy).

Results

A total of 735 possible UCU combinations can be created considering the classes shown in Tab. 1 (i.e. 21 x 7 x 5 = 735 UCUs). However, 210 UCUs were not represented in the study area. From the remaining 525 UCUs, 6 of them contained only landslide cells (i.e. their LSI was equal to 100) while 239 contained only non-landslide cells (i.e. their LSI was equal to 0). Tab. 3

shows a summary excerpt of 5 UCUs that contain both landslide and non-landslide cells. Due to their high LSI values, these UCUs fall in the "very high" susceptibility class.

Table 2 Summary excerpt of 5 UCUs containing landslide and non-landslide cells

Geol-ogy	Slope	Distance Drainage	LC	NLC	LSI
Qe2b	20-25	100-200	1	1	50
Krc	15-20	>400	47	52	47.47
Krc	20-25	>400	14	16	46.67
Krc	20-25	100-200	20	25	44.44
Krc	25-30	>400	2	3	40

LC = landslide cells, NLC = non-landslide cells, LSI = Landslide Susceptibility Index

Fig 4 shows the landslide susceptibility map. Five susceptibility classes are shown: very low (dark green), low (light green), moderate (yellow), high (orange), and very high (red). The landslide polygons are marked by the gray borders to provide a visual overview of the consistency between the color associated with the different susceptibility classes and the absence/presence of landslides cells. In general, most landslide polygons encompass red and orange cells, indicating that the selected variables are suitable for the development of a reliable susceptibility map. It can be seen that a great portion of the "very high susceptibility" cells are located in the northeast sector of Tegucigalpa, while most of the central and southern part of the city is considered very stable.

Fig. 5 shows the success rate curve for the landslide susceptibility map. The area under this curve is usually used as a parameter to evaluate the susceptibility map in terms of its efficiency to predict the landslide cells. In this study, the area under the success rate curve is 80%; such a high value indicates that the chosen explanatory variables have a strong connection with landslide occurrence in the study area.

The accuracy and error in assigning landslide cells to the different susceptibility classes were determined by the DoF measure. Tab. 3 shows the number of landslide cells, the total number of cells and the ratio of landslide to total number of cells in each class. It can be seen that the accuracy for the landslide susceptibility map (i.e. the sum of the DoF values in the "very high" and "high" susceptibility classes) is 73.8%, while the error (i.e. the sum of the DoF values in the "low" and "very low" susceptibility classes) is 8.4%. These values indicate that the majority of landslide cells are classified as "very high" or "high" and a few landslide cells are classified as "low" or "very low".
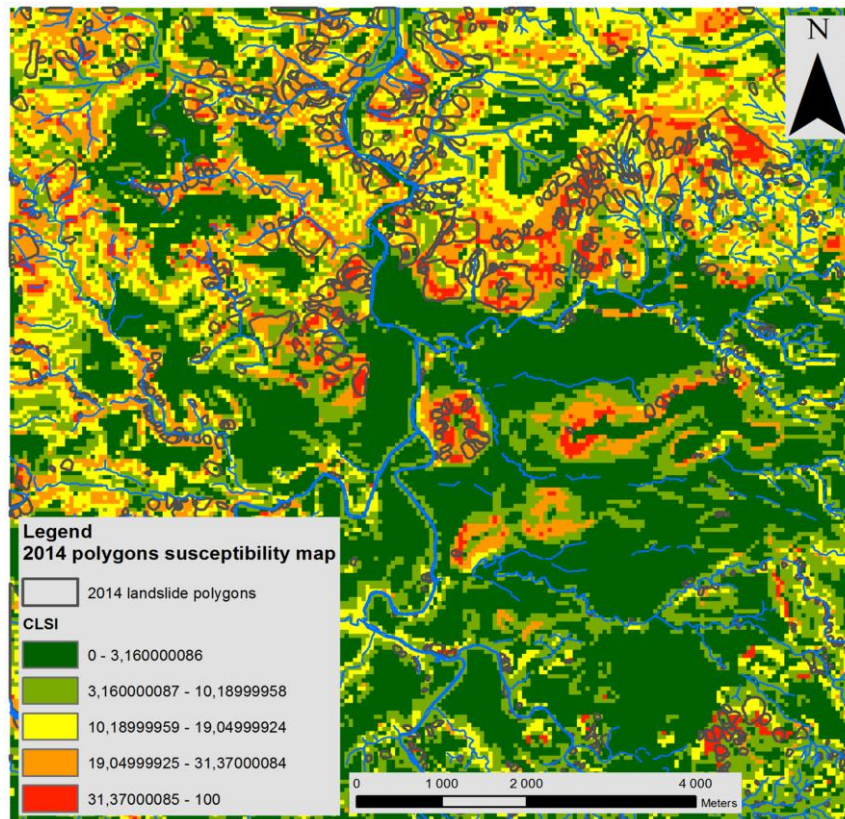
Fig. 4 Landslide susceptibility map. Five susceptibility classes are shown. The landslide polygons are marked with gray borders.
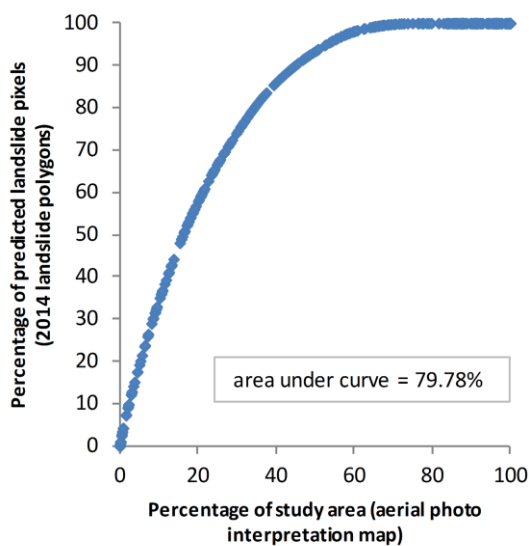
Fig. 5 Success rate curve for the landslide susceptibility map. The area under the curve is 80%.

Discussion

Tegucigalpa's landslide vulnerability is the result of an adverse physical setting weakened by the disorganized urban growth of its inhabitants and the constant exposure to triggering events during the rainy season. Given the city's urgent need of a future development plan, the landslide susceptibility map presented herein may be used as an important tool to provide insights on where development may be allowed and where it must be restricted. Even though the scarcity of data poses a challenge for landslide research studies for Tegucigalpa, the application of the matrix method has led to a reliable landslide susceptibility map capable of highlighting the areas prone to landslides.

The rich landslide history of the city requires the inclusion of old landslide events in the susceptibility analysis. Aerial photographs provide very useful information about the occurrence of past landslide events, especially in places where difficult access makes field surveys very difficult. However, there are three big limitations about landslide inventories based on this technique:

Table 3 Results of the calculation of the Degree of Fit for the landslide susceptibility map

Class	Area in class (%)	Number of landslide cells per class (z_i)	Total number of cells per class (s_i)	s_i/z_i	DoF
Very high	12.69	453	1201	0.377	0.477[a]
High	39.61	1414	5678	0.206	0.261[a]
Medium	29.66	1059	7514	0.141	0.178
Low	15.66	559	8988	0.062	0.078[b]
Very low	2.38	85	16617	0.005	0.006[b]
Total	100	3570	40000	0.791	1.0

[a] = the sum of *DoF* for the Very High and High classes represents the accuracy of the method
[b] = the sum of *DoF* for the Low and Very Low classes represent the error of the method

a. In urban environments where terrain modifications are frequent, the evidence of past landslide events may not be evident in the photographs.
b. In tropical environments, the rapid growth of vegetation may also obscure the evidence of past landslide events (Vranken et al., 2015).
c. Even if aerial photographs are taken immediately after an extraordinary triggering event capable of inducing multiple landslides simultaneously (e.g. Hurricane Mitch in October 1998, as described in Harp et al. (2002)), there is no guarantee that all landslides visible in the aerial photographs have been induced by the same triggering event. Some landslides may have occurred in prior triggering events (Garcia-Urquia & Axelsson, 2014).

The above limitations suggest that data derived from aerial photograph interpretation is very useful but needs to be complemented with other sources of landslide data. In many places around the world, historical data such as press archives, technical reports and scientific publications have provided temporal landslide data that is difficult to obtain from aerial photographs maps (Garcia-Urquia, 2015). The advantage of using the latter sources is the opportunity of developing landslide hazard and risk maps.

Conclusion

In data scarce regions, the matrix method has been employed successfully to evaluate the relationship between different explanatory variables and landslide occurrence. This method has been used in Tegucigalpa, Honduras for the construction of a landslide susceptibility map using a landslide inventory based on aerial photograph interpretation. The chosen explanatory variables were slope angle, geology and distance to drainage. The high value of the area under the success rate curve indicates that the chosen variables have a strong connection with landslide occurrence. The Degree of Fit also indicates that most landslide cells are classified under the "very high" and "high" classes while a few of them are considered as of "low" and "very low" susceptibility. There is no doubt that aerial photographs provide valuable landslide data; however, this data must be complemented with historical data to be able to portray a more reliable landslide analysis.

References

Angel, S., Bartley, K., & Derr, M. (2004). Rapid Urbanization in Tegucigalpa, Honduras: Preparing for the Doubling of the City's Population in the Next Twenty-Five Years.

Ayalew, L., & Yamagishi, H. (2005). The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains, Central Japan. Geomorphology, 65(1–2), 15-31. doi: 10.1016/j.geomorph.2004.06.010

Ayalew, L., Yamagishi, H., Marui, H., & Kanno, T. (2005). Landslides in Sado Island of Japan: Part II. GIS-based susceptibility mapping with comparisons of results from

two methods and verifications. Engineering Geology, 81(4), 432-445. doi: 10.1016/j.enggeo.2005.08.004

Clerici, A., Perego, S., Tellini, C., & Vescovi, P. (2002). A procedure for landslide susceptibility zonation by the conditional analysis method. Geomorphology, 48(4), 349-364. doi: 10.1016/S0169-555X(02)00079-X

Irigaray, C., Fernández, T., El Hamdouni, R., & Chacón, J. (2007). Evaluation and validation of landslide susceptibility maps obtained by a GIS matrix method: examples from the Betic Cordillera (southern Spain). Nat. Hazards, 41(1), 61-79. doi: 10.1007/s11069-006-9027-8

Garcia-Urquia, E. (2015). The Use of Press Archives in the Temporal and Spatial Analysis of Rainfall-Induced Landslides in Tegucigalpa, Honduras, 1980-2005. (Doctoral Degree), Uppsala University, Uppsala, Sweden.

Garcia-Urquia, E., & Axelsson, K. (2014). The Use of Press Data in the Development of a Database for Rainfall-Induced Landslides in Tegucigalpa, Honduras, 1980-2005. Nat Hazards, 73(2), 237-258. doi:10.1007/s11069-014-1043-5

Harp, E. L., Castañeda, M., & Held, M. D. (2002). Landslides triggered by Hurricane Mitch in Tegucigalpa, Honduras: U.S. Geologic Survey Open File Report 02-0033.

JICA. (2002). The Study on Flood Control and Landslide Prevention in Tegucigalpa Metropolitan Area of the Republic of Honduras.

Lee, S., & Sambath, T. (2006). Landslide susceptibility mapping in the Damrei Romel area, Cambodia using frequency ratio and logistic regression models. Environ. Geol, 50(6), 847-855. doi:10.1007/s00254-006-0256-7

Pardeshi, S. D., Autade, S. E., & Pardeshi, S. S. (2013). Landslide hazard assessment: recent trends and techniques. SpringerPlus, 2(1), 523. doi:10.1186/2193-1801-2-523

Pearce-Oroz, G. (2005). Causes and consequences of rapid urban spatial segregation. In D. Varady (Ed.), Desegragating The City: Ghettos, Enclaves and Inequality (pp. 108-124): Suny Press.

Pradhan, B., & Lee, S. (2010). Delineation of landslide hazard areas on Penang Island, Malaysia, by using frequency ratio, logistic regression, and artificial neural network models. Environ Earth Sci, 60(5), 1037 - 1054. doi:10.1007/s12665-009-0245-8

Vranken, L., Vantilt, G., Van Den Eeckhaut, M., Vandekerckhove, L., & Poesen, J. (2015). Landslide risk assessment in a densely populated hilly area. Landslides, 12(4), 787-798. doi:10.1007/s10346-014-0506-9

Yamagishi, H., Yagi, H., & Sato, G. (2014). Landslide hazard mapping of Tegucigalpa, Honduras - capacity building by JICA-JSPS Project (2012 to 2014). Proceedings of World Landslide Forum 3, 2-6 June 2014, Bejing, 712-715.

Elias Garcia-Urquia (✉)

National Autonomous University of Honduras, Department of Civil Engineering, Ciudad Universitaria, Boulevard Suyapa, Tegucigalpa, Honduras
e-mail: elias.urquia82@gmail.com

Hiromitsu Yamagishi

Asian Institute of Space Information, Shiroishi-ku, Hngo-dori 2, choume kita 3-10, Sapporo 003-0025, Japan
e-mail: hiromitsuyamagishi88@gmail.com

Identification of unstable slope indicators in Carrizal-Semane, Yamaranguila, southwest of Honduras

Ángela Morales, Diana Muñoz, Jorge Meléndez

Abstract The identification and mapping of unstable slopes require experience and precision, especially when it comes to highly urbanized areas or informal settlements in cities. However, in the case of rural communities where technical assistance is almost nonexistent, alternative methods and practices provide reliable results and alert residents about the risk areas in their villages.

Carrizal-Semane is a vulnerable community located in Las Lajas' village, south of the town of Yamaranguila, in the Department of Intibuca, in the southwest of Honduras. The community has a rugged topography and history of unstable slopes. A data collection sheet was designed to ease the identification of slope indicators with technical and practical criteria. In addition, necessary points were referenced with GPS to determine the exact location of places where landslides occurred in the past and slopes that pose a threat due to conditioning factors.

Necessary laboratory tests were held to determine the type of soil. Upon completion of the analysis, important information was obtained to communicate to the people of Carrizal-Semane.

The obtained results were satisfactory, and these show that the method can be replicated in other communities vulnerable to slope instabilities across the country. Its greater applicability is in rural areas where prior information about past events is available and where residents and authorities can follow a simple methodology to assess their own community's susceptibility to landslides.

Keywords unstable slopes, rural communities, risk, landslide

Introduction

A landslide is the movement of a rock mass, earth or debris down a slope (Cruden, 1991). It also refers to the landslide deposit itself and the slide materials in mountainous terrains that are typically separated from more stable underlying material by a zone of weakness, commonly referred to as the failure zone, plane, or surface. (FPB, 2015).

When a landslides occurs and there are human settlements near, it produces risk, which is the probability of harmful consequences, or expected losses (e.g., deaths, injuries, property, means of subsidence, economic activity disrupted or environmental damage) resulting from interactions between natural or human-induced threats and vulnerable conditions. Conventionally, risk is expressed as:

$$Risk = Threat * Vulnerability \qquad [1]$$

where threat is defined as the physical event, potentially harmful, phenomena and/or anthropogenic activity and vulnerability refers to the factors or conditions determined by physical, social, economic, and environmental processes that increase the susceptibility of a community to the impact of threats. (EIRD, 2004).

In Honduras, the instability of slopes and floods are the threats that have more impact in different sectors of the country's economy. Therefore, it is necessary to evaluate and understand their mechanisms to prevent disasters (IHCIT, 2007).

The study of the identification of landslides risk areas has had important precedents that have stimulated the investigation and application of different methodologies. These range from field analysis to the use of softwares that requires certain information to model and identify risk areas. It is important to clarify that each methodology has its advantages and disadvantages (Valencia, 2006).

The present article is based on the work of the Institute of Territorial Studies of Nicaragua (INETER) in collaboration with the Swiss Agency for Development and Cooperation (SDC). In 2005, they generated a document called "Technical recommendations for developing maps of hazard for slope instability", which compiles a set of minimum standards that must be taken into account for risk mapping of slope instability hazard, with easily applicable and feasible criteria. The methodology was

adapted to the specific conditions of the Carrizal-Semane community and intended to be used with few economic resources. This article aims to show the results obtained through the adapted methodology, but also to indicate the main limitations and how to focus future related studies in communities.

Study area

The community of Carrizal-Semane is located in Las Lajas' village, south of the town of Yamaranguila, in the Department of Intibuca, in the southwest of Honduras. It is a representative community of the indigenous Lenca culture in Honduras and has abundant natural resources (Fig. 1).

Fig. 1 Carrizal-Semane's natural resources

Its inhabitants are engaged in agriculture, especially the harvesting of corn and beans. They have access to drinking water, but not to electricity; however, some houses obtain their own electric power from solar panels. Around 55% of the inhabitants use latrines because they do not have a sewage system. Most of the houses are made of adobe with a zinc roof or clay tile and soil floors. Because of this, many of these homes have been repaired or completely rebuilt (Fig. 2), since heavy rainfall, high winds, small earthquakes and landslides have been recorded in the area.

Fig. 2 Example of house conditions in Carrizal-Semane

The town of Yamaranguila is currently one of the priorities of the Directorate of University-Society Linkage of the National Autonomous University of Honduras (UNAH), because the needs are rough and must be addressed.

Methodology

The first part of the methodology was to interact with the inhabitants of Carrizal-Semane. A survey was conducted by UNAH students of civil engineering and architecture. Information about occurrence of landslides was obtained. The results of the survey are shown in Fig. 3 and Fig. 4.
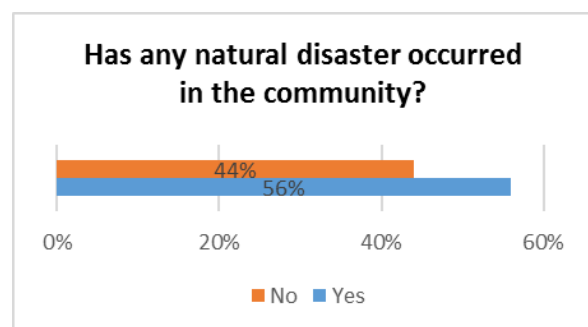
Fig. 3 Acknowledgement of natural events in the community
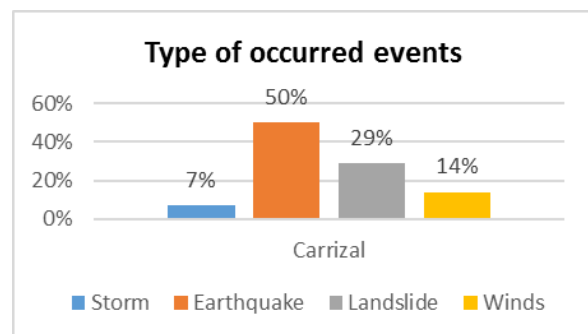
Fig. 4 Type of natural events occurred in the community

In a second assessment, field work was conducted in order to visit areas where landslides occurred in the past and to identify potentially unstable areas due to their characteristics and conditioning indicators. The identified indicators are described in Tab. 1 and are marked with a check to indicate that these where identified in the study area.

Landslides generate a series of changes in the characteristics of the rocks and landform, which allow us to detect areas that have been affected by instability (INETER-SDC, 2005). These indicators, which can be

observed directly on the ground and some of them through aerial photos, are called Background Indicators and indicate areas that have been affected by slope instability.

Table 1 Indicators according to their type.

Typology of indicators by their nature	Background Indicators	Potential Indicators
Geomorphological	☑ Small depressions in the land, undulating topography, existence of steeps.	☑ Small depressions in the land, undulating topography, small cracks.
Geological	☒ Not identified.	☑ Fractured planes across the slope, altered rocks, structures of irregular shapes, unconsolidated material.
Hydrogeological	☑ Relative abundance of water (more green areas), soil saturation, changing system of wellsprings, swamps in the crown, main body and foot of landslides.	☑ Relative abundance of water (more green areas), water upwelling zones, permanent moist or wet soil.
Vegetation	☒ Not identified.	☑ Existence of typical wetland plants, tense plant roots, twisted trees in the lower trunk.
Structural	☑ Inclined poles, tight or loose wires, cracked houses or buildings, displaced fences.	
Toponimy	☑ Names of places that might suggest unstable slopes.	
Historical	☑ Testimonials and documents from past events.	

Other indicators are those that enable us to identify areas that may not have been affected by slope instabilities, but where the terrain presents some characteristic that makes them potentially unstable.

Such indicators are called Potential indicators because they indicate areas that so far have not been affected by instabilities but can be affected in the near future. Fig. 5 shows images of the identified indicators that were captured during the evaluation of the area by the interdisciplinary team.
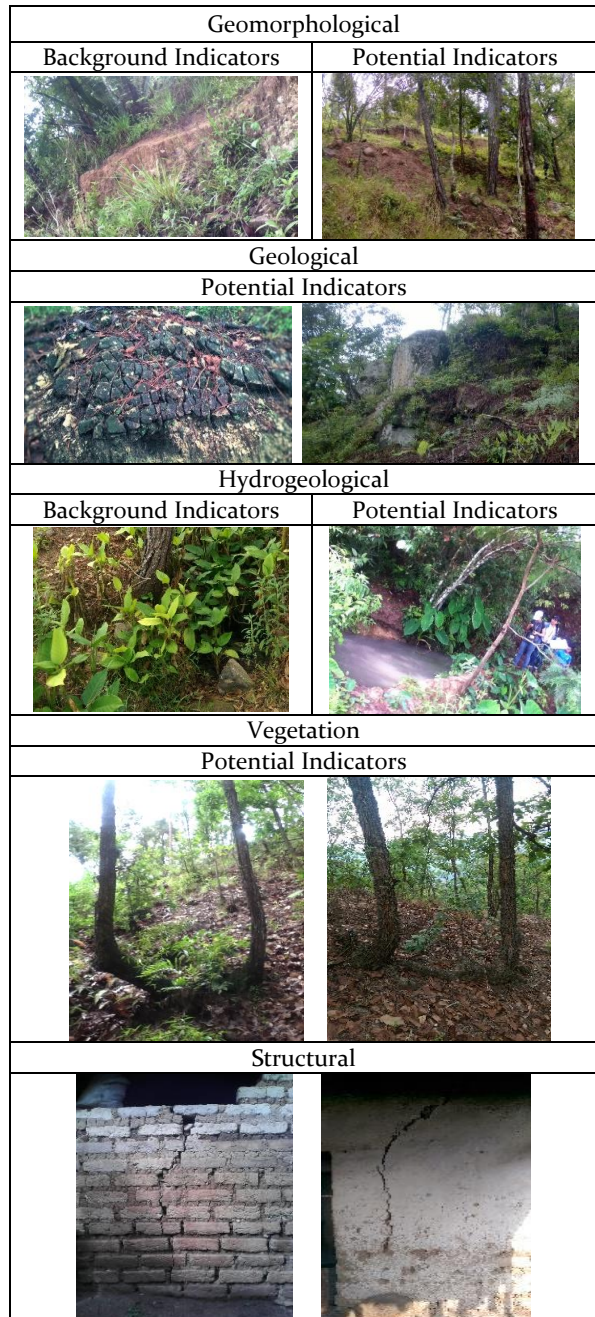
Fig. 5 Background and potential indicators identified in Carrizal-Semane

Although only one landslide and some background indicators were recorded in Carrizal-Semane, it was possible to identify all potential indicators, which were registered as waypoints with GPS. These waypoints were located on maps provided by Permanent Commission of Contingencies (COPECO) which will help for a future update (Fig. 6). In the map, high and moderate hazard areas (shown in red and yellow, respectively) in other communities near Carrizal-Semane can be observed.
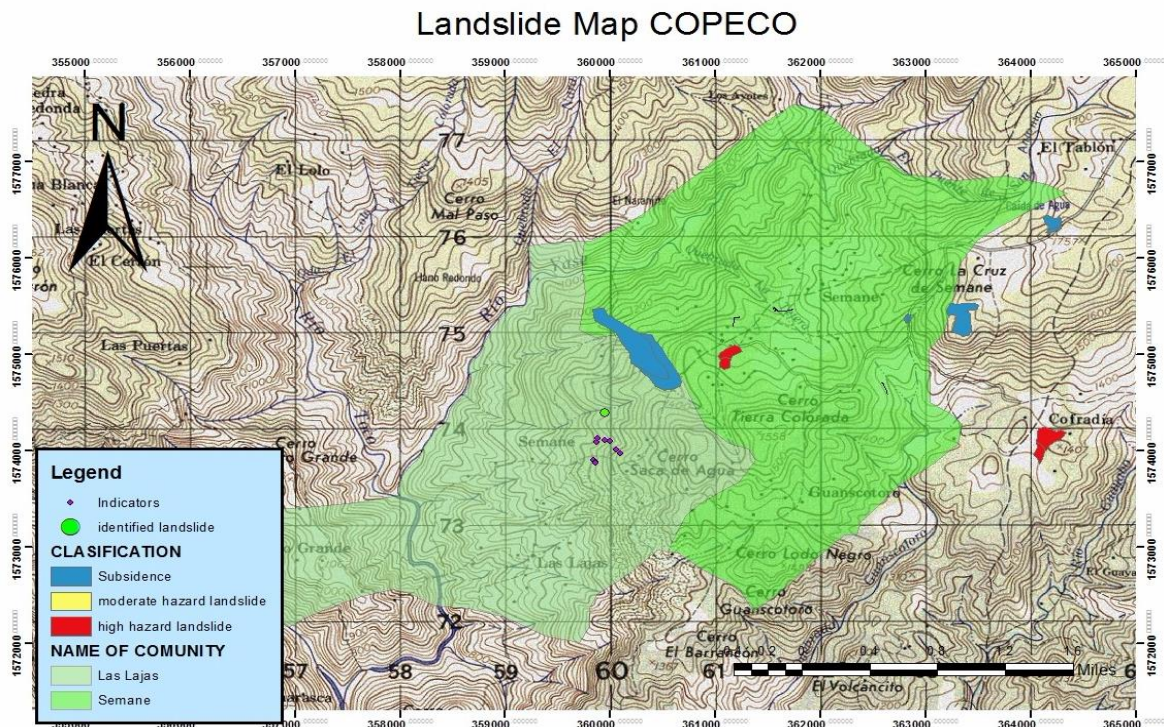
Fig. 6 Background potential indicators and landslides

The only known landslide recorded in Carrizal-Semane occurred in August 2012, according to the testimony of the inhabitants (see Fig. 7 and Fig. 8). It caused crop damages and cracks in nearby houses. The landslide trigger was a short and intense rainfall.

Fig. 7 The only landslide recorded in Carrizal-Semane

An unaltered sample from the landslide crown was taken to the Civil Engineering laboratory at UNAH in order to identify the soil type and its properties. The performed soil tests included specific gravity determination, sieve analysis, Atterberg limits determination and triaxial compression test (Fig. 9).

Fig. 8 Material detached due to the landslide

After identifying the indicators of unstable slopes, and the trigger for landslides in the Carrizal-Semane community, the information was shared with the people of the community, with special emphasis on leaders and teenagers. The covered topics included risk management, vulnerability, threat and prevention of

74

disasters and the difference between preventive actions and corrective actions. During the first workshop, community leaders were informed about the importance of identifying risk areas and actions that can be taken. The second workshop was addressed to teenagers from fifth to ninth grade at school. They understood the different threats available in their own communities.
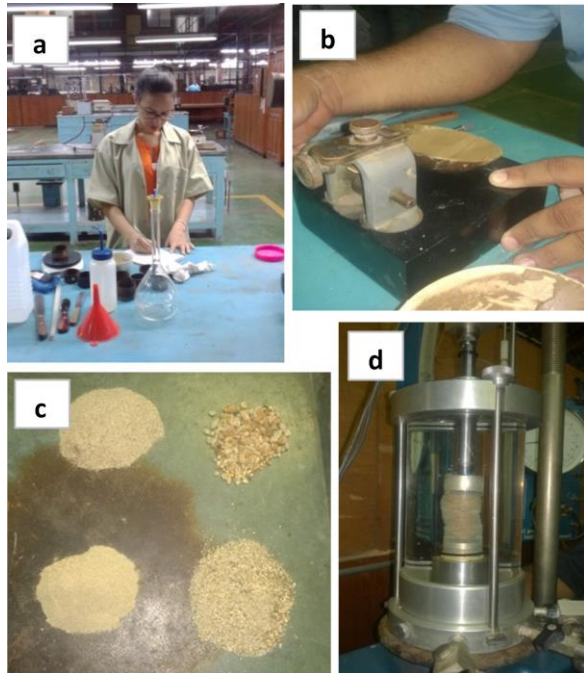
Fig. 9 Laboratory soil tests: a. specific gravity test, b. liquid limit test, c. particle size separation and d. triaxial compression test.

Results and Discussion

Although it was not possible to identify enough landslides to elaborate a hazard map, potential indicators of unstable slopes were registered, which helped people recognize the threats in their community. Even though the occurrence of events cannot be predicted from a single trigger, which in this case was rainfall, it is concluded that the most probable triggering scenario comprises a short and intense rainfall over a slope of unfavorable steepness.

The vulnerability of the area is evident by its rugged topography and steep slopes that provide the potential for a rockslide and debris flow, in addition to the events narrated by the people. Also, the difficult access to the region and the lack of phone signal makes communication with the community very difficult.

The material of the landslide has been classified as a clayey sand (see test results in Tab. 2). The values of

cohesion and friction angle give evidence that the soil is not entirely a clay; it also contains sand from decay and sedimentation of larger material at a higher elevation. When clayey sand is in permanent contact with water, it reaches saturation very easily. Since it has a low permeability capacity due its aquitard condition, water is trapped between the particles and its extraction takes a long period of time. For this type of soil, the intrinsic permeability value (Darcy's Law) ranges from 10^{-4} to 10^{-1} m/day (Llamas and Gimena, 1983). Therefore, when heavy rain occurs, soil weight increases because of the water that accumulates within the voids, resulting in a landslide under the influence of gravity.

Table 2 Soil tests results.

Concept	Result	Type of soil
Specific gravity	2.816	Inorganic clay (Bowles, 1980)
Liquid limit	27	AASHTO: clay ASTM: clayey sand (Das, 2001)
Plastic limit	5	
Plasticity index	22	
Cohesion	0.3 kg/cm^2	Plastic clay
Angle of friction	11.31 °	

Conclusions

It is imperative to identify and evaluate the landslide hazard zones in the country, because the degree of vulnerability of a community increases when the events that happen around it are unknown. Even though there have not been natural events recorded in the past, it is necessary to know the indicators that provide the potential for the occurrence of such events in order to avoid disasters.

It is important to generate a prevention culture, as well as a culture of mechanism of response, in community members. This is important not only for major emergencies such as hurricanes, but also for lower magnitude events that cause less economic losses but affect the subsistence activities of the people.

The workshops held by the team enabled the community members to learn more about the background and potential indicators of unstable slopes, and understand how to identify them in their own environment, taking into account disaster prevention and risk reduction measures in their communities. At the same time, a manual was provided where all the indicators are illustrated with photos, as well as recommendations to build houses in safe areas. Therefore, this kind of manual can be replicated in other communities experiencing landslides threats and can be adapted to their conditions and respond to their specific needs.

There are various limitations that might be present during the evaluation of unstable slopes through this method. These include the lack of accuracy in the information of the study area (e.g., date of occurred events, triggering factors, caused damages, etc.) and the lack of help from inhabitants. In addition, it is important to consider that the indicators vary according to the type of landslide and the site conditions. Many others exist and were not mentioned in this article because these do not apply to this study area.

References

Bowles, J. (1980). Manual de Laboratorio de Suelos. Bogotá: McGaw-Hill Latinomaericana S.A.

Cruden, D. M. (1991). A simple definition of a landslide. Boulletin of the International Association of Engineering and Geology No.43.

EIRD (2004). Main related terms to disaster risk reduction. United Nations International Strategy for Disaster Reduction.

FPB (2015). Section 16: Guidelines for evaluating potentially unstable slopes and landforms, Forest Practices Board Manual. Washington.

IHCIT (2007). Atlas climático y de gestión de riesgos en Honduras. Tegucigalpa.

INETER-SDC (2005). Technical recommendations for developing maps of hazard for slope instability. Managua, Nicaragua.

Llamas, M. R., Gimena, E. C. (1976) Hidrología Subterránea. Barcelona: Omega.

Valencia, J. E. (2006). Propuesta metodológica basada en un análisis multicriterio para la identificación de zonas de amenaza por deslizamientos e inundaciones. Ingenieras Universidad de Medellín, 59-70.

Angela Morales (✉)
National University of Honduras, Department of Civil Engineering, Tegucigalpa, Honduras
e-mail: angelagabrielams@hotmail.com

Diana Muñoz
National University of Honduras, Department of Civil Engineering, Tegucigalpa, Honduras
e-mail: diana_me5@hotmail.es

Jorge Meléndez
National University of Honduras, Department of Civil Engineering, Tegucigalpa, Honduras
e-mail: ja_melendezu@yahoo.com

The combined factors method for mapping susceptibility to landslides: a case of application

Oscar Elvir

Abstract In Honduras, slopes movements have caused many losses, both economic and human; the study of these processes is critical for understanding and to reduce their impact, therefore, it is necessary to have simple and quick for analysis methodologies. This work describes how to implement a methodology to assess the susceptibility to landslides in a region located in the central part of the country; in which factors such as lithology, slopes and land use (combined areas) with an inventory of slope movements are combined; and in which the proportions of affected by movements in the combined areas are statistically treated by a mathematical function (W function) to obtain the levels of susceptibility of an objective way, which determine one of the study products: map of susceptibility to landslides in the area. Finally, the susceptibility map is validated, observing whether there is any correspondence between the different areas of susceptibility and movements.

Keywords landslides, Combined Factors, inventory

Introduction

In Honduras have happened two major disasters that have greatly affected the operation of both state and civil gears: Fifi and Mitch (1972 and 1998 respectively), both hurricanes caused serious damage to the country's economy; destroying important infrastructure, many homes, thousands of hectares of crops and most importantly, the loss of many lives. One of the events that during these hurricanes caused more damage and lives destroyed were landslides (of all types), which occurred throughout the country affecting several cities. To mention some of the cases that occurred during Hurricane Mitch are: the great movement occurred in the Cerro El Berrinche in the capital of the Republic, which affected colonies on its slopes; the disaster in the municipality of La Libertad (Department of Comayagua, central region in the country) for movement of large proportions, which completely ended colonies that were in its path. Many cases like this happened, but not echoed as the two previous cases, which shows that the majority of Honduran

territory under specific conditions (such as excessive rainfall and earthquakes) is very prone to slope movements, this provides the "opportunity" that certain areas are suitable for the application of methodologies for assessing susceptibility.

To date, the country has not recovered from the ravages of Hurricane Mitch, which has been the worst disaster which comes to light in the history of Honduras. Those who lived through that tragedy wonder: is the nation prepared to face a situation like that occurred before? They not immediately respond. Lessons learned after Mitch and recent disasters have not made a profound effect on the consciousness of the rulers of the nation in terms of risk management, an issue that has not been treated with the level of importance it deserves and which is must carry a primary dimension or at least known. It is therefore vital to conduct research related to the topic.

This paper is intended to explain the application a methodology for analysis of susceptibility to slopes movement using the combination of factors and inventory of events; to establish susceptibility levels so as to avoid as far as possible, subjective criteria; Also, using Geographic Information Systems (GIS) for the same. The methodology uses the combination of factors such as slope, lithology and land use, just as a mathematical function (W function) to establish susceptibility levels so as to avoid as far as possible criteria subjective, to establish the susceptibility levels can make use of a specific program developed for this specific purpose or using a classification of groups equal intervals with a GIS.

For susceptibility analysis with this method it is necessary to have an inventory of landslides, taking into account all types, both past, present and potential . Finally, the results obtained from the methodology used for susceptibility analysis and their validation are discussed, pretending to give answers to questions like: What are the most prone to slope movements areas? What movements are the predominant? Does susceptibility methodology is valid? Really was contributed to the understanding of these processes were improved and studies available to the application area.

Application area

This methodology was applied by the author in the municipality of Ajuterique in 2005. Some historical and geographic area data are presented below: Historical data reveal that the municipality of Ajuterique is one of the oldest in Honduras. Some documents indicate that this population was part of the Lenca indigenous group. Its municipal head was founded in 1578 in a place called Quelepa, in a mountainous area where recently found traces of ancient buildings. It is said that the population moved to a place called Stone of Mesa because the village was destroyed by an earthquake, then it was moved to the current place; it was given the category of municipality in 1862. In 1889 already part of the District of Comayagua (Municipal Development Plan, 2003, in Elvir, 2005).

The municipal head of Ajuterique is located west of the valley of Comayagua, seven kilometers from the city of La Paz; its colonial architecture has been preserved. It is located at an altitude of 675 m (meters above sea level), is surrounded by the Goose River or Conce, north, the Sicaguara south, the Humuya east and Canguarita creek southeast (See Fig. 1) . In Fig.1 the boundary of the study area (Goose River Basin) which has an area of 30.3 km². The land area of the municipality is 61 km² , bordered to the north with the municipality of Comayagua is submitted, south with the municipality of Lejamaní and La Paz, east to the town of Comayagua and the West with the municipality of Santiago de Puringla.
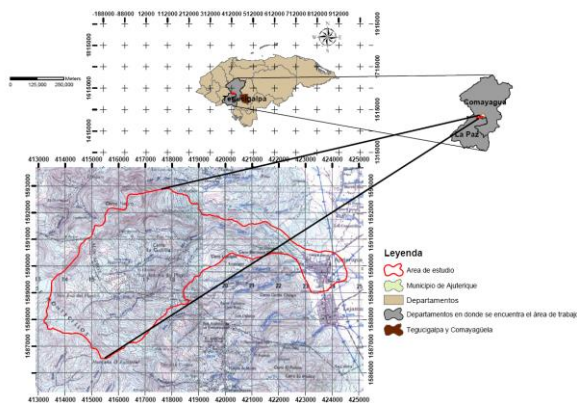
Fig.1. Location of the application site in Honduras (Elvir, 2005).

Methodology

The methodology developed in this paper was developed by DeGraff and Romesburg (1980) and consists identifying areas occurrence of slope movements taking into account overlapping maps factors affecting the generation of these processes. For this study, the following factors were taken: Inventory movements, geology (lithology), slopes and land use. In the scheme of the methodology used (see Fig . 2) maps lithology , slopes and land use are combined to obtain a combined map of factors (map combined areas), then this map overlaps with inventory movements slope for the proportion of involvement for each area combined factors and finally obtain the map of susceptibility.
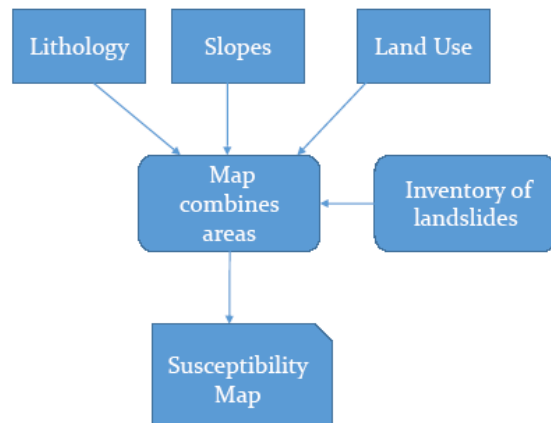
Fig.2. Scheme methodology used

Susceptibility map

This map identifies areas with different levels of susceptibility by the occurrence of landslides and is the result of the interpretation of the data provided by the inventory map movements correlated with the combined factors of slopes, lithology and land use. Four levels of susceptibility were proposed, those identified in the final map as: Very Low, Low, Medium and High susceptibility. The procedure allowed to obtain these levels of susceptibility presented in the following paragraphs.

Map of factors combined

This map represents the key to produce the final map of slope-movements susceptibility base. After obtaining maps lithology, slopes and land use, they are superimposed to originate the map of "combined factors". In integrating these, it can be seen that each lithological unit and each category of land use, can present two options of slopes and therefore two possibilities for different behavior. Each factor is assigned a symbol to encode each combination (see Tab. 1, Fig. 2 and Fig. 3) and thus facilitate work.

The slope map sets two ranges which are presented Tab. 1, these ranges are well established, because the movements inventoried occur on slopes from 21º (angle break in header) and to facilitate the combination of

areas, and that to classify slopes greater ranges, would have had more areas combined and loaded (many items on the map) further factors combined map. Map lithology has four units of behavior as identified in Tab. 2. In the map land use for the applications is listed in Tab. 3. For combined units obtained by superimposing lithological factors, slopes and land use , the total sum of the areas of each combination was calculated, this through the software ArcGIS, the results are shown in Tab.4 . The combined areas are in square meters.

Table 1 Slopes ranges

Slopes	Symbol
< 21º	1
≥ 21º	2

Table 2 Lithological units

Lithology	Symbol
Andesite-dacite Pyroclastic flow (dacites)(Semicoherent)	An/D
Rhyolites (Coherent)	R
Heterogeneous Redbeds, limestone Jaitique (limonite) (Semicoherent)	Cr
Alluvium (Incoherent)	Al

Table 3 Land use

Use	Symbol
Farming	A
Forest	B
Latifolied forest	BL
Scrup	M
Savannah	S
Bare Soil	SD
Populates area	ZP

Inventory map overlay slopes movement

This stage was to superimpose the map of inventory movements slopes to the map obtained from combined factors. This shows what the combined units of lithology, slope and land use that are associated with the occurrence of these movements are.

All areas of slope movements mapped in the study area were calculated and recorded in the Tab.5 the area occupied by each combination of factors. Affectation surfaces for different areas combined appear in m² (square meters). Importantly, not all areas combined were affected by movements, this can be seen in the Tab.5 (in this table of the results presented).

Table 4 Total amount corresponding to each combination of factors areas

Slopes/Land Use/Lithology	Total area (m²)
1-M-An/D	5,513,052.35
2-M-An/D	4,185,600.19
1-M-R	593,101.63
2-M-R	1,669,476.72
1-M-Cr	1,475,695.16
2-M-Cr	1,723,179.77
1-M-Al	759,986.74
2-M-Al	38,108.39
1-A-An/D	525,872.04
2-A-An/D	226,413.12
1-A-R	350,494.82
2-A-R	49,235.32
1-A-Cr	67,480.04
2-A-Cr	48,784.28
1-A-Al	989,004.99
2-A-Al	----------
...	...

Note: The ellipsis indicates that the table only shows a portion of all results

Table 5 Area affected by landslides for each combination of factors

Slopes/Land use/Lithology	Total area (m²)
1-M-An/D	377,276.94
2-M-An/D	468,090.18
1-M-R	70.58
2-M-R	5,637.42
1-M-Cr	5,408.86
2-M-Cr	5,372.41
1-M-Al	-------
2-M-Al	-------
...	...

Note: The ellipsis indicates that the table only shows a portion of all results

Map overlay inventory movements

For achieve the calculation of these ratios the area occupied by slope movements for each combination of factors including the total area occupied by the same combination, that is, data area of the Tab. 5 split between data Tab. 4 area. The results were recorded in the Tab. 6.

Application of the W function to define levels of susceptibility

The W function (Anderberg, 1973) is a statistical equation used for cluster analysis. Cluster analysis attempts to classify objects into categories or things even when the characteristics of the groups are unknown. The aim is to identify homogeneous groups (clusters).

Table 6 Proportion of landslides for each combination of factors

Slopes/Land use/Lithology	Proportion of landslides
1-M-An/D	0.068433404
2-M-An/D	0.111833467
1-M-R	0.000119002
2-M-R	0.003376759
1-M-Cr	0.00665296
2-M-Cr	0.00311773
1-A-An/D	0.113225092
2-A-An/D	0.11780341
1-B-An/D	0.101042052
2-B-An/D	0.025456899
1-BL-An/D	0.100935736
2-BL-An/D	0.053927042
1-BL-Cr	0.019459636
2-BL-Cr	0.009013206
1-S-An/D	0.004708928
1-ZP-An/D	0.097644777
2-ZP-An/D	0.107693285

The fundamental concepts of group analysis are: The concept of distance which determines how two objects move away from each other. The concept of similarity serves a measure of closeness between objects. In the particular case of the function applied to establish the susceptibility levels, the proportions observed above, they are ordered from the smallest to the largest. This range of values is divided into three groups to represent susceptibility in the study area. And to ensure that the points used to define the three groups are determined objectively, it is that use analysis nonhierarchical group is.

Based on the W function it is achieved an initial division into three groups breaking equally the range of proportional values. The upper and lower limits of each group are retained or are adjusted to ensure that the final division represents the minimum sum of squared deviations around the three group averages. The goal is to minimize the value of W. In other words, find the smallest W values that can be calculated for three groups of proportional values. This applies the principle of least squares, a common statistical method, to this dimensional problem by minimizing the sum of squared deviations regarding group averages.

The proportions are already indications that there are combinations of factors that have a higher degree of susceptibility slope movements. Value ratios correspond to combinations representing high susceptibility, as they have the largest areas affected by these processes. The proportion group with the lowest values represents the lowest susceptibility. Between the two extremes of the proportions it is what could be considered as means susceptibilities.

Estimate the boundaries between these proportions to consider far is low, medium or high susceptibility, may be subjectively established by the researcher, or can be calculated using the function ensures that the end groups resulting susceptibility division represents the minimum sum of squared deviations of the mean of each group. This function defines the limits on the scale considered in a completely objective way. The equation that defines the function is as follows:

$$W = \sum_{i=1}^{i=3}\sum_{j=1}^{Ni} (X_{ij} - X_{ij})^2 = W_1 + W_2 + W_3 \quad [1]$$

Where X_{ij} = j-th average of observations (proportions in this case) in the group i, N_i = Number of observations of group i and X_{ij} = Observation of group i.

The W function was used to establish three levels of the slopes movement susceptibility: low, medium and high; the level classified as very low susceptibility was obtained with other criteria unrelated to the function W. The procedure to achieve the classification of levels was as follows:

- It was considered very low susceptibility all combinations of lithology, slopes and land uses that did not show areas affected by landslides; current, former or potential.
- In order to get the three missing susceptibility ranges, an initial division is made into three equal groups depending on the two ends of the resulting scale ratios; that goes from 0.000119002 to 0.117890341, later to apply the W function that allowed adjust these limits arbitrarily chosen.

The goal is to find the lowest values of the W function that can be calculated for the three selected groups. To achieve this, it moves down or up the lower or upper limit, respectively, of each group and calculated again for the new W function blocks grouped. This is done several times to estimate the right direction that will allow achieve the lowest value of W, which, to happen, objectively identifies the

definitive limits of the three groups of "susceptibility " preselected.

For the study area, the following results were calculated:

- Low susceptibility: here, are the following combinations: 1-M-R, 2-M-R, 1-M-Cr, 2-M-Cr, 2-B-An/D, 1-BL-Cr, 2-BL-Cr, 1-S-An/D.
- Medium susceptibility: here, are the following combinations: 1-M-An/D, 2-BL-An/D.
- High susceptibility: here, are the following combinations: 2-M-An/D, 1-A-An/D, 2-A-An/D, 1-B-An/D, 1-BL-An/D, 1-ZP-An/D, 2-ZP-An/D.

Results

The following results were obtained: inventory map of landslides characterizing their type, map characterization of the lithology, land use map, map of combined factors and final map of susceptibility to landslides. Here are the most important results are described.

101 movements mapped (see Fig. 3), among which the following were mapped: debris flows, landslides translational, rotational landslides, landslides complex (translational- flows), falling blocks, lobular bodies and deposits of blocks or rocks (such as indicators of ancient lava flows and material removal) and zones of slow movements (indicators of potential movements).
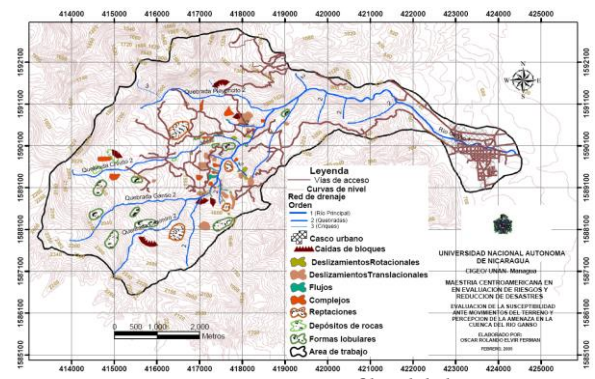
Fig.3 Inventory map of landslides

Map of combined factors

The combination of lithological units with different land uses and slopes produced basic invaluable information to determine areas of susceptibility to be affected by movements of slopes. This map shows 41 units combination (see Fig. 4), which allowed individualize each lithological behavior and land use in pending ranges established.

Map of susceptibility to landslides

The development of this map is the main product of this work. It was obtained by the superposition of inventory map landslides with the map of combined factors. The resulting map contains the proportion of areas affected by movements that have each of the 41 combinations of lithology, land use and slopes that exist in the area. All ratios obtained from the analysis of this overlap were subjected to a statistical treatment that produced three basic areas of behavior: susceptibility zone low, medium and high.
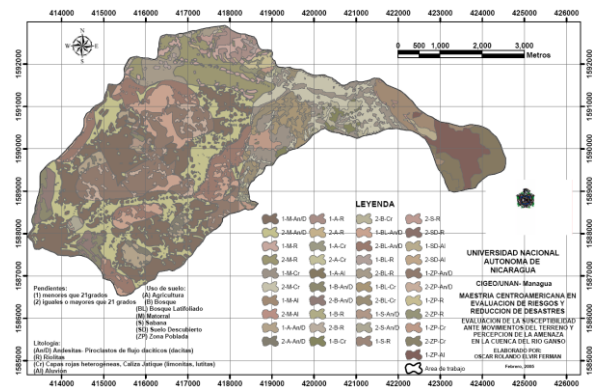
Fig. 4 Map of combined factors.
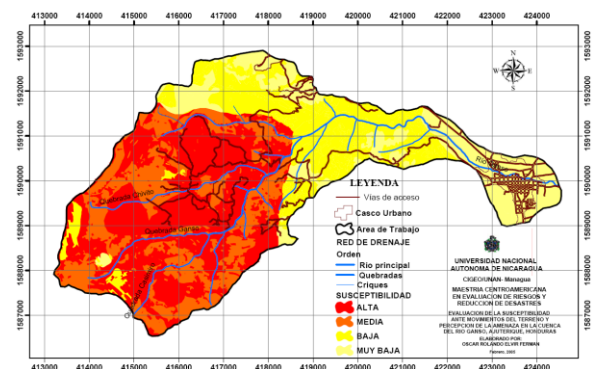
Fig.5 Map of combined factors

Conclusion

The methodological framework susceptibility uses three physical factors (lithology, slope, and land use) that are interrelated, and are essential to study the susceptibility of a region by the occurrence of slope movements.

Susceptibility levels obtained with this methodology, indicate which areas studied have a higher level of susceptibility in relation to another, but does not indicate how many times is more susceptible, a fact that can be considered as a limitation .

By taking into consideration the events by superimposing the inventory map and zoning map susceptibility of slopes, different areas of susceptibility calculated by the method used is validated.

References

Anderberg R. (1973). Cluster Analysis for applications. Academic Press. New York.

DeGraff J. & Romesburg H. (1980). Regional Landslide-susceptibility Assessment for Wildland Managemet: A Matrix Approach in D.R. Coates, and J.Vitek (eds.). Thresholdes in Geomorphology (Boston: George Allen and Unwin) pp.401-414.

Elvir O. (2005). Thesis: assessment of the susceptibility to landslides and perception of threat in Goose River Basin, Municipality of Ajuterique, Honduras.

Oscar Elvir (✉)

National Autonomous University of Honduras. Honduran Earth Science Institute. Ciudad Universitaria E-1, Blvd. Suyapa.

e-mail: oscar.elvir@unah.edu.hn

Implementation and future of LIDAR Technology for identification and study of landslides in Honduras

Carlos Aguilar, José Arce

Abstract Honduras is one of the most exposed and vulnerable to natural disasters in Central America due to environmental degradation, lack of land use, urban planning and the slow implementation of emergency protocols and prevention. LiDAR system begins to position itself as an aid to the generation of the information to cover large and inaccessible land areas.

The first LiDAR works in Honduran territory showed the advantages of this system in the data acquisition as well as the processing and delivery of valuable information.

Use of LiDAR Technology in the world began over 20 years ago through military uses. Later, this technology has been released for civil purposes and has been a great deal in the engineering and surveying sciences.

Over time it has diversified its uses and applications. Digital Terrain Models(DTM) obtained by LiDAR systems have positioned as an effective tool for identifying and mapping hazardous and high vulnerabilities and risks for landslide all over the world.

One of the main advantages of data acquisition by LiDAR systems is easy and fast access to difficult areas or dangerous zones through the airborne system, Mobile LiDAR or with the use of Drones, scanning any area at high resolution.

Keywords LiDAR, Landslides, Honduras, DTM, Drones

LiDAR System Components

Equipment and Data Acquisition

LiDAR system essentially consists of three subsystems which are described below:

- Transmitter/Receiver Laser: this component is responsible to transmit the laser pulses and receive the rebounds of these pulses on the surface which can accurately determine the distance between the sensor and the surface to be scanned.
- GNSS differential: by using a GNSS receiver in the system and one or more in ground control stations (with known coordinates) is obtained accurately, the position and height of LiDAR equipment.
- INS (Inertial Navigation System): this component is responsible to determine all movements of the equipment which is important in order to calculate the orientation of the LiDAR equipment and thus obtain the best accuracy and precision in the performed trajectory.

Fig. 1 Aircraft of LiDAR system based on Honduras. Courtesy of ACI
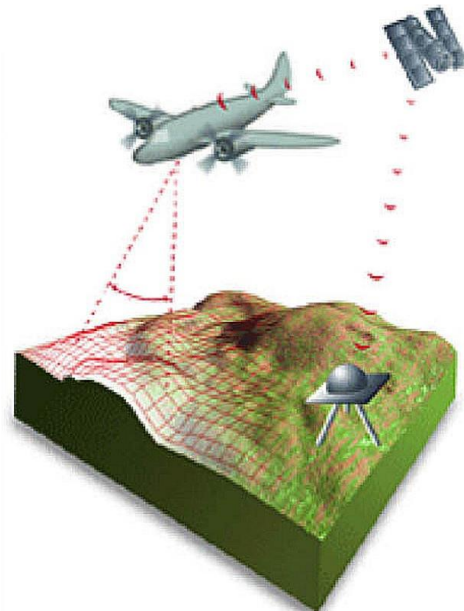
Fig. 2 Schematic data acquisition system and GPS referencing

Data Acquisition

After determining the study area to be scanned and the kind of details to be obtained from the survey, it proceeds to plan with the parameters that are suited to the requirements which are mentioned above. This planning basically determines points or control sections to be implemented in the field, the straights to follow in the case of Airborne Systems or the routes to follow in the case of Terrestrial Mobil Systems.

After this planning, it proceeds with the execution which starts with the GNSS receiver base in the point with known coordinates (preferably the point on the local or global geodetic network) and then the LiDAR system is located on the routes or flight lines planned to get the data.

After the scanning ends, the information obtained from the transmitter/receiver laser, GNSS both the LiDAR system and the ground station and the Inertial Navigation System are stored.
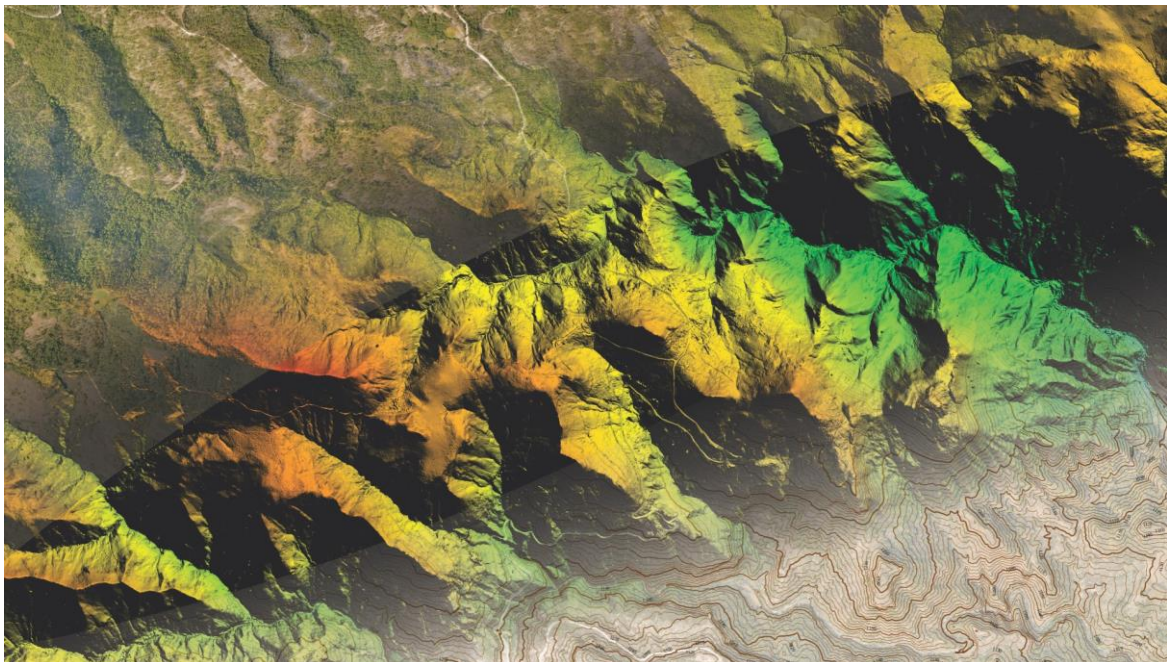
Fig. 3 Photo collage of the area where is combined the orthophotograph, the cloud of points and curves level. All the information was generated by the LiDAR system.

Deliverable Information

For multispectral and multiparameter analysis, LiDAR system provides a single work of the necessary data for conducting risk analysis with high resolution which is impossible to achieve with traditional methods. In addition, reducing time for obtaining the information shall be achieved.

The following are the characteristics of the information which is provided from LiDAR system:

DTM

LiDAR provides a DTM whose contour resolution is up to 10 cm. This level of resolution is very difficult to obtain using traditional sources such as map sheets or field survey; with better resolution it is easier to see changes in terrain such as creeps or displacements by comparison different data.

Layers

The multilayers data output provides higher resolutions.
- Vegetation coverage: Provides greater scope of observation where the vegetation coverage changes on the slopes.
- Infrastructure: We can filter or include infrastructures so that we can generate easily exposure and vulnerability maps, especially in urban areas locating them accurately to populated areas, roads or any infrastructures.

Slopes

Maps are generated based on the critical slope parameters (elevation, angle, bank aspect and curvature or slope) locating them faster than aerial photographs and conventional morphometric analysis on physical maps.

Orthophotography

High resolution photography provides a secondary analysis of the area and serves to support and collate the LiDAR information.

Traditional Studies vs LiDAR

The accomplishment of risk analysis of landslide with LiDAR System provides an opportunity to update and improve the existing information.

Honduran topographic maps are usually outdated and because of their scale/resolution cannot be used to study small landslides (such as those which affect many neighborhoods around some cities). This information is the basis of analysis by traditional methods.

Traditional Methods

Traditional study of landslide needs mapping methods by scanning topographic maps (with limited resolution and irregular contours), interpretation of aerial photographs using a stereoscope and observing directly the landslide morphology in the field.

Therefore, the research success will depend on the production, quality, availability of information; delaying ample time with low quality. Simultaneously, it is necessary to get soil characterization and geology and get their parameters.

With all information, the final analysis is performed; having to correct data that topographic maps analysis doesn't reveal like vegetated areas or structures.

LiDAR Method

Manual

It requires experts to analyze the DTM identifying areas that present landslide morphometry.
The proposed methodology to be followed by this method of analysis is as follows:

Flight Planning

Delimitation of the study area and marking of flight lines that overlap the area. Also determine the flight altitude and number of passes to obtain higher point density and therefore greater resolution and detail.

Flight

Flight will be done according to the objectives keeping on the ground control points using GPS / RTK.

Obtaining orthophotographs of the area and LiDAR data recollecting.

During the flight, operators on the ground, office and in the airplane could supervise data collection in real time, avoiding issues such as lack of data, flight plan deviation, etc.

Processing

It is done through software and by the operators.
Who analyze and classify the point cloud.
Creating DTM, location of infrastructures and creating multilayer content files.
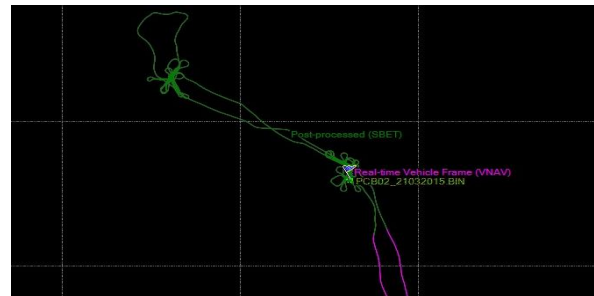
Fig. 4 Trajectory processing to improve the data accurate.

Information analysis

The specialist will begin with the orthophotos checking elements such as slopes changes, erosional scars and slope maps. He will also check the slope intensity maps.

Then he could use the DTM to review items such as tilt trees, creeping surface of land, materials etc.
In this phase it could dimension the movements as identify impacts. Field work could be planned once identified in this process the most critical points or those where there is evidence of landslides and movements.

Generated Products

Generated products are slope maps, topography with movements detected, the information generated on the orthophoto and finally thematic maps according to the objectives.

Fig. 5 Determining the flight plan using several parameters such as altitude, speed, passes, point density, etc.
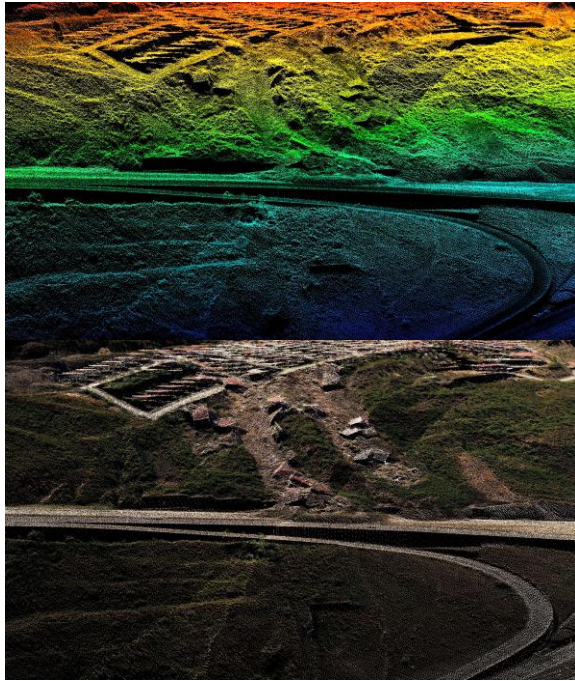
Fig.6 Point cloud and orthophotograph / cloud mounting points LiDAR for "Ciudad del Angel" Landslide, Tegucigalpa; Honduras

Automatic

In the case of large areas, it can make filtered output data or classified for landslide parameters (escarpments, slopes, landslide body and its material, etc.)

- This is performed through a simple methodology:
- Creating a Digital Elevation Model (DEM).
- Importing DTM to a software like ArcGIS or Global Mapper in order to visualize, analyze and digitalize.
- Field verification.

Passing data to DTM is automatic, so it takes less time for digitalizing of data from physical formats. (Jaboyedoff, M 2010).

Review mass movements by Lidar

LiDAR system can be used for verification of landslides or mass movements previously detected in the field.

Thus it can perform a more accurate evaluation of the characteristics of the event.

So the dimensions can be measured accurately and precisely mark the nearby infrastructure.

Easily generating risk maps, exposure and vulnerability more accurately than traditional resources.

This is very important in conflicting or difficult access areas which are recurring factors in Honduras.

Conclusion

Use of LiDAR system is the most efficient and complete for updating landslide situation, hazard, vulnerability and risk maps.

It provides, in one study, all necessary parameters for traditional methods of landslides analysis and slopes.

Additionally, orthophotographs and infrastructures inventory provide basic tools in the development of local and regional emergency plans.

In Honduras, it is possible to study landslide areas with difficult access where there is a significant number of vulnerable or exposed population.

Time factor is very important because LiDAR studies mean there are saving time for study, so it can expect to update information by faster way.

Therefore, LiDAR System becomes the main analysis tool in the world that help us for identification, landslides characterization and other natural risks.

Its implementation in Honduras has been through small cooperation projects or in civil engineering.

For Honduras, it is the most optimal tool to characterize large areas in detail; it also facilitates updating topographic information and maps for infrastructure distribution and services.

Being the fastest and most reliable option, LiDAR generates more useful information.

References

Jaboyedoff, M., T. Oppikofer and A. Abellan (2010): Use of LiDAR in landslide investigations: a review. Institute of Geomatics and Risk Analysis, University of Lausanne. Springerlink.com.

Carlos Eduardo Aguilar (✉)
Asociación de Consultores en Ingeniería; Colonia El Prado Edificio Ámbar, Tegucigalpa, Honduras.
e-mail: carlosaguilar@aci.hn

José Arce Díaz (✉)
Asociación de Consultores en Ingeniería; Colonia El Prado – Edificio Ámbar, Tegucigalpa, Honduras.
e-mail: josearce@aci.hn

Geomorphometry, statistics and data mining for landslide susceptibility mapping in data scarce areas

Anika Braun, Hans-Balder Havenith, Tomás Fernández-Steeger

Abstract Landslides are the result of a complex interplay of geological, geomorphological, hydrological, climatic and anthropogenic factors, whose relationships have to be clarified in order to understand spatial patterns of landslide susceptibility. Even for regions poor in data a lot can be done to improve this understanding using a simple dataset and suitable methods for enhancing the information content of the data. We here propose a procedure based on a case study carried out in the mountainous area around the former mining town Maily-Say, Kyrgyzstan. The basis of this study is a dataset consisting of a landslide inventory, a geological map and a 20 m digital elevation model (DEM). With the help of a geomorphometry analysis a total of 23 factors related to slope morphology and hydrology could be derived from the DEM in a geographic information system (GIS). Together with five factors derived from the geological map and the landslide inventory a dataset consisting of 28 variables covering an area of 115600 20x20 m raster cells was established. The dataset was then analysed regarding relationships between the factors and the occurrence of landslides using bivariate statistical methods in a GIS and multivariate statistical methods in a data mining software. Finally, the landslide susceptibility was modelled with a simple GIS-based approach on the one hand and a more sophisticated approach, employing data mining algorithms, such as artificial neural networks, Bayes networks and decision trees, on the other hand. The performance of the resulting models was evaluated using skill scores, success rate curves and expert knowledge. Some of the models developed remarkable skills that allowed a correct prediction of more than 90% of all cases and thus our strategy proofed to be promising for modelling landslide susceptibility based on a simple dataset.

Keywords landslide susceptibility, geomorphometry, bivariate statistics, data mining

Introduction

Landslides are a major natural hazard causing significant losses to individuals, infrastructure and economy in populated mountainous areas all over the world. Compared to other natural hazards that occur rapidly and that are difficult to predict in time and/or space, such as earthquakes or meteorological hazards, the occurrence of landslides is often spatially and temporally limited and losses could be avoided or reduced by the implementation of an adequate risk management system. In this context a fundamental step is the analysis and mapping of landslide susceptibility, which is defined as the spatial probability of landslide occurrence and which depends on site related geological, geomorphological, hydrological and anthropogenic factors. Landslide susceptibility maps can help to identify endangered areas and they are moreover input for landslide hazard analyses, which consider also the temporal variability of landslides, and for risk analyses, which further take into account the elements at risk and their vulnerability (Varnes 1984).

A recent review of the status of landslide susceptibility assessment is given by Corominas et al. (2013), other overviews can be found in Aleotti and Chowdhury (1999) or Fell et al. (2008). According to Corominas et al. (2013), methods for landslide susceptibility assessment can be grouped into qualitative (knowledge-driven) and quantitative (data driven and physically based) methods, while all methods are based on the availability of a landslide inventory. Basically, the choice of the method depends on the anticipated scale of the analysis, but also on the availability of data and resources, such as software and personnel. In knowledge-driven methods landslide susceptibility is directly mapped by experts based on the observation of past landslides and related factors. These methods may be work-intensive, subjective, and landslide susceptibility can only be expressed in a qualitative manner (Corominas et al. 2013). Physically based methods employ process-based models of slope

stability, which may be static or dynamic, and they vary mainly according to the scale of the study. Regional studies are usually GIS-based and landslide susceptibility is quantified in terms of factor of safety. The other extreme would be single case studies employing numerical modelling methods. All physically based methods have in common that they require extensive amounts of reliable input data that is often not available, especially in a regional context (Corominas et al. 2013). Thus, for regional studies, and especially in data scarce regions, data-driven methods are the most commonly used approach. After Corominas et al. (2013), data-driven methods can be grouped into bivariate, multivariate and active learning statistical approaches. The fundamental concept of data-driven landslide susceptibility analysis is to discover and quantify relationships between the occurrence of landslides and various conditioning factors under the assumption that future landslides are likely to occur where landslides have already occurred in the past and present (Varnes 1984). The conditioning factors are basically intrinsic properties of the site, such as lithology, slope morphology and hydrology, and regarded as independent of time. In bivariate statistical methods, such as the Information Value method (Yin and Yan 1988), factor maps are combined with landslide inventory maps in order to calculate factor-dependent landslide densities and weight values that can then be added for different factors to obtain a quantitative measure of landslide susceptibility. These methods are rather simple, and they do not allow for the analysis of possible interrelations of the factors. However, they provide a good tool for the initial exploration of a dataset (Corominas et al. 2013). Multivariate statistical and active learning or data mining methods provide more sophisticated tools for quantifying landslide susceptibility, exploring large datasets for landslide controlling factors and their interrelations and improving the process understanding of landslides in a certain area where due to limited capacities no extensive field work or physically-based analyses can be carried out.

The objective of the present study is to show, based on a case study, how the information content of a simple dataset can be enhanced and exploited for the prediction of landslide susceptibility. For this purpose a DEM was analysed with tools from geomorphometry in order to derive factors related to slope morphology and hydrology. Together with several geological factors derived from a geological map a relatively large dataset could be established that was then analysed regarding landslide susceptibility and the interdependence of the conditioning factors using a bivariate statistical and a data mining approach.

Setting

Maily-Say is a small mining town in Kyrgyzstan, Central Asia, located in the North of the Ferghana Valley within the foothills of the Tien Shan high mountain belt. The region is highly prone to landslides due to steep slopes, high seismo-tectonic activity, the presence of soft sedimentary rocks and climatic conditions causing high run off associated with snow melt and intense precipitations in spring. Another important factor causing slope destabilisation was the mining activity between 1946 and 1968, resulting in the collapse of underground galleries, rock weakening, rapid groundwater rise after mines were abandoned, an intensified land use due to the use of machines and a growing population. Today still more than 3 million m³ of mining waste are piled up in tailings on slopes all around the town, bearing the risk of a major environmental catastrophe in case the contaminated material is mobilized by a landslide and washed into the main river that is discharging into the fertile Ferghana Valley in Uzbekistan.

Materials and Methods

Input data

The input data used in this study are a SPOT DEM with a 20 m cell size that was smoothed with a low pass filter, a geological map that contains the main lithological units as well as Quaternary deposits (loess, alluvium, colluvium) and faults (Fig. 1), and a landslide inventory. We were in the lucky situation to have a multi temporal landslide inventory available for the years 1962, 1984, 1996, 2002 and 2007, which was compiled based on old Soviet maps, aerial photographs, older landslide inventories, satellite images and field observations. In this study landslide susceptibility is analysed based on the 1962 inventory and the result compared to the 2007 inventory (Fig. 1, Tab. 1). All data was converted to grid format in ArcGIS with a 20 m cell size and the analysis extend was selected according to the coverage of the geological map, comprising an area of 46.24 km² or 115,600 grid cells.

Table 1 Data on landslide inventories used in this study.

Year	n	n pixels ls	n pixels no ls	% ls
1962	157	4189	111411	3.62
2007	208	12175	103425	10.53

Geomorphometric analysis

In a geomorphometric analysis of the DEM additional parameters characterizing slope morphology, slope hydrology and landform were derived. The idea was to create a dataset containing as many variables as possi-
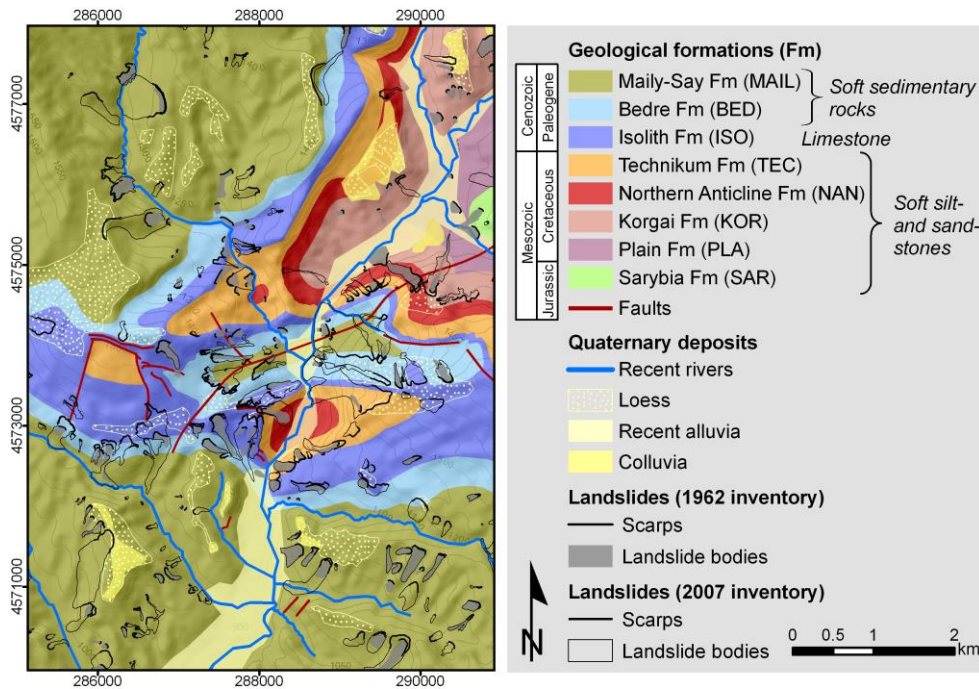
Fig. 1 Geological map of the study area overlain by the 1962 and 2007 landslide inventories.

ble that can later be selected regarding their importance for landslide occurrence. Tab. 2 provides an overview of the derived parameters. They can be grouped into primary topographic attributes that are calculated from directional derivatives of DEM, such as slope angle, aspect or flow direction, and secondary topographic attributes, calculated from two or more primary topographic attributes, like the topographic wetness index (TWI).

For the sake of briefness, not all attributes are explained in detail here. The interested reader is kindly asked to refer to the references given below for more information. Parameters 7-9 and 11-28 in Tab. 2 were computed based on the filtered and filled (depression less) DEM using Arc Macro Language (AML) scripts in ArcInfo Workstation, which is unfortunately rather out-dated nowadays. However, all attributes can also be computed in ArcGIS with tools of the Spatial Analyst or by substituting them using the raster calculator. Moreover, it is worth noting that meanwhile most tools, among many other geomorphometry tools, are also available within the open source GIS platforms QGIS, GRASS GIS and SAGA GIS.

In a hydrological analysis of the DEM the stream network was extracted that was then used to compute the distance to rivers parameter. Three secondary attributes were calculated from flow accumulation and slope angle according to Moore et al. (1993), the TWI, a measure for the spatial distribution of surface saturation and soil water content in the landscape, the stream power index (SPI), a measure for the erosive power of overland flow, and the sediment transport capacity (STC), which characterizes erosion and deposition processes. Moreover, the curvature over a 3x3 cell moving window, the plan (contour, horizontal) and the profile (slope, vertical) curvature were calculated and then classified into different landform indices after Pennock et al. (1994) (parameters 23-25), Riley et al. (1999) (parameter 26), Bolstad et al. (1998) (parameter 27) and McNab (1989) (parameter 28). Curvature and landforms are believed to play an important role regarding run-off convergence, divergence and infiltration processes (Pennock et al. 1987), and thus, for slope hydrology. They are however also important for instance for the amplification of seismic waves and for seismically induced landslide triggering or slope weakening, where convex landforms are basically regarded as more susceptible. A measure for the terrain roughness, the topographic ruggedness index (TRI), is calculated from the elevation change of the surrounding cells (Riley et al. 1999). The different landform indices work differently well depending on the input data quality and landscape type. The intention was to figure out during the analysis process, which indices are useful for the correlation with landslide occurrence in our study area.

Table 2 Factors derived from the geological map and the DEM. Column 'Input': factor used for a) bivariate statistical analysis, b) data mining analysis.

No.	Description	Input
1	Lithological formations	a, b
2	Alluvium	a
3	Colluvium	a
4	Loess	a
5	Distance to faults (m)	a, b
6	Altitude +NN (m)	a, b
7	Slope angle (°)	a, b
8	Slope aspect (°)	a, b
9	Slope length	b
10	Distance to rivers (m)	a, b
11	Flow direction	b
12	Flow accumulation (m^2)	b
13	Stream network	
14	Ridges	b
15	Basin area (m^2)	b
16	Watershed area (m^2)	b
17	Topographic wetness index	b
18	Stream power index	b
19	Sediment transport capacity	b
20	Curvature (1/100 m)	a, b
21	Profile curvature (1/100 m)	b
22	Plan curvature (1/100 m)	b
23	Raw landforms	b
24	Filtered landforms	b
25	Aggregated raw landforms	b
26	Topographic ruggedness index (m)	b
27	Landform index, Bolstad (m/m)	b
28	Landform index, McNab (m/m)	b

Bivariate statistical analysis

A bivariate statistical landslide susceptibility analysis was performed using the information value method (Yin and Yan 1988). The grid based landslide inventory of 1962 was combined in ArcGIS with some selected classified factor maps indicated with an 'a' in the 'Input' column of Tab. 2. Briefly, in this method the landslide density within a particular parameter class is divided by the landslide density of the whole study area to calculate a weight index Wi. By applying the natural logarithm to the result, negative values refer to parameter classes with landslide densities lower than normal and positive values refer to classes with landslide densities higher than normal. The Wi maps of all parameters were finally added and the resulting landslide susceptibility index (LSI) was classified into five classes using quantiles. The result was optimized by stepwise dismissal and inclusion of single parameters and evaluation of the result by comparison with the 1962 and 2007 landslide inventories.

Data mining analysis

The grid based landslide map and the parameter maps were transferred into a table format using the 'sample' command in ArcGIS and for further analysis imported into the IBM SPSS Modeler. In a pre-processing step the data quality was assessed, the dataset was cleaned for missing values and variables were transformed and coded. Moreover, the dataset was balanced to compensate for the under-representation of landslide events and partitioned into training and test dataset.

An Artificial Neural Network (ANN), a Bayesian Network, a C5.0 Decision Tree, a CHAID Decision Tree, and a C&R Decision Tree were employed for landslide prediction in this study. These are all classification tools, and what basically happens is that the algorithms are trained to classify a dataset with a known result (training dataset) into the cases landslide or no landslide. The resulting models are then evaluated for their ability to generalize the learned knowledge for an unknown dataset by applying them to the test dataset. The different tools use different mathematical methods used for the classification process. A comprehensive introduction to the different algorithms can be found in Hand et al. (2001). The classification result was compared with the 1962 and 2007 landslide inventories and transferred back into the GIS for evaluating the plausibility of the prediction in a spatial context.

Results and discussion

Bivariate statistics

A first survey of the calculated weight values made it possible to identify some problematic variables. Binary variables, like the Quaternary deposits, have relatively small positive categories and often the negative category has more landslides and subsequently a higher weight value, which would distort the result. Moreover, lithology has a small class (SAR, Fig. 1) containing one large landslide, which results in a highly overestimated weight value. Some landslide deposition areas were located in flat areas of the slope aspect, resulting in a high weight value for flat areas, which is physically not plausible. There are other effects that cannot physically be explained, like increased landslide densities within certain random classes of distance to rivers and distance to faults, while higher landslide densities would be expected closer to rivers and faults. One source of uncertainty in bivariate statistics is the classification of the parameter maps, which is controlled by the user. For instance, too large classes might cover interesting effects. Another issue is certainly the size of the study area, which is quite small (46.24 km^2). The effects described above would stand out less in a larger area with more variability.

For the LSI calculation the problematic binary factors were neglected, while different combinations of the factors aspect (a), curvature (c), distance to faults (f), lithology (l), distance to rivers (r), slope angle (s) and TRI (t) were used to create LSI maps. The results were compared with the help of success rate curves (SRC, Fig. 2), skill scores (Tab. 3) and in their spatial context. SRC plot the cumulative percentage of landslides against the cumulative percentage of the study area from high to low LSI. Thus, the steeper the curve, the more landslides are contained in the high susceptibility classes. The skill scores are defined as hit rate H (ratio of predicted and total landslides), false alarm rate F (ratio of false landslide predictions and no landslide events) and the total proportion of correct predictions PC when considering the highest LSI class as landslide prediction. Skill scores were calculated for the prediction of the 1962 landslides and also regarding the prediction of new landslides in 2007. The SRC and skill scores show that the models considering six or more factors perform relatively well with hit rates above 40% and PC of over 80%, while more simple models, with five or less factors that are well understood, decrease in prediction performance. This is interesting, since the more complex models contain
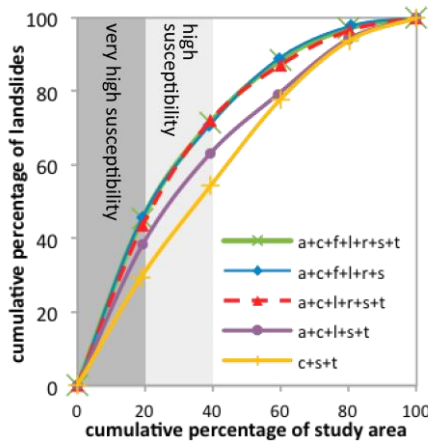

Fig. 2 Success rate curves for landslide susceptibility calculated with the information value method and different combinations of factors.

Some problematic factors, as discussed above. Regarding the new landslides in 2007, the best model was able to capture 35 % of the new landslides in the highest LSI class (Tab. 3). In the spatial context it could be seen that for instance the high Wi value in two random high distance to fault classes has a major impact on the final result. Moreover, it seemed that the TRI has a smoothing effect on the spatial distribution of landslide susceptibility, while the overall performance of models considering the TRI was slightly poorer.

Table 3 Hit rates (H), false alarm rates (F) and proportion correct rates (PC) for the prediction of the 1962 landslides and new landslides in 2007 yielded with the Information Value method using different factor combinations.

Model	Landslides 1962			New landslides 2007		
	H (%)	F (%)	PC (%)	H (%)	F (%)	PC (%)
a+c+f+l+r+s+t	45.3	18.1	80.6	34.4	17.7	78.5
a+c+f+l+r+s	45.6	18.0	80.6	35.1	17.7	78.6
a+c+l+r+s+t	43.7	18.3	80.3	33.5	18.0	78.1
a+c+l+s+t	38.4	18.5	80.6	27.9	18.5	77.3
c+s+t	29.5	18.4	79.7	25.6	18.2	77.4

Data mining

Data mining techniques have many advantages compared to bivariate statistical approaches, allowing for the analysis of large datasets. The algorithms are able to process non-classified data, they are more stable regarding incomplete or noisy data and they can describe non-linear problems. Moreover, the whole data mining procedure, which is in our study embedded within the SPSS Modeler, is more flexible and efficient for handling the data, including the preliminary exploration and treatment of problematic data. During the pre-processing step the importance of the input variables was checked and the binary factors were identified as problematic and omitted for the analysis. 'Aspect', which is actually a circular variable with very small and very large values for the N sector, was coded into N and S sectors, which were transformed with a cosine function, resulting in values approaching 1 for the N/S sector and 0 for the E/W sector, while the 'flat' category was coded as '0' and thus unimportant. All factors were checked for intercorrelations and as a result TRI, flow accumulation and the aggregated raw landforms were discarded.

All models developed good skills in characterizing the current situation. They were able to predict more than 85 % of the dataset correctly, while the C5.0 Decision Tree reached even 96 %. The C5.0 Decision Tree had also the highest H, more than 85 % of the landslides were predicted in the test dataset (Tab. 4).

The performance of the other models varied especially in the hit rate H, however except for the C&R Decision Tree all models had better skills than the Information Value models. The ranking of the model skills also manifests in the gain charts (Fig. 3). Regarding the prediction of new landslides in 2007, the performance of most models was relatively poor particularly when compared to the outcomes of the Information Value method. The Bayesian network developed the best skills to detect potential areas for future landslides, which manifests in an elevated false alarm rate regarding the 1962 landslides. A comparison

of the spatial distribution of areas of high landslide susceptibility computed with bivariate statistics and Bayesian Networks is given in Fig. 4.

Table 4 Hit rates (H), false alarm rates (F) and proportion correct rates (PC) for landslide susceptibility models established with different data mining algorithms.

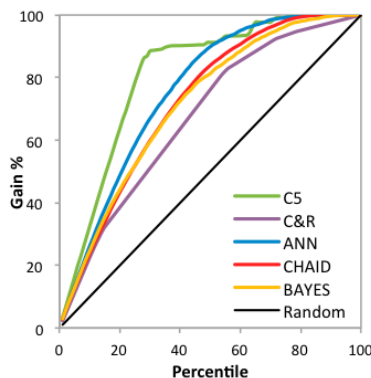| Model	Landslides 1962			New landslides 2007		
	H (%)	F (%)	PC (%)	H (%)	F (%)	PC (%)
C5.0	85.8	3.6	96.0	8.4	6.4	86.8
C&R	31.8	7.4	90.4	13.4	7.9	85.8
ANN	58.3	11.0	87.9	22.3	11.9	82.9
CHAID	46.7	12.1	86.4	18.9	12.8	81.7
BAYES	50.2	12.8	85.8	27.0	13.1	82.2

Fig. 3 Gain charts for the landslides susceptibility models obtained with data mining methods.
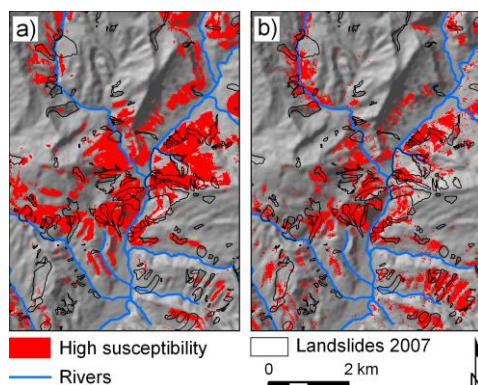
Fig. 4 Comparison of zones with high landslide susceptibility as computed with the Information Value method (a, a+c+f+l+r+s+t) and a Bayesian network (b).

Conclusions

A landslide susceptibility analysis was performed for a case study in the high mountain areas of Kyrgyzstan using methods from geomorphometry, bivariate statistics and data mining. The results demonstrate that with a simple dataset, based on a DEM, a geological map and a landslide inventory, good performances of landslide susceptibility models can be achieved.

References

Aleotti P, Chowdhury R (1999) Landslide hazard assessment: summary review and new perspectives. Bulletin of Engineering Geology and the Environment. 58:21–44.

Bolstad PV, Swank W, Vose J (1998) Predicting Southern Appalachian overstory vegetation with digital terrain data. Landscape Ecology, 13:271-283.

Corominas J, van Westen C, Frattini P, et al (2013) Recommendations for the quantitative analysis of landslide risk. Bulletin of Engineering Geology and the Environment. 73:209-263.

Fell R, Corominas J, Bonnard C, et al. (2008) Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning. Engineering Geology. 102:99–111.

Hand DJ, Mannila H, Smyth P (2001) Principles of Data Mining, Cambridge, MIT Press, 456p.

McNab H (1989) Terrain Shape Index: Quantifying Effect of Minor Landforms on Tree Height. Forest Science. 35:91-104.

Moore ID, Gessler PE, Nielsen GA (1993) Soil attribute prediction using terrain analysis. Soil Science Society of America Journal. 57:443-452.

Pennock DJ, Zebarth BJ, Jong E (1987) Landform classification and soil distribution in hummocky terrain, Saskatchewan, Canada. Geoderma. 40:297–315.

Riley S J, DeGloria S D, Elliot R. (1999) A terrain ruggedness index that quantifies topographic heterogeneity. Intermountain Journal of Sciences. 5:23–27.

Varnes DJ (1984) Landslide hazard zonation: a review of principles and practise. UNESCO, Paris, p.63.

Yin KL, Yan TZ (1988) Statistical prediction model for slope instability of metamorphosed rocks. In: Proceedings of 5th International Symposium on landslides, Lausanne, Switzerland. 2:1269–1272.

Anika Braun (✉)

Chinese Academy of Sciences, Institute of Geology and Geophysics, Beitucheng Xilu 19, Beijing 100029, China
e-mail: anika.braun@rwth-aachen.de

Hans-Balder Havenith

University of Liége, Department of Geology, Liége, Belgium
e-mail: hb.havenith@ulg.ac.be

Tomás Manuel Fernández-Steeger

Universität Berlin, Institute of Applied Geosciences, Department of Engineering Geology, Berlin, Germany
e-mail: fernandez-steeger@tu-berlin.de

Landslides susceptibility analysis in the Jamapa and La Antigua basins in Mexico

Gilbert Torres, Miguel Suárez, Raymundo Dávalos, Saúl Castillo, Ignacio Mora

Abstract As part of the project "Geological and hydrometeorological microzonation hazards for the urban areas of Orizaba, Veracruz in Mexico, and the main towns located in the lower sub-basins of Antigua and Jamapa", sponsored by the Joint Funds CONACyT-Government of the State of Veracruz, where it is studied comprehensively the natural phenomena hazards in the sub-basins and its main urban areas: Jamapa and Antigua, preliminary results of the evaluation of susceptibility to landslides and the basins are presented.

In the assessment, the Mora-Vahrson method was used to establish, approximately, the sectors with potential to present landslides by the combination of shooting factors: rain and earthquake. To accomplish this, diverse cartographic information published by the Institue of Statistics and Geography (INEGI) was used: geology, lithology, humidity and rain, scale 1: 250,000. The slope maps were obtained from digital terrain elevation models available in the CEM3.0 tool, with a pixel resolution of 15 x 15 meters.

The results are presented through maps showing areas with different degrees of susceptibility to slip, where the overall objective of the study is to establish public policy for risk mitigation, properly regulating land and natural resources use in urban areas that are affected by this type of geological phenomena within the study area, setting a scenario showing the sliding threat for prevention purposes.

Keywords microzonation, hazard, vulnerability, risk

Introduction

Veracruz State in the United Mexican States is characterized by a humid temperate climate with an annual rainfall of 1,500 millimeters. Throughout the state, landscape is dominated by plains, hills and valleys. The central region has a rugged topography formed by abundant hills that are part of Neovolcanic Axis of Mexico. Its geographical boundaries cover much of the Gulf Coast of Mexico, coastal boundary where occur many hurricanes and tropical cyclones generated in the Gulf of Mexico and Caribbean Sea, which generate numerous landslides in the state.

Because of this, it aroused the need to analyze the geological and hydrological variables that contribute to the generation of landslides, giving categories to their potential through observation and measurement of indicators and morpho-dynamic spatio-temporal distribution in the Jamapa and La Antigua river basins.

This paper presents the results obtained in evaluating the regional landslide susceptibility in those two basins. In the assessment, the Mora-Vahrson method (Mora et al., 1992) was used to establish, approximately, the sectors with the potential to present slides by the combination of shooting factors: rain and earthquake.

Description of the study area

Location

The study area is located within the geographical limits: 97.40º W - 95.80º W longitude and 18.60º N - 19.60 N latitude. The region is dominated by hills and valleys. It presents a rugged topography consisting of hills that are part of the Neovolcanic mountain range of Mexico. The highest elevation in the area is represented by the Citlaltépetl Volcano, with 5610 meters and the lowest altitude is in the Sierra La Garganta 860 meters.

Climate

The area is characterized by a humid temperate climate with an annual rainfall of 1,500 millimeters. The climates that predominate are: warm humid and humid temperate; however, a small percentage of this region is in the high parts of mountains (around the Citlaltépetl Volcano and Cofre de Perote) where the weather is cold, reaching snow in winter season.

The average annual temperature is 23 °C, the average maximum temperature is around 32 °C in the months of April and May; the average minimum temperature is 13 °C and it occurs in January. The predominant rainfall occurs during much of the summer, between June and October, however there are

places where rainfall occurs all year. The average monthly evapotranspiration is 100 mm.

Geology

The region is located in an area of confluence between two geologic provinces, Sierra Madre Oriental (SMO) and the Trans-Mexican Volcanic Belt (TMVB). The rocks belonging to the SMO are limestones and shales stratified Middle and Upper Cretaceous, which are major topographic barriers with maximum heights ranging between 3,000 and 1,500 meters. Stratigraphically, these rocks form the pre-volcanic basement of the area, are intensely folded and faulted, forming a complex pattern of anticlines, synclines, normal and reverse faults, whose axes and planes are oriented NW-SE direction.

Rocks and volcanic materials are pyroclastic deposits and lava emitted by volcanoes Pico de Orizaba and Sierra Negra, as well as some cinder cones. In middle and high areas there is a predominance of pyroclastic flow deposits and falls, which are associated with explosive eruptions that occurred in the past in both volcanoes.

Lahar deposits are abundant and are associated with volcanic eruptions and torrential rains. In some places unconformably cover the Cretaceous rocks and are found mostly along the cliffs. Structural differences, textural and resistance between the limestone, pyroclastic deposits and lavas, are decisive factors that determine the course of watercourses, as well as the quantity and characteristics of the material is transported to the lower areas.

Approximately between heights of 4,500 and 2,500 m there is an abundance of volcanic material on the cliffs. They are unconsolidated pyroclastic deposits and epiclastic, with a grain size ranging between blocks of several meters in diameter (moved by rolling) to gravels, sands, silts and clays that are transported by entrainment, suspension and dissolution. In this area are located the main sources of supply of material carried by water currents.

The main urban settlements are in the floodplain. In this unit are grouped the alluvial deposits and deposits left by hyper-concentrated flows whose particle size fraction is concentrated in the sands, silts and clays. This is material from pyroclastic deposits.

Methodology

To carry out the assessment, diverse cartographic information published by the Institute of Statistics and Geography (INEGI) was used: geology, lithology, humidity and rain, scale 1: 250,000. The slope maps were obtained from digital terrain elevation models available in the Continuous Elevation Mexico CEM3.0

tool (INEGI), with a pixel resolution of 15 x 15 meters. Due to the small increases in precipitation rates in the study area it was not possible to independently evaluate and detail the influence of heavy rains and trigger parameter, therefore, the influence of the two parameters, rain and earthquake had to be evaluated in a single analysis.

The results are presented through maps showing areas with different degrees of susceptibility to slip, with the overall objective of establishing public policies risk mitigation, regulating properly land use and natural resources in urban areas that are affected by this type of geological phenomena within the study area.

Mora-Vahrson Method

The Mora-Vahrson Method (MVM), heuristic type, consists of the evaluation and combination of the various factors and parameters involved in the process of sliding of a slope, which can be classified into two groups: Passive (conditioning) and Dynamic (triggers) (Mora et al., 1992). The first group is composed of lithology, moisture and topography of the site under study. Dynamic factors are natural and anthropogenic phenomena that can disrupt balance and trigger a hillside sliding; however, it considers only MVM earthquakes and heavy rains as trigger parameters.

It is so that the degree of susceptibility slip is expressed as the product of the passive and dynamic factors (Mora et al., 1992), as expressed in the formula:

$$H = F_P * F_D \qquad [1]$$

$$F_P = S_L * S_H * S_R \qquad [2]$$

$$F_D = D_{LL} + D_S \qquad [3]$$

$$H = (S_L * S_H * S_R) * (D_{LL} + D_S) \qquad [4]$$

Where: F_P passive factors, F_D dynamic factors, S_L lithologic susceptibility parameter, S_H soil moisture parameter, S_R parameter of the slope, D_S earthquake trigger parameter and D_{LL} rain trigger parameter. These parameters are obtained regularly, observation and measurement of indicators and morphodynamic spatiotemporal distribution.

Evaluation of susceptibility parameters

The evaluation of the factors was performed by assigning relative weights, according to their degree of influence on susceptibility to sliding. To do this, it was necessary to create a layer in raster format for each of the parameters involved in the analysis: Lithology (S_L), soil moisture (S_H), Slope (S_R), Earthquake (D_S) and Rain (D_{LL}). The procedure for evaluating each of the factors involved in the analysis and assigned according to the relative ranking of susceptibility of each factor,

established in Mora et al. (1992) and (2002) is described next.

Evaluation parameter the slope (Sp)

The assessment of this parameter is based on the classification of slopes proposed by Van Zuidam (1986) Tab. 1, which associates different slope categories to different characteristics and processes of denudation of the land. This is based on the fact that, in general, high slope values (> 50 ° -60 °) are associated to areas with removal processes such as turning and rock fall (Gonzalez et al., 2002); average slopes (20-50 °) are associated with falls by rolling, sliding, reptation and minor slopes (<20 °) to solifluction, creep and flows.

The calculation of the angle of the slope was carried out using a digital terrain elevation model with a resolution of 15 m per pixel: north, south, east and west: For each raster point (base point), the slope in four directions was calculated. The angle of the slope employed corresponds to the maximum value of the four directions analyzed. The unit in which the value of the slope is expressed is a percentage, which represents the ratio of the difference of elevation and horizontal distance between the base point and the point in the direction analysed (Fig. 1).

Table 1 Rating slope parameter (SP)

Classification pending		Pending qualifier	Value SP
Degrees (º)	Percentage (%)		
0 – 4	0 – 7	Plain	1
4 – 8	7 – 15	Short	2
8 – 16	15 – 30	moderate	3
16 – 35	30 – 70	Strong	4
35 – 55	70 – 140	Very strong	5
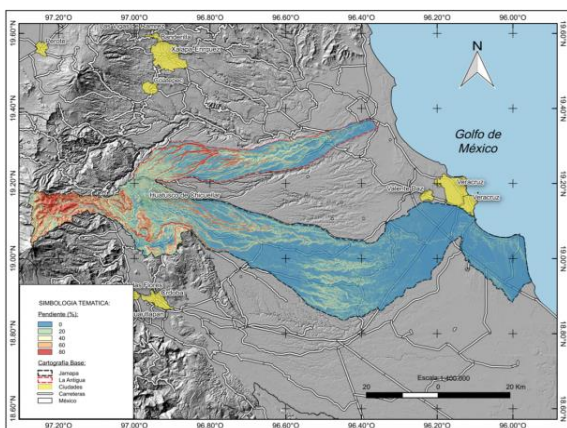
Fig. 1 Map of slopes in the basins: Jamapa and La Antigua

Evaluation parameter field lithology (SL)

The types of soils and rocks have an important role in the dynamic behavior of the slopes. Mineralogical composition, moisture holding capacity, thickness and degree of weathering, the state of fracturing, dip angle, position and variation of groundwater levels, etc., clearly influence the stability or instability of the slopes (Mora et al., 1992). Geological and lithological information from INEGI was used in the calculation of this factor, as well as tables of average values of mechanical properties of representative soil of each lithological group used for the purposes of this study (specific gravity: γ', cohesion: c', and angle of friction: ϕ'); the values have been compiled by various authors (Barton, 1974; Hoek and Bray, 1981; Suarez, 1998; Jibson et al., 2000; González et al., 2002). For the assessment of the lithological units that make up the study area (Fig. 2) the proposed values in Tab. 2 were used.

Table 2 Classification and measurement of lithological units (SL)

Geological Unit	Lithology	SL Value
Q(legb)	Igneous extrusive	2
Q(ar-cg), Q(legb), Q(Tr), Q(cg) Ts(legi), Ts(legb)	Sandstone - Cluster	3
Ks(cz), Ki(cz), Q(Vc)	Limestone - Siltstone, Limestone- Shale, Gypsum Caliza	4
Q(s)	Alluvial Deposits	5
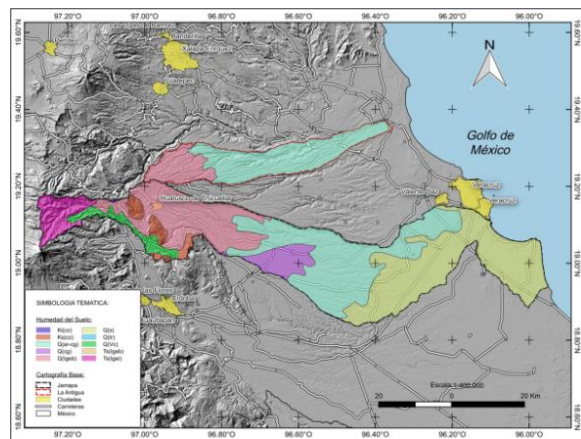
Fig. 2 Lithologic map of basins: Jamapa and La Antigua

Evaluation of soil moisture parameter (SH)

To evaluate the soil moisture parameter, information from the monthly averages of precipitation published by the CLICOM System National Climatology Database (Base de Datos Climatológica Nacional – Sistema

CLICOM) (CLICOM, 2016) was used. The Soil Moisture and Evapotranspiration chart of Mexico (scale 1:1,000,000), which was published by the INEGI, was also employed. From the information gathered and according to what was proposed by Mora et al. (1992), a simplified hydric balance was used. A reference value, as established in Tab. 3, is assigned to the average monthly precipitation making the sum of these values for the 12 months of the year, thus obtaining a value ranging between 0 and 24 units. This value is classified according to Tab. 4. The result reflects aspects of saturation and temporal distribution of soil moisture (Mora et al., 1992). It should be noted that the monthly evapotranspiration average, which turned out to be 100 mm / month, was deducted from the average monthly precipitation of the study area.

Table 3 Value assigned to the average monthly rainfall.

Average precipitation	Assigned value
< 125	0
125 − 250	1
> 250	2

Table 4 Parameter values soil moisture (SH).

Sum of values assigned to each month	Qualification	Value SH
0 − 4	Very low	1
5 − 9	Low	2
10 − 14	Medium	3
15 − 19	High	4
20 - 24	Very high	5

Fig. 3 shows the map of soil moisture obtained by analyzing the average monthly rainfall values and assigning them a reference value in Tab. 3. When making the sum of these values for the 12 months of the year, a map with values ranging from 12 to 24 units was obtained and classified according to Tab. 4 to apply the MVM.

Evaluation parameter by Earthquake (DS)

Due to the high uncertainties in predicting occurrence of a seismic event and the high seismic demands that induces the sliding of a slope, it became necessary to carry out a Probabilistic Seismic Hazard Analysis (PSHA). PSHA accounts for these uncertainties through probabilistic models that estimate the intensity of an earthquake at a particular site, from its magnitude in the source that generated it, and the distance between the source and the site of interest.

The seismic hazard in the study area is governed by three types of seismogenic regions: subduction, mid-
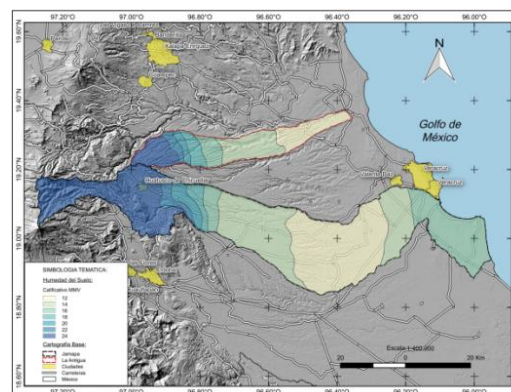

Fig. 3 Map of moisture of basins: Jamapa and La Antigua

water (inslab) and superficial. The interplate events correspond to subduction earthquakes generated by the friction between the North American plate and the oceanic Cocos and Rivera plates along their contact area. The inslab events correspond to normal faulting earthquakes of intermediate depth, located within the subducting oceanic plate under the continental plate. The shallow crust earthquakes correspond to shallow earthquakes occurring within the North American plate. Model attenuations used were as follows: Abrahamson and Silva (1997) for earthquakes of surface crust, Arroyo et al. (2010) for subduction earthquakes and García et al. (2005) for earthquakes of normal fault of intermediate depth.

The data processing was performed with the Program for computing seismic hazard CRISIS 2015 (Ordaz et al., 2012), which allows the inclusion of the site effects in the calculation of seismic hazard through amplification factors (ratios spectra response), which depend on the location of the site, the structural period and the level of soil movement.

To take into account the effects of site in the study area, the parameter of the shear wave velocity (Vs 30) was used to calculate local amplification factors. This comes from the hypothesis that it is possible to calculate the "average" Vs 30 from the slope. To do this, the average values Vs 30 recommended by the United States Geological Survey (USGS) for active tectonic regions with a sharp and stable continental regions where changes in topography are smoother (Tab. 5), were used. These values were obtained by correlating geological information and measurements Vs 30 with land slope in several countries including: US, Japan, Australia and Italy (Trevor et al, 2007).

The information for shear wave velocity was obtained from the "Global Vs 30 Map Server" Web application (USGS, 2016). This application allows the user to calculate Vs 30 maps for a specific region of the world.

Table 5 Slope ranges for various categories of Vs 30 according to National Earthquake Hazards Reduction Program (NERHP) www.nehrp.gov/.

Soil Classifi-cation	Range (m/s)	Slope range (m/m)	
		Tectonically active	Continental stable
E	< 180	< 3.00E-4	< 2.00E-5
	180 – 240	3.00E-4 – 3.50E-3	2.00E-5 – 2.00E-3
D	240 – 300	3.50E-3 – 1.00E-2	2.00E-3 – 4.00E-3
	300 – 360	1.00E-2 – 1.80E-2	4.00E-3 – 7.20E-3
	360 – 490	1.80E-2 – 5.00E-2	7.20E-3 – 1.30E-2
C	490 – 620	5.00E-2 – 1.00E-1	1.30E-2 – 1.80E-2
	620 – 760	1.00E-1 – 1.38E-1	1.80E-2 – 2.50E-2
B	> 760	> 1.38E-1	> 2.5E-2

The intensity level of ground motion in the study area (Jamapa and La Antigua,) was measured in terms of ordered response spectrum (5% of critical damping) for seven structural periods (Te) from 0.01 to 3 seconds, associated with a return period (Tr) of 100 years. To assign values to the seismic parameter, the acceleration values associated to spectral ordinate (Te) equal to 0.15 seconds (Fig. 4)were used and classified according to those values proposed by Mora et al.(1992), shown in Tab. 6.

Evaluation parameter shot by Rain (DLL)

The assessment of this parameter is performed according to what is stated in Mora et al., (1992). Intervals classification and respective weights are shown in Tab. 7. The series of annual daily maximum values recorded at weather stations distributed in the study area were used for evaluating this factor. The calculation of the maximum rainfall associated with a return period (Tr) 100 years, was obtained by applying the method of Gumbel.

Results

As a result of the combination of the parameters, a zoning of the susceptibility to slip for the study area was obtained, as shown in Fig. 5. This map shows that the site most likely to slip is near the Citlaltépetl Volcano (elevation 5747 m), consisting of materials of volcanic origin and interspersed with fluvial deposits with low cementation, and on the banks of the rivers that form the Jamapa basins and Antigua, which have a very steep topography with steep slopes and above 60°

cuts. Some of the major municipalities that may be affected by landslides are: Alpatlahua, Calcahualco, Escola, Huatusco, Ixhuatlan del Cafe, Ocotitlan, Sochiapa and Vaquería.

One of the logical applications of these studies is to establish public policies for risk mitigation, properly regulating land use and natural resources in urban areas that are affected by this type of geological phenomena.

Table 6 Earthquake triggered factor (DS).

Modified Mercalli Intensity	Acceleration (cm/s2)	Value DS
III	0.3 – 2.2	1
IV	2.2 – 4.5	2
V	4.5 – 8.9	3
VI	8.9 – 17.7	4
VII	17.7 – 35.4	5
VIII	35.4 – 70.5	6
IX	70.5 – 140.8	7
X	140.8 – 280.8	8
XI	280.8 – 560.4	9
XII	>560.4	10

Table 7 Rating factor triggering rainfall (DLL)

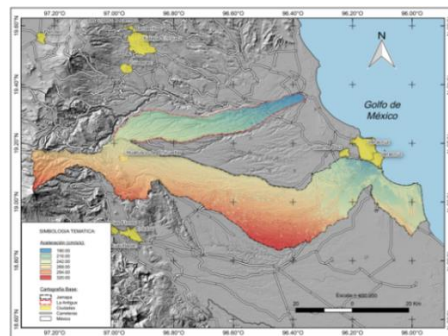| Tr = maximum rainfall 100 years (mm)	Qualification	Value DLL
<100	Very low	1
100 – 200	Low	2
201 – 300	Medium	3
301 – 400	High	4
>400	Very high	5

Fig. 4 Map intensity of ground motion associated with the spectral ordinate (Te) equal to 0.15 seconds and a return period (Tr) of 100 years.

Some general recommendations for risk mitigation are: rehabilitation of vegetated slopes exposed to the weather, do not urbanize strategic areas that may start mass movements and subsidence. In urbanized areas,

stabilize the slopes and hillsides susceptible to slide through some type of civil work (retaining walls, anchors, coatings, terrain cuts, mass compensation, etc.) to control the movement of sediment or rocks, as well as secondary works necessary (storm drains, sinks, fittings, cultivation of plant species that help control runoff, etc.) to allow proper surface drainage and underground drainage to eliminate leaks when making walls that support the unstable slopes.
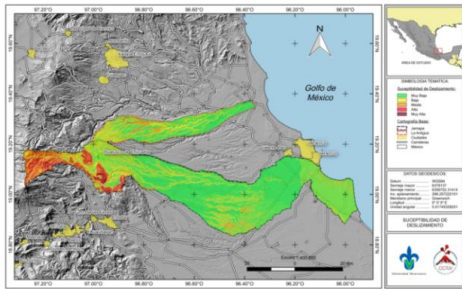

Fig. 5 Map of susceptibility to slip in slopes of the basins Jamapa and La Antigua.

References

Abrahamson A. y Silva W. (1997). Empirical Response Spectral Attenuation Relations for Crustal Earthquakes. Seismological Research Letters, Vol. 68, No 1, pp. 94-127

Arroyo, D., García D., Ordaz M., Mora M.A., y Singh S.K. (2010). Strong ground-motion relations for Mexican interplate earthquakes. Journal of Seismology, No 14, pp. 769-785.

Barton, N.R. (1974). A review of the shear strength of filled discontinuities in rock. Norwegian Geotech. Inst. Publ. No. 105. Oslo: Norwegian Geotech. Inst.

CLICOM (2016). Base de Datos Climatológica Nacional, datos climáticos diarios del CLICOM del SMN con gráficas del CICESE (http://clicom-mex.cicese.mx).

García D., Singh S. K., Herráiz M., Ordaz M., Pacheco J. (2005). Inslab Earthquakes of Central México: Peak Ground-Motion Parameters and Response Spectra. Bulletin of the Seismological Society of America, Vol. 95, No 6, pp. 2272-2282.

González, L., Ferrer, M., Ortuño, L. y Oteo, C. (2002). Ingeniería geológica, Prentice Hall, Pearson Education, Madrid, 715 p.

Hoek, E. y Bray, J. W. (1981). Rock slope engineering. Institution of Mining and Metallurgy, 3a edition, 358 p.

Instituto de Estadística y Geografía (INEGI) (2016). Continuo de Elevaciones Mexicano (CEM 3.0). http://www.inegi.org.mx/geo/contenidos/datosrelieve/continental/continuoelevaciones.aspx

Jibson, R.W., Harp, E.L. y Michael, J.M. (2000). A method for producing digital probabilistic seismic landslide hazard maps. Engineering Geology, Vol. 58, No. 3-4, pp. 271-289.

Mora, R., Chávez, J. Vásquez, M. (2002). Zonificación de la susceptibilidad al deslizamiento: Resultados obtenidos para la Península de Papagayo mediante la modificación del método Mora & Vahrson (Mora et al., 1992). Memoria del tercer curso internacional sobre microzonificación y su aplicación en la mitigación de desastres. Lima, Perú. 38-46.

Mora, R., Mora, S. Vahrson, W. (1992). Microzonificación de la amenaza de deslizamientos y resultados obtenidos en el área del valle central de Costa Rica - Escala 1:286 000, CEPREDENAC, San José de Costa Rica.

Ordaz M., Martinelli, F., Aguilar, A., Arboleda, J., Meletti, C., and D'Amico, V. (2012). CRISIS: Program for computing seismic hazard.Instituto de Ingeniería, UNAM, México City.

Trevor I. Allen and Wald J. David (2007). Topographic Slope as a Proxy for Seismic Site-Conditions (Vs30) and Amplification around the Globe. Open-File Report 2007-1357. USGS (United State Geological Survey). http://pubs.usgs.gov/of/2007/1357/pdf/OF07-1357_508.pdf

U.S. Geological Survey (2016). Estimates of site conditions from topographic slope. Global Vs30 Map Server. http://earthquake.usgs.gov/hazards/apps/vs30/custom.php.

Van Ziudam, R.A., 1986: Aerial photointerpretation in terrain analysis and geomorphologic mapping. Smits Publishers, The Hague. 442

Gilbert Francisco Torres Morales (✉)
Centro de Ciencias de la Tierra, Universidad Veracruzana, CCTUV Francisco J. Moreno No. 207, Col. Emiliano Zapata, Xalapa, Ver. México.
e-mail: gitorres@uv.mx.

Miguel Leonardo Suárez
Instituto de Ingeniería, UNAM, Coyoacán, México.
e-mail: mleonardosuarez@gmail.com.

Raymundo Dávalos Sotelo
Instituto de Ecología A.C., Carretera Coatepec No. 351, Xalapa, Ver., 91170, México.
e-mail: raymundo.davalos@inecol.mx

Saúl Castillo Aguilar
Facultad de Ingeniería Civil, UV, Lomas del estadio. C.P. 91000, Xalapa, Ver. México.
e-mail: sacastillo@uv.mx

Ignacio Mora González
Centro de Ciencias de la Tierra, Universidad Veracruzana, Francisco J. Moreno No. 207, Col. Emiliano Zapata, Xalapa, Ver. México
e-mail: imora@uv.mx

Development of risk rating system for small-scale landslides affecting settlements in Guatemala City

Ethan Faber, Brittany Moreland, Scott McDougall, Stephanie Hunter, Lauren Hockin, Alex Strouth

Abstract Guatemala City is now the most populous city in Central America, in part due to rapid migration of people from rural areas. Resulting population pressure on the limited geographic area of the city has led to many settlements in steep ravines. The ravines are prone to landslide activity and the inhabitants are at risk. Mitigation of the landslide risk to acceptable levels is typically cost-prohibitive. Permanent relocation is the only option to eliminate the risk; however, there are several economic and social obstacles impeding successful implementation of a relocation program. In response, landslide risk-reduction projects focusing on education of community members have been developed. In the present project, called CERRPED (translated as: Empowering Communities in Risk Reduction of Small Landslides), a training course has been developed to teach community leaders how to use a landslide risk classification tool to assess their risk to small landslides (typically the size of a house or smaller). Affordable mitigation options are also introduced. To date, pilot training sessions have been well received by community members. Use of the components of the CERRPED project by the communities will be evaluated in the future to determine if it is having a positive effect on landslide risk reduction.

Keywords landslide, risk, Guatemala, communities

Introduction

CERRPED (translated as: Empowering Communities in Risk Reduction of Small Landslides) is a project designed to help residents of the Guatemala City Metropolitan Area (GCMA) better understand landslide hazards, risk concepts, and landslide risk management options. Its goal is to empower at-risk communities to take part in managing landslide risks and, as a result, reduce the overall risk from landslides in the GCMA.

- Specifically, CERRPED is composed of two main components:

- Small-Scale Landslide Risk Classification Tool (Classification Tool)
- Landslide Mitigation Options List

Social and Physical Setting

The GCMA is located on poorly welded silicic pumice and ash (pyroclastic material) from a series of volcanic eruptions over the past 2 million years (Koch and McLean, 1975). Surface water runoff has formed steep-sided gullies and ravines in this material. In many of the stronger layers of pyroclastic material, vertical slopes stand over 30 meters high, and vegetated slopes as steep as 40 degrees are common.

Individual cut slopes in the GCMA tend to remain at a steep angle in a state of 'short-term' equilibrium, but experience periodic failures at a frequency on the order of tens of years. Slope failure events that do occur are often lost from memory because of the relatively long period of 'short-term' stability (Sitar and Clough, 1983). Consequently, excavations into these geologic materials are commonly made as steeply as possible, exceeding what is stable in the long-term for the geologic materials. This condition leads to frequent small landslides at cut slopes across the GCMA.

Along with the hazard of landslides, the GCMA also faces challenges with rapid unplanned development, which is comparable to the fastest-growing cities in developed and undeveloped countries (Roberts, 1973). Due to the rapid growth, many communities form illegally by over-night invasions in the ravines of the GCMA. These invasions, in turn, become informal settlements due to the limited enforcement and resources required to evict the settlers. Since almost all land with low landslide hazard is already developed, these newer settlements typically occur on the steep, landslide-prone slopes. Furthermore, construction materials of the houses are of poor quality and the houses are almost never constructed in accordance with a standard building code (Anderson and Holcombe, 2013). Thus, when landslides occur in these communities, the houses are easily damaged and

destroyed by relatively small landslides. Fatalities sometimes occur as a result.

In general, most families are aware of the landslide risk that threatens the settlements, but are not fully aware of many economically-feasible risk reduction options. Permanent relocation is widely recognized as the best method to reduce the landslide risk to a tolerable level. However, relocation is not a realistic option for most families who have immigrated to the GCMA seeking economic opportunities.

Materials and Methods

The Classification Tool is intended for use by trained community members to rate the landslide risk at individual houses. It is intended only for evaluation of small landslides (the size of a house, or smaller), and it focuses on the risk of a fatality or injury caused by a small landslide impacting a house.

A trained community member uses the tool to estimate a Landslide Susceptibility score and a Landslide Exposure score. These scores are combined using a matrix to assign risk levels of Low, Average, High, or Very High. The tool has been calibrated such that a house exposed to average landslide risk in a GCMA settlement will receive a risk level of "Average". Houses with a higher than average landslide risk receive a score of "High" or "Very High", while houses with a lower than average landslide risk receive a score of "Low".

The Classification Tool's relative risk levels complement community-wide landslide susceptibility zones produced by CONRED (National Coordinator of Reduction of Disasters). The relative risk score does not replace the landslide susceptibility zone defined by CONRED, but instead can be used to differentiate landslide risk levels of individual houses within a CONRED zone (Fig. 1). Given this relationship with CONRED's existing landslide susceptibility zonation, the Classification Tool has two primary purposes:

- Planning: The Classification Tool can be used by trained community leaders, municipalities, COLRED (Local Coordinator of Reduction of Disasters), COMRED (Municipal Coordinator of Reduction of Disasters), and CONRED to identify the highest risk houses within a given community or CONRED landslide susceptibility zone. This information can be used for evacuation planning, allocation of resources, and landslide risk management planning.
- Education: The Classification Tool can be used to educate residents about the factors that contribute to landslide risk at their homes, which can empower residents to initiate actions to manage their own landslide risk.
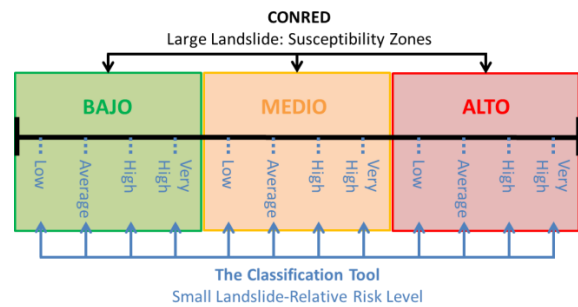

Fig. 1 CONRED Landslide Susceptibility Zones and the Classification Tool Relative Risk Levels

Data Collection

The Classification Tool was developed based on data collected in four communities distributed across the GCMA. Representative slopes within each community were characterized with a focus on factors that contribute to landslide risk. Data was collected in the field using hand equipment, including a camera, compass, clinometer, and tape measure (Faber, 2016).

Results

Selection of Factors

The Classification Tool risk ratings are assigned to individual houses and slopes based on assessment of six key factors. The Landslide Susceptibility Factors are Slope Height, Slope Angle, and Slope Material. The Landslide Exposure Factors are House-to-Slope Distance, Number of People, and House (Construction) Material. In combination with each other, the Landslide Susceptibility factors estimate the likelihood of a landslide occurring at a specific slope. In simple terms, slopes that are most likely to experience landslides are high, steeply inclined, and comprised of weak materials. The Landslide Exposure factors provide an indication of the consequences (in terms of injury or loss of life) that could occur as a result of the landslide. Injury or loss of life is most likely to occur at densely populated houses located within the landslide impact area that are composed of materials that do not strongly resist the landslide impact.

Factors included in the Classification Tool were selected following review of the collected data. Each selected factor meets all of the following criteria:

- Primary Contributor to Landslide Risk – The factor is widely recognized as contributing to increasing the likelihood, magnitude, frequency, impact intensity, or impact area of landslides (e.g. Cruden and Varnes, 1996); or the factor directly affects the likelihood a person is injured or killed when the landslide occurs.

- Accurately and Consistently Characterized by a Layperson – The Classification Tool is intended to be used by community members who are trained to use the tools, but who have highly variable educational backgrounds and life experiences. The primary users are not geotechnical engineers or geologists, and typically would have very limited training or experience in those fields. All selected factors must be characterized accurately, consistently, and easily by the trained users, using tools commonly available in GCMA communities.

Points, Weightings, and Scores

When the Classification Tool is used at a site, points are assigned to each factor based on data collected at the site. The points are combined, as instructed by the Classification Tool, to estimate the Landslide Susceptibility Score and the Landslide Exposure Score. Weightings have been incorporated in the score calculations based on the relative importance of each factor to small landslide risk.

The points and weightings were selected using the collected data set and a process of trial and error to balance two competing criteria:

- Maximize the spread in the Landslide Susceptibility and Landslide Exposure scores to allow a better discretization of relative risk between houses.
- Provide a formulation that can be computed with simple arithmetic by the intended users, without requiring a calculator.

Points assigned to each factor include "1", "2" or "4". The full range of factor values measured during the data collection phase was considered when assigning points to each factor. One point was assigned to values that contribute to low landslide risk, and four points were assigned to values that contribute to high landslide risk. Two points were assigned to intermediate values. Tab. 1 summarizes the points assigned to different parameter values.

Eq. 1 and Eq. 2 summarize the formulas used to estimate the Landslide Susceptibility Score (LSS) and Landslide Exposure Score (LES), which can both range from "4" to "16". Higher scores indicate conditions that contribute to higher landslide risk. A weight of "2" was assigned to the factors that most contribute to landslide risk: Slope Height and House-to-Slope Distance. Slope Height is critical because it contributes to the potential landslide magnitude, impact energy, and spatial area of impact. House–to-Slope Distance is the primary factor that determines if a house is exposed to landslide hazards.

In addition, the following special cases were defined in which a very low value for a single factor results in

the minimum Landslide Susceptibility or Exposure score ("4"), regardless of the value of the other factors:

- Slope height less than 1 m (slope above house) or less than 3 m (slope below house): a person is likely to survive landslide impact
- Slope angle less than 20 degrees: slopes are typically stable
- Distance from the slope to house exceeds the slope height: house is unlikely to be impacted
- A house with no people: no individuals are at risk

$$LSS = 2*(Slope\ Height\ Points)+ \\ (Slope\ Angle\ Points)+(Slope\ Material\ Points) \quad [1]$$

$$LES = (Number\ of\ People\ Points)+ \\ 2*(Distance\ Points)+(House\ Material\ Points) \quad [2]$$

Risk Matrix Boundaries

The Landslide Susceptibility Score and Landslide Exposure Score are combined to estimate a risk level using a risk matrix (Fig. 2).

The risk levels are defined as follow:

- Low: Below Average Risk - Risk of a fatality or injury due to small landslides is less at this house than at a typical house in a GCMA settlement.
- Average: Average Risk – Risk of a fatality or injury due to small landslides is similar to the risk at a typical house in a GCMA settlement.
- High: Above Average Risk – Risk of a fatality or injury due to small landslides is greater at this house than at a typical house in a GCMA settlement.
- Very High: Highest Risk – Risk of a fatality or injury due to small landslides is highest at this house, compared to a typical house in a GCMA settlement.
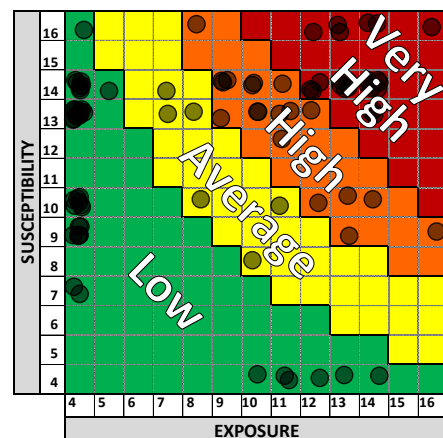

Fig. 2 Risk Matrix Boundaries Derived from Data

Table 1 Points assigned to factor values

Factor	1 Point		4 Points	
	Values	Notes	Values	Notes
Slope Height (m)	3 – 4 (above) 4 – 5 (below)	Contributes to small volume landslide with small area of impact	7+ (above) 10+ (below)	Potential for large volume landslide and large area of impact
Slope Angle (°)	15 – 45	Landslides uncommon, slopes typically stable	71 – 90	Landslides commonly occur, unstable in the long-term
Slope Material	Rock	Slopes typically stable	Top soil, fill, weak material	Landslides commonly occur
House-to-Slope Distance (m)	6+ (above) 4+ (below)	Most landslide deposits are unlikely to reach the house	0 – 2 (above) 0 – 1 (below)	A landslide or rock fall will almost certainly impact the house
Number of People	1 – 4	A person might not be occupying the impacted portion of the house when the landslide occurs	9+	A person will very likely occupy the impacted portion of the house
House (Construction) Material	Reinforced concrete	Able to resist some landslide and rock fall impacts without collapse	Tin	Provides no protection from small landslides will be destroyed by small impacts.

Notes: 1. (above) refers to the Classification Tool for slope above house; (below) refers to the Classification Tool for slope below house
2. Values assigned 2 points are provided in the Classification Tool forms

Required actions have not been defined for any of the risk levels, and a tolerable risk level has not been defined. CERRPED encourages all residents to implement all reasonable measures to reduce small landslide risk regardless of risk level. The relative risk levels can be used to prioritize houses for risk management planning.

The following method was used to define the boundaries between risk levels:

- Risk evaluation was completed at 51 slopes across three communities in the GCMA using the Classification Tool. These houses are considered to be a random sample of small landslide risk in the study area.
- Risk at all houses in the random sample was plotted on the matrix.
- Risk level boundaries were drawn approximately as follows:
  o The plotted data is centered around "Average"; that is, approximately half of the houses plot above and below the mid-line of the "Average" range.
  o "Very High" is assigned to the highest 25% of data.
  o The width of the "Average" level on the risk chart is set approximately equal to the "High" risk level.

o The remainder of the matrix is assigned "Low". The Classification tool is shown in Fig. 3.

Landslide Mitigation Options List

The landslide mitigation options provided by the CERRPED project have varying levels of cost and complexity, but most options are focused on being affordable and easy to implement by a typical family in a settlement in the GCMA. In addition, all the mitigation options are taken from already existing techniques found in settlements throughout the GCMA. While most of the mitigation options are simple enough for any family to implement on their own with basic guidelines, three of the options require support by the local municipality because the three options are much more complex and if done incorrectly, can make situations worse.

- Options Implementable by Families Themselves
  o Permanent relocation
  o Rearrange furniture and items in house to be further from dangerous slope
  o Move house to or build in safer area
  o Ensure/Grow healthy vegetation
  o Place impermeable cover over slopes
  o Remove weak material from slope

- o Install gutters, drains, and pipes to transport water to non-hazardous area
- o Temporary evacuation during unstable times

- Options Requiring Local Municipality Support
  - o Benched cut (only for slopes above)
  - o Retaining wall
  - o Upgrade construction material of house
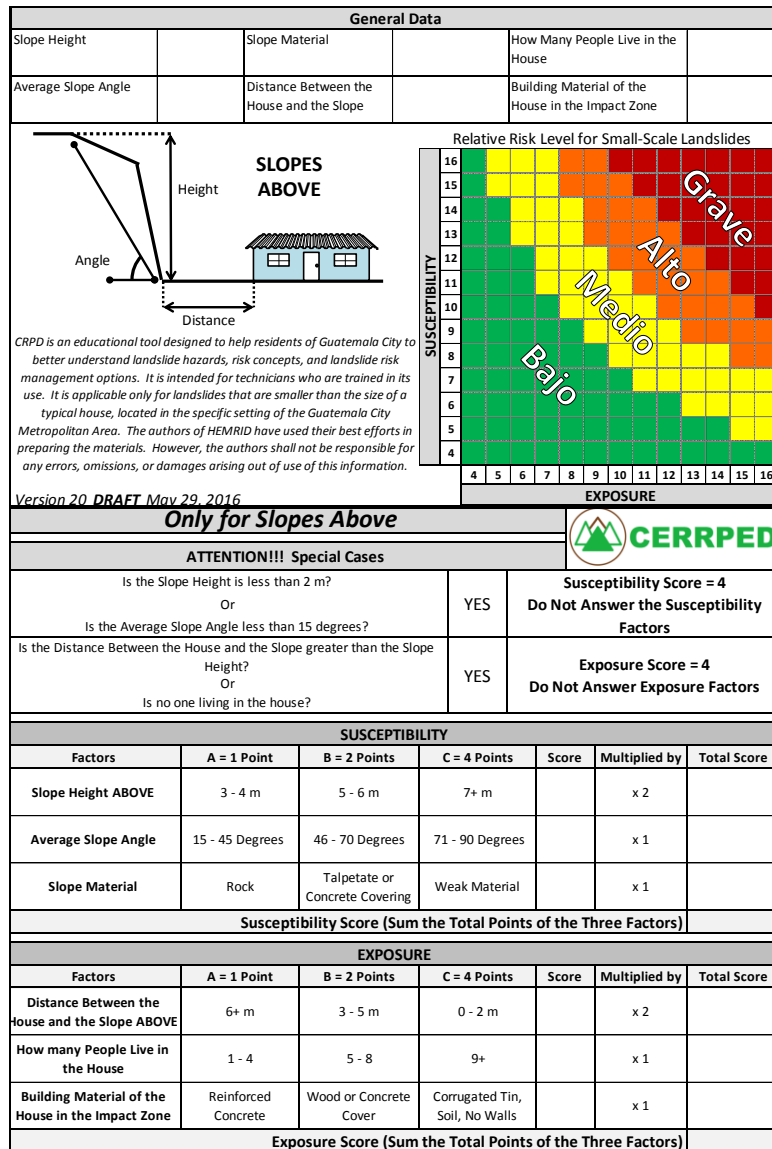
Fig. 3 The classification tool for slopes above (there is a very similar form to evaluate slopes below a house)

Illustrations and additional information is provided for each mitigation option in the CERRPED training to help trained community leaders be able to know where each mitigation option is beneficial to implement and to make sure it is implemented correctly by the family.

Training Course Material

The Classification tool is intended to be used by community leaders who have completed a training course. A five day training course has been developed to teach community leaders about landslides, risk concepts, the Classification tool, and landslide mitigation options. The training course is intended to be led by professionals who are experienced in landslide hazards and risk management principles.

Discussion and Conclusions

Through the course of this project, important limitations of CERRPED were discovered. These limitations include:

- Landslide risk at settlements in the GCMA increases with increasing population. It is critical that residents understand that permanent relocation from landslide risk areas is the only method for eliminating landslide risk.

- The Classification Tool is intended for evaluating risk of "small" landslides only, where "small" is defined as the size of a house or smaller. The Classification Tool is not useful for evaluating risk associated with larger landslides.

- The Classification Tool is a simple tool designed to apply to "typical" situations in the GCMA. It does not apply to all situations that may be found; it is only applicable in communities with similar conditions as those used to calibrate the tool.

- CERRPED has been developed for the unique geologic, topographic, climatic, and social conditions of the GCMA. The tools are specific to the typical slope height, pyroclastic composition of slopes, and building materials that are typical to the GCMA. Changes to CERRPED are required before it can be applied in other settings.

- Agencies that apply CERRPED must take actions to manage the accuracy and consistency of data results. An experienced professional in landslide risk management should be engaged, as needed, to ensure CERRPED is properly implemented.

- CERRPED would benefit from updates based on future research, that may include:
  - Collection of a database of small landslide events, including date of occurrence, volume, travel angle, weather, surface water conditions, etc.
  - Investigation of rainfall thresholds that tend to trigger widespread small landslide events

CERRPED's intended audience is for community leaders in areas with significant small-scale landslide risk. However, community leaders must be certified through an official five-day course before they can use any part of CERRPED. The training course should be given by organizations that have experience with projects addressing risk management for settlements in the GCMA, similar to CONRED, Fundación Ecuménica Guatemalteca Esperanza y Fraternidad (ESFRA), and BGC Engineering (BGC) and requires the organization to have certified facilitators (approved by CONRED) to give the training.

After the training, a CERRPED committee is formed consisting of the certified community leaders. The facilitators must remain engaged with the project for the foreseeable future in order to support, follow up, and collect the data from each community with a CERRPED committee. Furthermore, the data collected should be recorded in a communal database for all organizations to track the effects of CERRPED.

Finally, this project has held several pilot trainings with communities and community leaders have shown they are able to meet all the main objectives and requirments of the project. The project is currently seeking CONRED's approval. After approval is granted, this project, and all its subsidiaries, will be available to the public. If any organization is interested in obtaining more detailed information on implementation, the scientific methodology, or anything else please feel free to contact the authors with the provided contact information below.

Acknowledgements

References

Anderson, M.G. and Holcombe, E., 2013, Community-Based Landslide Risk Reduction: Managing Disasters in Small Steps. 2013 International Bank for Reconstruction and Development / the World Bank.

Cruden, D.M., and Varnes, D.J. 1996. Landslide Types and Processes. Chapter 3 of Landslides: Investigation and Mitigation. Transportation Research Board, National Academy of Sciences, 247:36-75.

Faber, E.J. 2016. Development of a landslide risk rating system for small-scale landslides affecting settlements in Guatemala City (Master's thesis). Retrieved from ProQuest Dissertations and Theses. (Accession Order No. 10014960)

Koch, A.J. and McLean, H., 1975, Pleistocene Tephra and Ash-Flows Deposits in the Volcanic Highlands of Guatemala, Geological Society of America Bulletin, v. 86, p. 529-541. Kockelman, W.J., 1986,. Some tezhniques for reducing landslide hazards. Bull. Ass. Eng. Geologists, 23 (1) (1986), pp. 29–52.

Roberts, B.R., 1973. Organizing strangers: poor families in Guatemala City. Austin: University of Texas Press.

Sitar, N. and Clough, G.W., 1983, Seismic Response of Steep Slopes in Cemented Soils, Journal of Geotechnical Engineering, Vol. 109, No. 2, February, 1983.

Ethan Faber (✉)

Fundacion ESFRA, 4ta. avenidad 3-14 zona 1, Ciudad de Guatemala

e-mail: ethan.j.faber@gmail.com

Technical and prospective evaluation of landslide risk in Granma province, Cuba

Eberto Luis Hernández Suros, Yanet Sam Pascual

Abstract Nearly one third of Granma province is occupied by the mountains of Sierra Maestra. Important population centers as well as outstanding economic, social, electrical, communication and water supply infrastructure is susceptible to the occurrence of landslides. This paper aims at providing a qualitative evaluation of landslide risk in the territory of Granma province considering both the active and passive elements that determine the occurrence of landslides; it also aims at identifying the areas with higher risk in order to include them in social and economic development projects and programs. The study also assessed the level of risk perception of the population as well as the capabilities to face and mitigate, in an autonomous way, the effects of landslides that may occur. The work provided a set of structural and nonstructural measures to deal with the causes and effects of landslides before, during and after their occurrence.

Keywords risk assessment, landslides, vulnerability

Introduction

Rock and landslides down the slope driven by the force of gravity can be caused naturally or by man-made actions. They have become one of the most dangerous geological phenomena. They can sweep away people's lives, infrastructure and devastate natural landscapes. Thus, knowing the processes and conditions favoring landslide occurrence makes it possible to improve the risk management as well as the decision making process regarding economic and social planning and land distribution in the most vulnerable territories.

Experience shows that landslides occur due to a combination of conditions and very rarely due to a single one. There are many factors that can induce ground mass instability, such as local topography of natural slopes, rock and soil origin, slope geometry, discontinuity and stratification of rock masses, the presence of deep clay deposits in rock sequence as well as rock mechanical properties, their hydro- thermal

erosion and many others. These are considered as passive or conditioning factors. In the present study, other factors were also considered. These, though occasional in nature, can also trigger or aggravate landslides occurrence. Some of them are average and heavy rainfall, water infiltration, temperature variation, erosion, floods and earthquakes. Deforestation and other human actions also affect the slope stability or shape and are also considered as active factors for the purpose of this research.

After the analysis of the interaction of passive and active factors, three hazard categories were defined. In order to establish the vulnerability level of each territory and location, physical, natural, social and economic elements were also considered.

Up to the moment when this research was conducted in Granma province, landslides were considered merely as local and random phenomena. The relations between the elements of the ecosystem and the need for a comprehensive land planning and management in order to reduce the vulnerabilities had been disregarded.

Materials and Methods

The research was conducted in the Granma province territory where six municipalities are located in the Sierra Maestra mountain range, approximately between 19 ^{o} 54' 7" , 20 ^{o} 24' 39" North and -77 ^{o} 27' 0" , - 76 ^{o} 11' 56" West. The mountain areas are located at altitudes over 600 meters above sea level.

The research was based on the *Methodological guidelines for landslides hazard, vulnerability and risk at municipality level* issued by the Cuban Ministry of Science, Technology and Environment on April 2009. (AMA, 2009).

Landslide risk evaluation took into account the susceptibility indexes for each of the active or passive factors that influence landslide occurrence. These include: intense rain, seismic activity, geomorphologic and tectonic factors, human activities, and physical and mechanical properties of soils. Data was provided by

governmental and scientific institutions in charge of monitoring and measuring environmental, social and economic variables. The results of the analysis of historical data collected and processed for a period of more than 50 years by meteorological stations and the studies conducted by the seismological stations located in Granma province proved that intense rainfall and seismic activity were the main catalyzers for landslides in the territory. Data was integrated into a GIS and included the assessment of the conditions present in neighborhoods and small zones within each municipality. Interviews with community leaders and elder people, working meetings with specialists and civil defense officials, and workshops with the people were vital in order to evaluate risk perception of the inhabitants. In-situ field observations and measurements of sites prone or being affected by landslides were crucial element as well. Finally, results were analyzed and documented in risk charts and maps.

Results and Discussion

The study showed variations in landslide risk values depending on geological and climatic conditions. Mountain municipalities like Jiguani, Guisa, Buey Arriba, Bartolome Maso, and Pilon had a higher risk factor. However, in flat land municipalities, the higher risk was observed in the Cauto River riverbanks.

The biggest landslides that have taken place in Granma province were associated to strong hydrometeorological events such as hurricanes Flora, Dennis, Lili, Noel and intense rainfall episodes as well as significant seismic events like the earthquake with epicenter south of Pilon municipality on February 19, 1976.

Considering both geological and climatic conditions, landslide hazard is present in each and every mountain municipality as well as in all eroded river banks, mainly when they are affected by deforestation and strong rain drainage.

Mountain municipalities share a common rock origin made out of effusive rocks formed in submarine conditions and also out of plenty of carbonated material. Pilon and El Cobre formations are predominantly represented by volcanogenic and volcanogenic–sedimentary rocks distributed in different combinations, both vertically and laterally.

The hydric system is determined by the tropical climate with two well established seasons: the rainy season (May through October) and the dry season (November through April). Fluvial network, though extensive, is composed of rivers of short extension (especially in the mountain region) with deep valleys at

their birth place and predominant background erosion that is deposited in the mid and lower parts of the river course. Strong currents and floods are frequent during the rainy season.

Large- and middle-sized rockfalls are the commonest of landslides documented in Granma province territories. Some have produced displacements of hundreds of meters from their original site.

Geological susceptibility analysis

Previous researches, field studies, technical reports of landslides and the Geological Map of the Republic of Cuba were used to determine the geologic susceptibility indexes. According to these elements, the areas with a very high geological susceptibility are located in the municipalities of Rio Cauto, Bayamo, Cauto Cristo, Yara, Manzanillo, Campechuela, and also in areas of Jiguani and Bartolome Maso (see Fig. 1).
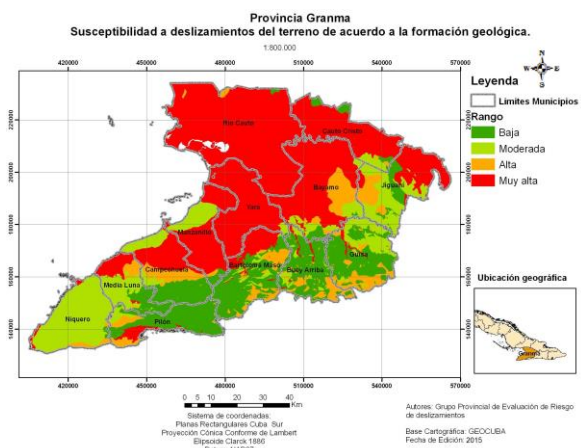

Fig. 1 Geological susceptibility

A chart for the landslide susceptibility evaluation of the geological units was adapted from the original classification by Mora Castro and Vahrson (1993), based on the physical and mechanical properties of the different rock groups.

Tectonic susceptibility analysis

Tectonic factors can influence ground mass alterations and changes particularly during landslides. The tectonic map of the region showed the complexity of the tectonic fault systems. Zones and locations at a distance of 100 meter or less from the fault were ranked as zones of very high tectonic susceptibility. High, medium, low and very low tectonic susceptibility zones are located between 200 and 500 meters away from the geological fault.

Rainfall susceptibility

Most of landslide occurrences are related to heavy and steady rainfall. The increase in the hydraulic pressure in clay and sand materials of the river banks combined with erosive processes like deforestation and underground water level rise can contribute to trigger landslides during the heavy rain.

The analysis of a 39-year series of monthly average rainfall of Granma province showed that the higher values of rainfall occur from June to October and the most affected zones are located in the mountain municipalities of Guisa, Buey Arriba and Bartolome Maso, where landslides are frequent.

The analysis of a 50-year series of maximum accumulated rainfall in 24 hours fluctuated between 100 and 600 mm. These values are considered significantly dangerous due to the negative effects produced on rock and soil properties. Jiguani, Guisa, Buey Arriba and Bartolome Maso received the heaviest day-long rainfall accumulation. However, the zones and municipalities with a lower average rainfall can be affected by landslides causing floods due to the drains coming from the higher parts of river basins.

Geomorphology susceptibility

A 1:25 000 digital land model aided to establish a 5-rank slope classification (see Fig. 2.) In general, this classification defines the susceptibility between very low to moderate. The steepest slopes are located in the southern part of the province comprising vast zones of Pilon, B. Maso, Buey Arriba, Guisa y Jiguani. In the northern part, in Cauto River plains, slopes fluctuate between $0°$ – $15°$; in this region, slopes above $15°$ are located in river banks where the landslide risk varies from moderate to high.
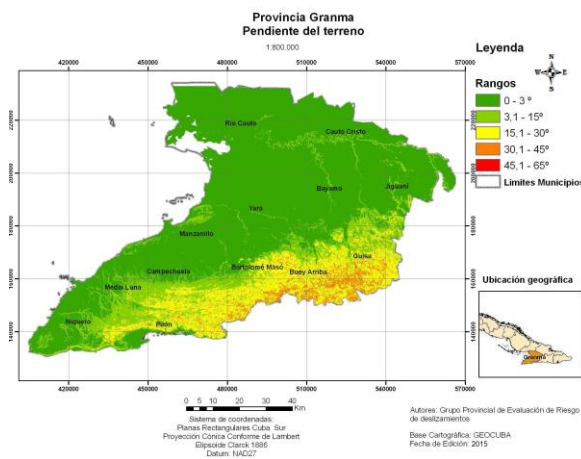

Fig. 2 Land slope in Granma province

Landslide hazard in Granma province

Landslide hazard was established by relating susceptibility factors. As a result, three categories were defined: low, medium and high hazard. The high hazard areas are located mostly in the southern part of the province, in the mountain municipalities of Guisa, Buey Arriba, Bartolome Maso and Pilon. This is due to more complex tectonic characteristics, higher slopes, higher values of rainfall that combine with heavily-weathered sedimentary rocks and with anthropic disrupting activities. The municipality of Rio Cauto also has a zone ranked as high risk; in this zone, located downstream of Cauto El Paso Dam, there is presence of loose soils made of clay, steep slopes and strong drain and infiltration of water coming from the upper parts of the basin. Medium and low hazard zones are distributed in the rest of the territory (see Fig. 3). Tab. 1 shows the areas comprised in each landslide hazard level.
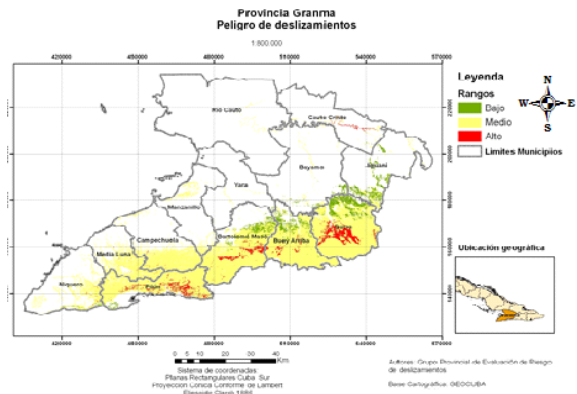

Fig. 3 Landslide hazard in Granma province

Table 1 Landslide hazard level by area

Hazard level	Area (km^2)
High	184,9
Medium	1504,4
Low	124,9

Landslide vulnerability calculation and assessment

Landslide vulnerability calculation took into account the information collected in each neighborhood through interviews, historical records and field trips. Different kinds of vulnerabilities were considered: social, physical, economic, ecologic, and by response capabilities, as can be seen in Tab. 2.

Although generally in Granma, landslide vulnerability values are low as a result of the rather scattered spatial and time variability, this doesn't imply that the causes could be slanted or ignored. On the

contrary, as research showed, the main vulnerabilities are linked to social issues like a low risk perception of the population. This fact can hinder the resilience capacities of organizations and the population of the risk zones. The physical vulnerabilities are mainly related to bad construction conditions of housing and infrastructure. Fig. 4 shows the vulnerability of Granma province.

Table 2 Rank of calculated vulnerability

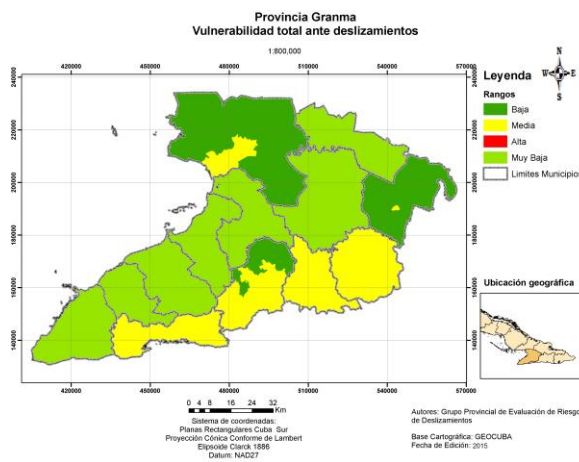| Vulnerability	Mean value	Level of vulnerability
Social	0,37	Medium
Physical	0,46	Medium
Economic	0,25	Low
Ecologic	0,13	Very low
By response capabilities	0,274	Very low

Fig. 4 Total vulnerability

Risk assessment

Knowing the risk can be the first step to the appropriate management. Landslide risk is the result of a combination of the dynamics of natural processes that interact with social and economic issues and the weakness or lack of cultural and legislative tools that educate and regulate the proper use of the land in the long term and prospective way.

In Granma province, risk values in areas with any kind of hazard are around a mean of 0.21. Besides, 90 % of the values range between 0.12 and 0.29. This indicates that landslide risk in Granma is low due to the absence of correlation between the spatial distribution of risk zones and other vulnerability indicators (see Fig. 5).

In the mountain zones where susceptibility elements combine with other catalyzing factors to favor

the occurrence of landslides, however, there is not much population or a significant amount of buildings and infrastructure. Economic activity is mostly extensive agriculture.

Fig. 5 Risk value distribution
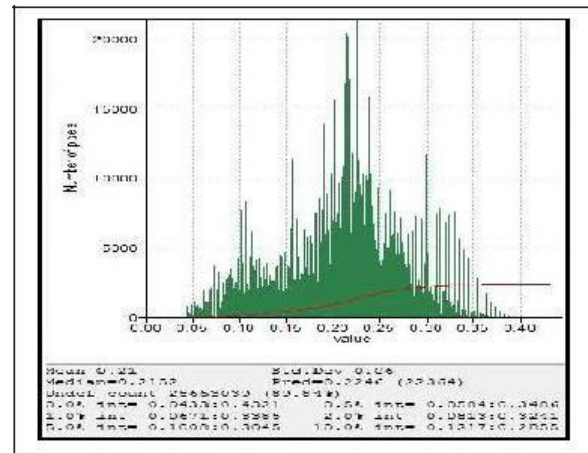
Three levels (high, medium, low) were defined for the spatial risk distribution. Low risk comprises values from 0 to 0.14, medium risk from 0.14 to 0.28 and high risk from 0.28 to 0.44, as shown in Fig. 6.
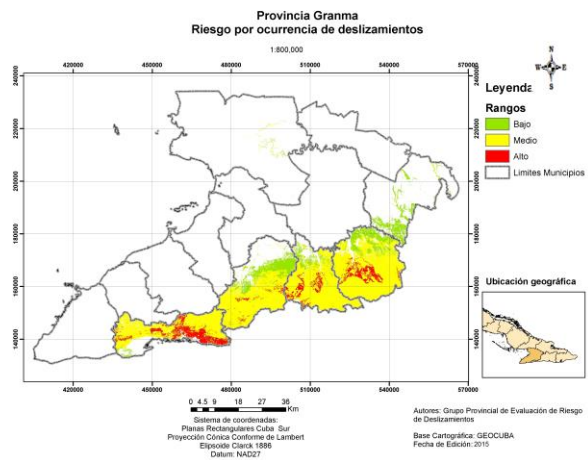

Fig. 6 Landslide risk in Granma province

Conclusions

1. The mountainous municipalities of the province (Jiguaní, Guisa, Buey Arriba, Bartolomé Masó, Pilón) present the greatest landslide hazard due to their high level of geological, lithological, and tectonic susceptibility, as well as the accumulated higher rainfall and the effect of human activities on natural resources.

2. Intense and prolonged rainfall is the main catalyzing factor for landslides in Granma. Seismic activity in the southern part of the province can also trigger rock and landslides.

3. River banks can be prone to the occurrence of landslides during floods as a consequence of drastic changes in river bed soil, particularly in Cauto River because of the population centers and infrastructure built nearby. It is recommendable to relocate the constructions within the hydro-regulating frame and promote appropriate reforestation with deep-root plants.

4. Roads and highways are the most affected infrastructure by landslides in Granma. Pilon could suffer the simultaneous disruption of the three main roads that connect the municipality with the rest of the country. Different neighborhoods of Guisa, Bartolome Maso and Buey Arriba can suffer cuts in terrestrial transport, communication and also electric power supply.

5. The areas with the higher hazard density are located in Pilon and Jiguani; these areas also have a low risk perception in the population, thus increasing social vulnerability.

6. Human settlements located in hazard zones, the bad technical conditions of housing infrastructure and a low risk perception are listed as the most vulnerable conditions in the municipalities of Bartolome Maso, Buey Arriba, Jiguani, Guisa, Pilon and Rio Cauto. These are also the main priorities for decision makers to consider in land planning programs and efforts to protect the population by reducing vulnerability.

Acknowledgments

References

AMA, 2009. Guía metodológica para el estudio de peligro, vulnerabilidad y riesgo por deslizamiento de terreno a nivel municipal. Agencia de Medio Ambiente. Ministerio de Ciencia, Tecnología y Medio Ambiente (CITMA). La Habana.

Mora Castro, S., & Vahrson, W. (1993). Tecnología Determinación apriori de la amenaza de deslizamiento utilizando indicadores morfodinámicos. ICE 3.

Eberto Hernández (✉)
National Center of Seismological Research, Department of Seismic Risk, Calle 17 % 4 y 6, Rept: Vista Alegre, Santiago de Cuba, Cuba
e-mail: eberto@citma.granma.inf.cu

Yanet Sam Pascual
Granma Province Territorial Office, Ministry of Science, Technology and Environment. Carretera Central Vial, Santiago de Cuba, Km 3 ½ Rept. Viviendas campesinas, Bayamo, Granma, Cuba

Threat Assessment in Juco Basin, Orosi, Paraiso, Cartago, Costa Rica

Luis Salazar-Mondragón

Abstract This paper is a result of a Master's thesis at the University of Costa Rica, based on the assessment of natural hazards affecting the Río Jucó, located 10 km south of El Paraiso city, Canton of Paraiso, Cartago, Costa Rica.

The study area is located near the physical boundary between two major mountain ranges of Costa Rica. This is a complex scenario because of the geological, geomorphological, tectonic and morpho-tectonic characteristics. The rocks are from Miocene to Pliocene age, covered by Quaternary materials. Other important features of the area are: The prolonged rainy season and extreme storms, which have events with a recurrence of 10 to 12 years. In the past 96 mm of rainfall in the district have caused landslides, fatalities, soil moisture exceeds 250 mm for 6 months a year. In addition, maximum seismic activity of 7 degrees' earthquakes has been observed, but it is estimated that due to the failures system that crosses the region, 9 degrees' earthquakes could generate.

In this research the Mora-Vahrson Method, was used and all the data was evaluated in a geographic information system, as a result a final map overlaying the local infrastructure was created, for an overview of the basin. This map can be used as a basis for risk management in Juco Basin.

Keywords geology, geomorphology, threats, faults, earthquakes, rains, modeling risk.

Introduction

The main objective of this research is to recognize, evaluate and model the potential threats that affect Juco River Basin, in order to understand the dynamics of the basin and thus collaborate with the preparation of the local population to face various natural events that could force them to leave the place.

To describe natural events that may affect the population should highlight the undeniable relationship of natural event and socio-cultural or anthropogenic environment, failure to take into account the relationship between these factors caused local disasters in the past, such as 7 fatalities (2002) in the Orosidistrict, damage to housing, sewage system, power lines, access roads, etc.

Location of the Study Area

The research area is located in the province of Cartago, in the Canton of Paradise, and belongs mainly to the district of Orosi (Fig. 1).

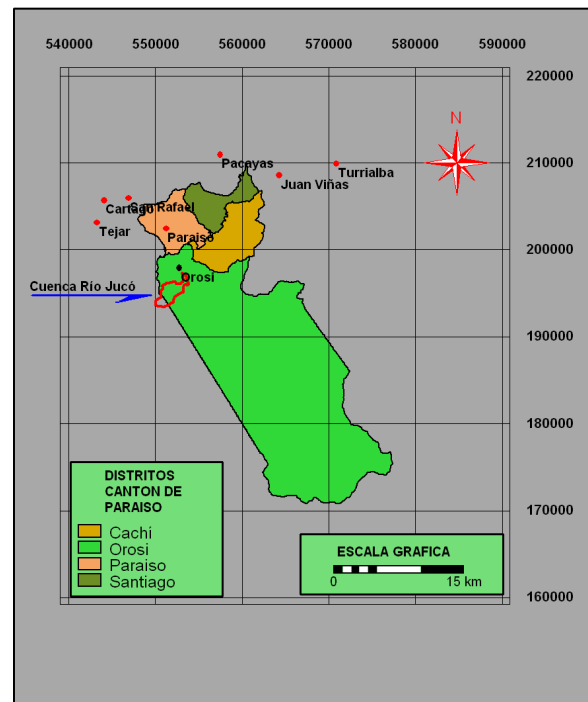Fig. 1 Political map of Paraiso

Morpho-tectonic structure of the area

The territory of Costa Rica is located on the Caribbean and Coco tectonic plates. Morphotectonic structures corresponds to an intra-arc (basin): Turrialba-Atirro and Orosi-Cachí. Thebasin originis related to West-East fault system, which was named in Astorga et al. (1989, 1991), as "Cuenca Central de CostaRica", that was

generated by a transtensive regime from Upper Eocene to Oligocene.

Geological Setting

In order to understand the complex relationships between geology-geomorphology and natural hazards that affect the area of Orosi, a brief description of the morphotectonic units of Costa Rica, the geology and sequence stratigraphy, as well as the tectonic structure of the area is done.

Stratigraphy

The base of the stratigraphy column iscomposed by a shallow marine series (Alvarado, 1982; Denyer & Arias, 1991; Astorga et al., 1989, 1991), deposited between the Oligocene and the Upper Miocene, which includes the following lithostratigraphic units: Pacacua, Peña Negra (Fig. 2a), Turrúcares, San Miguel and Coris (Fig. 2b).
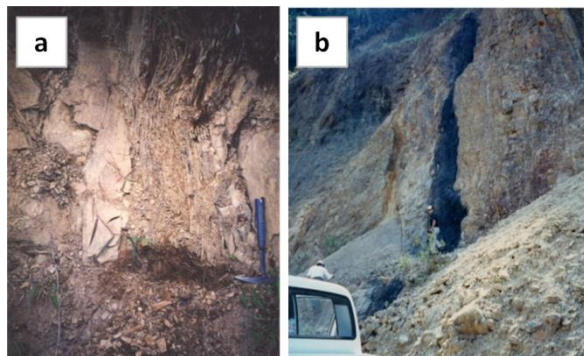

Fig. 2 a.Peña Negra Formation b. Coris Formation

Marine sedimentation is followed by deposition of a powerful volcanogenic series involving volcanic and volcanoclastic deposits (Aguacate Group), which together with intense plutonic activity (Comagmatic Group Talamanca sensu (Berrange & Wittaker (1977) and Training Monzonite - gabbro de Escazu, cf. Kussmaul & Sprechmann (1982) indicate the occurrence of a major magmatic event for the region in the Upper Miocene. The plutonismgeneratedmetasomatismo in the area, for example, CornubianitasEscazu and Orosi.A new volcanic activity in the Pleistocene - Holocene finally obstructs the Valley watershed of Candelaria, with continental environments from Upper Miocene (Astorga et al., 1989; 1991), the percentage differential increase in the basin led to wear and erosion and subsequent deposition of lahars, colluvium and alluvial (Fig. 3). The geological map is shown in Fig. 4.

This causes the final installation of the bridge isthmus of Central America, causing migration of spices from North and South America, as well as the closure of

the canal between the Caribbean Sea and the Pacific Ocean.
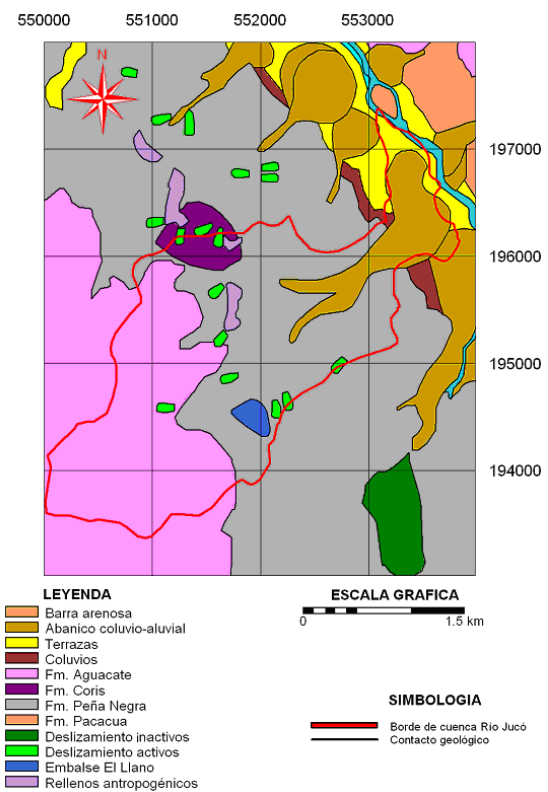

Fig. 3 Alluvial deposits

Fig. 4 Geological map of the Jucó River Basin

Regional Tectonic Structure

The Central Valley of Costa Rica is formed by two transtensive originbasins, characterized by systems horst and graben, tilted blocks, flower structures and normal faulting peripheral; and by folding in echelon

and systems failures synthetic and antithetic tear(Astorga et al., 1989; 1991).

South margin of the Central Valley East is affected by failures, from Paradise west to Salitralof Santa Ana, the outcrops lined thermal waters, with general direction E-W, make clear the presence of a fault system located at the foot of the Talamanca Mountain Range and its foothills; the seismic activity observed in the area support this hypothesis.

Each fault is characterized according to their morphology and its length is emphasized and related to historical earthquakes (Fig. 5).

Fig. 5 Tectonic faults of the East Central Valley of Costa Rica

Geomorphology

The geomorphological map shown in Fig. 6 was done using aerial photographs, relief maps (Fig. 7a) and maps of classified slopes (Fig. 7b). Through the integration of morphological and tectonic elements, an attempt to explain the origin and evolution of the landscape was done. A systematic morphological characterization was performed.

This area is characterized by denudational, fluvial and tectonic morphologies (see Fig.6). These include bonded morphologies south of the Juco River and alluvial fan areas, where the materials carried by the mass movements lie and which are highlighted. Fig. 8 shows images of the landslide that occurred in 2002.

Fig. 6 Geomorphological map of the Juco River Basin

Fig. 7 a. Relief map (shadow map) b. Slope map (classified)

Fig. 8 a Landslide that occurred in the Juco River Basin in 2002. b and c. Rupture zone (crown)

Soil moisture

The variables described previouslyare used by the Mora-Vahrson Method (Mora, 2002), as passive medium parametersanother used parameters is the soil moisture, themethod authors indicate that monthly rainfall of less 125 mm, do not influence too much, 250 minors if they cause problems and greater than 250 mm, are very important for the excessive rainfall and runoff generation. For this, the weather station influences the basin is located, using the polygon method and Thiessen. Based on the Mora-Vahrson Method, a value of 3 was assigned to the soil moisture.

Comprehensive evaluation of natural hazards

Burton et al. (1994) and OEA (1993) defines natural hazards as those elements of the physical environment or the environment that are harmful to man and are caused by forces outside it. This term is used in reference to all (especially seismic and volcanic), atmospheric, hydrological and geological phenomena or caused by fire which, because of here they occur, their severity and frequency may adversely affect humans, their structures or activities.

OEA (1993) supports this idea of the need for this type of assessment of hazards posing it as follows "studies that assess hazards provide information on the probable location and severity of dangerous natural phenomena and the likelihood of occurring in a given time and area".

Using the Mora-Vahrson Method (Mora, 2002) Method and collecting and evaluating the information of all the variables, through a system of geographic information (ILWISS-Holland), athreatmodel as a whole integratedmodel was performance, but it emphasized in sporadic and specific events that occur in the area and affected Juco residents.

The method is based on regional and easy to collect data in both databases as fieldwork: soil moisture (monthly rainfall, monthly extreme storms), earrings, geology and geomorphology, as passive elements; and as event triggers; extreme rainfall events with return periods of 100 years and maximum seismic intensities, estimated the bases of historical earthquake and / or seismic potential of each faults in the area.

Each variable that has a pre-characterization method can be obtained and total or partial results of its application should be done, for example depending whether the area is seismically active or not. It can characterize the area in the rainy season or during the dry season, although they can produce erroneous interpretations or undercutting.

This method, as the authors say is general in nature and does not replace soil studies or slopes, which should be treated in detail, at each site are available for an infrastructure project.

New variables for the implementation of the method

Soil moisture (Mora-Vahrson Method)

It was oobtained from meteorological stations, and is based on the amount of rainwater per month. If the amount of rainwater is<125 mm (v = 0) water deficit is assumed, if it is<250 moderate (V = 1 and if it is > 250 mm (V = 2) excess water and therefore, likelihood of rain to cause problems. In the study areas, this period of excess is observed from May to October. The method has several tables to classify this parameter to obtain a value of 3 for moisture.

The weather station influences, is verified using the method of Thiessen; described in Guevara & Cartaza (1991), Fig. 9.
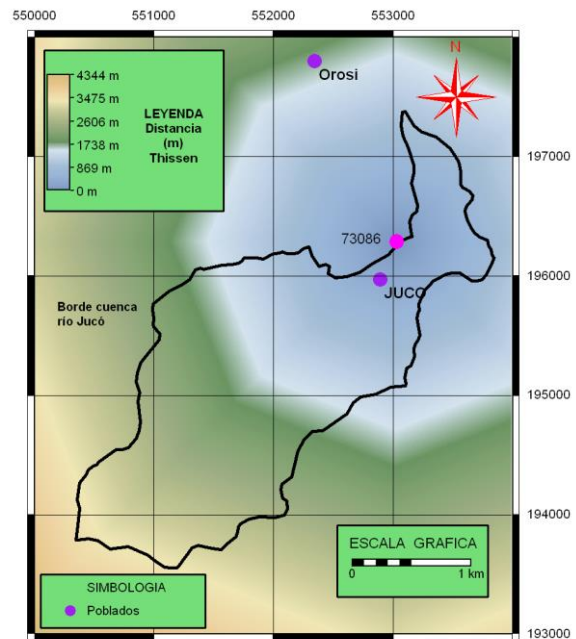

Fig. 9 Polygons of Thiessen

Components of the method

The method is based on specific landscape parameters called passive and triggering landslides or generators, which are described below.

Liability parameters: MVM (2002)

Liabilities parameters are typical to evaluate landscape, such as lithology (L), slope (P), morphologies (M) and

humidity (H). Those parameters have been described previously.

Landslide triggers

The landslide triggers are seismic intensity (I) and extreme rainfall 100-year return period (L) were postulated. The seismic intensity was previously evaluated. In terms of heavy rain, data for the storms of each year is available in the entire record of the Powerhouse station. Registration is 1971 - 2003. The end result is 196 mm, with 10.6% probability of occurrence every 9.4 years. By classifying this data, a value of 2 is assigned.

Algebra maps

The landslide susceptibility is determined using the following equation:

$$SD = (L + P + M + H) * (I + L) \qquad [1]$$

Through the use of the equation, all maps standardize the Geographic Information System ILWISS (ITC-Holland) and the algebra of maps is done, to achieve a qualitative final map. Fig. 10.
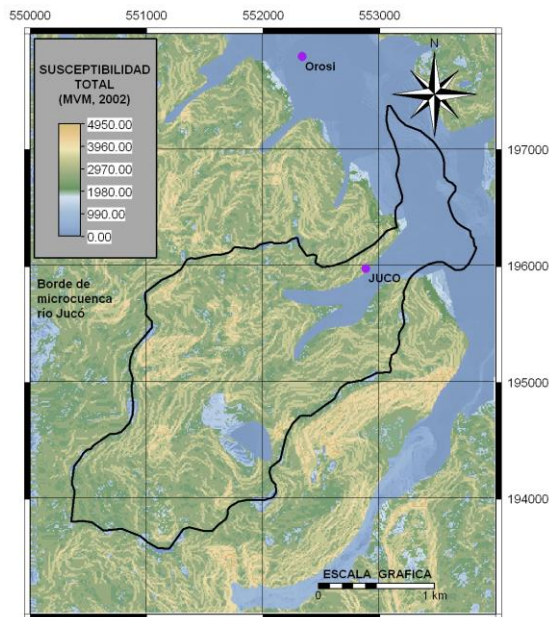

Fig. 10 Quantitative slip susceptibility map

Results and Discussion

The results of the algebra of maps (quantitative) is transformed to a qualitative map, it is able to be read and used by any user. For this research, six classes are

used The result is a quantitative map, with additional information on local infrastructure Fig. 11 and Fig. 12 show the detailed situation in the towns of Juco and Anita.
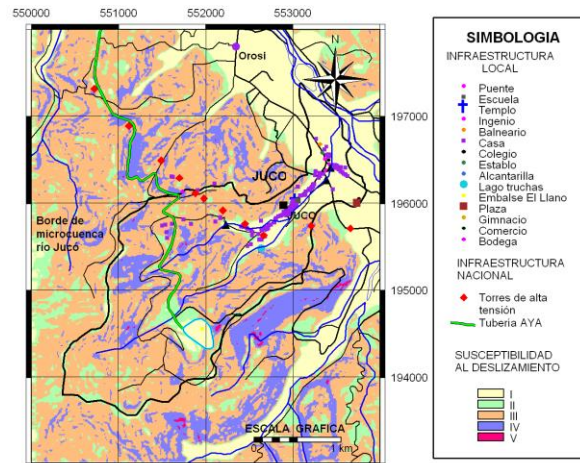

Fig. 11 Qualitative slip susceptibility map and local infrastructure

Practical Application

In the quantitative map the entire infrastructure of the basin overlap, in order to give a clear answer to the users of this research, expert criteria and knowledge of the geological history of the small valley of Juco river is modified very dangerous class, especially for its history of events as well as being a receiving basin materials slipped and fallen from the slopes around it (see Fig. 12).

Event of 2005

Fig. 11 show a detailed map of the Juco town sector, but with the 2005 event slip superimposed, from this map clearly should be observed the negative relationship between slip event and the infrastructure of the area.

From these maps, it can be seen that the area of JUCO and Anita (North) have steep slopes and the value of the total susceptibility (H) is high, the transition to the riverbeds are characterized by (H) Average and finally the riverbeds has a (H) low to very low. The houses are located in area H equal to the class II, called by Mora (2002) as low, however this area is prone to traffic flows rocks and mud during the events of landslides as in 2005 and previous events deposited in the valley.

Also the outline of the Metropolitan Aqueduct pipeline south of the basin has a middle to high susceptibility (see Fig. 12).
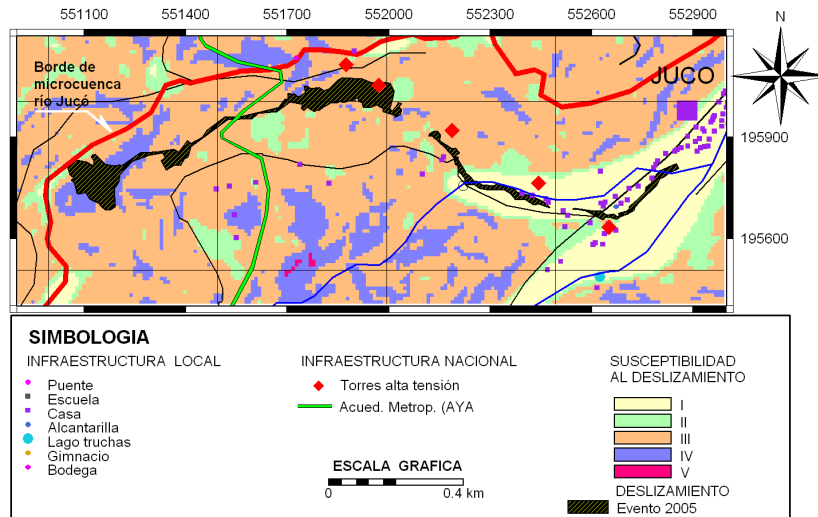
Fig. 12 The high tension towers that were affected during the 2005 event are located in areas with high susceptibility (H) equal to grade IV

References

Alvarado, M. E. (1982). Estudios sedimentológicos en la Formación Pacacua (Mioceno, CR). -185 págs. [Tesis Lic.].

Astorga, A., Fernández, J., Barboza, G., Campos L., Obando, J., Aguilar A., & Obando, L. (1989). Cuencas Sedimentarias de Costa Rica: Evolución Cretácico Superior Cenozoico y Potencial de Hidrocarburos (1989). Symposium of the Energy and Mineral potencial of the Central American – Caribean Region. Circumpacific Council: 23 p.

Astorga A., Fernández J., Barboza G., Campos L., Obando J., Aguilar A., & Obando L. (1991). Cuencas Sedimentarias de Costa Rica: Evolución Geodinámica y Potencial de Hidrocarburos. - Rev. Geol. Amér. Central. (13): 25 – 59.

Berrange, J., Wittaker, J. E. (1977). Reconnaisaance geology of the Tapantí Quadrangle, Talamanca, Cordillera, Costa Rica. 72 págs, Inst. of Geol. Sciences Overseas Division Report 37, Londres.

Burton, I., Kates, R. W., White, G.F. (1994) Evaluation of the Effects of the 1982/83 Floods on Economic and Social Development (New York: ECLAC, 1983). Catálogo de mapas de isosistas de temblores y terremotos de Costa Rica. Barquero, R. & Rojas, W. Red Sismológica Nacional RSN (ICE-UCR). San José [Inf. Interno].

Denyer P., Arias O. (1991). Estratigrafía de la Región Central de Costa Rica. Rev. Geol. Amer. Central, 12: 1-59.

Guevara, E., Cartaza, H. (1991). Hidrología: una introducción a la Ciencia Hidrológica Aplicada, 357 págs. Univ. Carabobo. Valencia. Venezuela.

Kussmaul, S., Sprechmann, P. (1982). Estratigrafía de Costa Rica (América Central), II Unidades Estratigráficas Igneas. Actas 5 to Congr. Latinoamericano. Geol., Buenos Aires, 1: 73- 79.

Mora, S., Vahrson, W. (1991). Determinación a priori de la Amenaza de Deslizamientos sobre grandes áreas, utilizando Indicadores Morfodinámicos. In Alzate, J. B. (ed) Memoria sobre el primer simposio internacional sobre sensores remotos, sistemas de información Geográfica (SIG), para estudios de Riesgos naturales, Bogotá, Colombia. 259 - 273.

OEA (1993) Manual Sobre el Manejo de Peligros Naturales en la Planificación para el Desarrollo Regional Integrado. http://www.oas.org/DSD/publications/Unit/oea65s/begin.htm

_____

Luis Guillermo Salazar (✉)

Universidad de Costa Rica, Escuela Centroamericana de Geología. Heredia: 1,5 km al norte de la Escuela del Palmar de Heredia, Distrito Los Ángeles del Cantón de San Rafael de Heredia.

e-mail: salazarm@geologia.ucr.ac.cr

Cuban methodology for landslide hazard, vulnerability and risk studies in Villa Clara province, Cuba

Francisco Viera, **Luis Pichardo**

Abstract Landslides are the most dangerous geological hazards, which produce biggest damages to the human activity. Cuba is not exempt from this problematic and it has many regions with favorable conditions for this phenomena.

Directive No.1 of 2010 Chairman of the National Defense Council, "For Disaster Reduction" instructs the Ministry of Science, Technology and Environment (CITMA) performing "Hazard, Vulnerability and Disaster Risk Studies" with the use of scientific potential of the country, which result an important tool for risk management.

At the present those studies are executing at national level, to approach this problematic. Hazard, Vulnerability and Risks studies, by multidisciplinary groups have been done with the advised of the Environment Agency (AMA) and the Cuban Geologic Survey (IGP) which is responsible for carrying out the landslides risks analyses.

The overall aim of the present research was the application of this methodology in the Villa Clara province that is to carry out Hazard, Vulnerability and Risks of landslides studies. The main objective of it was to identify, quantify and mapping the landslides susceptibility and hazard of the study area. On the other hand, the vulnerability was calculated too, for elements at risk and losses during event of landslides disasters, constituting an important instrument for risk management and government's decisions making tool to disasters prevention.

Keywords Landslides, vulnerability, methodology, risk, hazard.

Objectives

General

Identify and characterize the hazard, vulnerability and risk of landslide disasters in Villa Clara.

Specifics

- To zone and identify hazard areas, vulnerability and risk assessment according to different intensities.
- To make a plan of measures for disaster reduction at province, municipality and sector levels, for the prevention and mitigation of landslide hazard and disasters caused by them.
- To improve a territorial and urban planning in municipalities and the province, providing information to risk management for decision-making.

Methods and materials

Theoretical basis – methodology for landslides hazard assessing

Methodological guide about hazard, vulnerability and risk for landslides at the municipal level were used for the assessment of landslides hazards.

Susceptibility Scenarios Identification

Susceptibility Evaluation: Methodological variant applies to areas where the inventory of landslides does not exist or is minimal. It was used to evaluate and mapping the susceptible landslides occurrence in the studied area. Similar work has been conducted in other countries (see Varnes and IAEG, 1984; Carrara et al., 1991; Mora Castro and Vahrson, 1993, Dominican Republic, 2016).

Their analysis is based on the selection of a group of hazard indicators, which are evaluated by assigning weights to different variables in a hierarchical manner, thus the factors evaluated were heavy for determining susceptibility to landslides (eg. geology, geomorphometry, soils, land use, among others). These factors influence the stability of the slopes causing them to move from stable to unstable. Moreover, triggers factors induce the occurrence of slope movements (Fig. 1).

Map of heavy rains for a return period of 100 years, was used as a trigger factor (figure 2).

This case study was executed using partial evaluation multi-criteria using the tool provided by the GIS Integrated land and Water Information System (ILWIS); version 3.4Open.
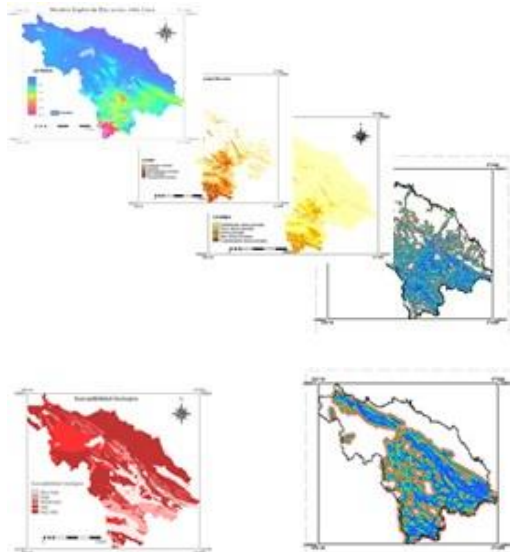

Fig. 1 Example of geomorphological and geological factor for susceptibility landslides map

Applying the following general equation:

$$Hazard = susceptibility\ factors * triggering\ factors \qquad [1]$$

Landslides hazard map
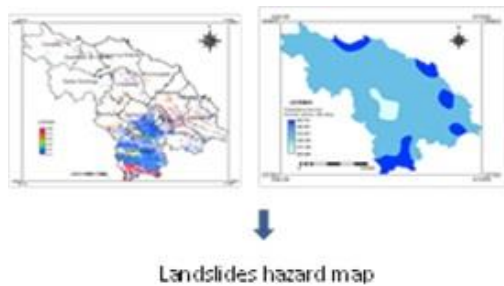
Fig.2 Triggering factor to obtain landslides hazard map.

After the estimated landslides susceptibility and hazard, the vulnerability estimation will be done.

A first analysis is necessary to determine what percent of the territory is affected by high (P_A), middle (P_Mo) and low (P_b) hazard. It is made crossing the map of the locations A_{CP} and the hazard map, obtaining the hazard density in each area. $Dens_P^i$

$$Dens_P^{\ i} = \frac{A(P_A) + A(P_M) + A(P_B)}{A_{CP}} \qquad [2]$$

It is considered essential before calculating the values of vulnerability, to recognize and study the socio-economic conditions of the municipality. Three elements must be considered: the natural factors, human factors and the relationship of both factors in the generation of landslides.

Finally, it is necessary to relate natural and human factors with landslides, either because they can be triggers or because they can be factors that affect them. For example, a very important road to the city runs through mountainous areas is being cultivated on slopes without due care soils are conducting major water leaks, etc. Analysis of these socio-economic conditions should draw conclusions for the estimation of vulnerability and final recommendations at the conclusion of the risk assessment. Using the following formula

$$R = P \cdot V \qquad [3]$$

Achieved results

In the province we have developed Hazard, Vulnerability and Disaster Risk landslide studies, in order to identify, quantify the hazards, vulnerability calculated for resources exposed and the estimated risk of losses in the event of Landslide disasters.

High hazard

The geographical distribution of the areas of High hazard correspond with the premountainous and hilly with steep slopes, with values between the 35° and 50° and areas of more steep slopes linked to tectonic and erosion escarpments, on the other hand the presence of lithological groups with weathering and cracked rocks, finally the effect of heavy rainfall occurring due to the orographic influence, that makes the most of the storm water discharge occurs on the slopes mountain.

Middle hazard

The medium landslide hazard in the province, has a wider distribution, but not for this reason represent high danger for the economy of the territories or losses to human life on a large scale, however it is necessary to refer to them to serve as analysis when planning future activities in these location. Most of these areas relates to hilly areas, with moderate to severe slopes and steep areas with varied geological composition, susceptible to a greater or lesser degree the development of gravitational processes; used mainly in agricultural activities.

Low hazard

The areal extent of the landslides low hazard covers large areas, but has no influence on the development of economic and social activities in the territories affected.

It is characterized by covering areas with moderate slope sand lithological conditions, for occurrence of gravitational movements, and erosive phenomena such as small gullies and dragging the alluvial-colluvial

deposits, because of rainfall incidence (Fig. 3) classified hazard map of Villa Clara province.

Fig. 3 Landslides classified Hazard map of Villa Clara. Note that the small southern part of the province has a high hazard, belonging to the Manicaragua municipality.

Vulnerability and risk analysis

The selection and evaluation of vulnerability indicators have been organized in a hierarchical manner as follow:

Social vulnerability

According to the diagnoses made there are 6085 people in the province in landslide hazard areas and many homes with some level of hazard.

Physical vulnerability

Many villages with the high number of houses in hazard zones are present in mountain areas, those villages are the following: Escambray, Condado Sur, Capiro – Santa Catalina, Sakenaf – Caracatey in the municipality of Santa Clara, Rancho Veloz in Corralillo, General Carrillo, Calabazar of Sagua in Encrucijada and Falcón in Placetas (Fig. 4)

Road vulnerability

There are some sections in areas at landslides risk on the roads and highways of mountain municipalities. Also they are reports of significant vulnerabilities related streets on steep slopes.

Economic vulnerability

Vulnerability on industrial economic objectives, arable areas, animals, etc. has been observed. The most vulnerable was the liquefied gas plant on Capiro hills in Santa Clara.

Responses capability vulnerability

This vulnerability was an indicator of the preparation of municipalities to respond in case of occurrence of

landslides. There a good preparation, hospitals, power supply and equipment for search and rescue.

Fig. 4 Santa Catalina west part of the Santa Clara city with low and middle landslides hazard

Total vulnerability

The total vulnerability is the result of the sum of all vulnerabilities. Our result reveals that all municipalities have low vulnerabilities, as can be showed in Fig. 5 and 6.

$$Vul_t = 0.46 \cdot Vul_{soc} + 0.26 \cdot Vul_{fis} + 0.16 \cdot Vul_{ecn} \qquad [4]$$
$$+ 0.09 \cdot Vul_{eco} + 0.04 \cdot Vul_{cap}$$

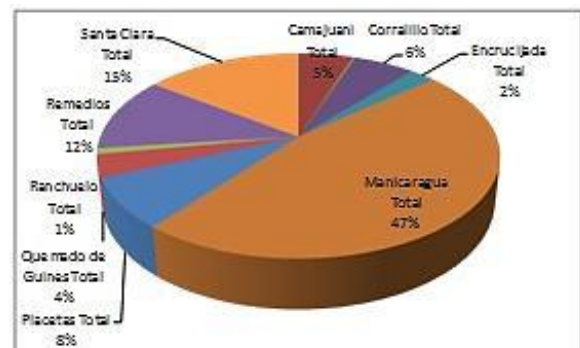Fig.5 Total vulnerability map of Villa Clara province

Fig.6 Graphic of total vulnerability in the municipalities

119

Risk estimation

The results show that the mountain municipalities are at higher risk of landslide disaster, for example Manicaragua, Jibacoa, Capiro and Caracatey villages.

Other municipalities with risk of landslides are Remedios and Camajuaní by the presence of chains of residual heights limestone origin.

Fig. 7 Risk map of Villa Clara province

Conclusions

The geology, geomorphology and soil conditions of the territory and the rain factor significantly affect the occurrence of landslides in the territories, mainly mountainous and foothill areas. The landslides hazard in Villa Clara, despite having a large surface area, does not represent great interest in the lower and middle areas, only the upper areas it is important.

Anthropogenic factor in hazard analysis, related to roads that cross mountain areas, disrupt and affect the longitudinal profile of the slopes, which create anthropic escarpments, making these prone sites landslide occurrence.

The presence of hydraulic works in mountain areas, are potential hazard factors, to the occurrences of breakdowns or failures operation to release large volumes of water down slope inducing the occurrence of these phenomena. This intensifies in period avenues, carrying large amounts of sediment and weakening the base of the slopes and thus causes the occurrence of landslides.

Suggestions for cycle of disaster reduction

Prevention

Publish and implement results of Hazard, Vulnerability and Risk of Landslides research, in order to incorporate findings and recommendations to plan for disaster reduction. In addition, performed training to managers and specialists related to hazard, vulnerability and risk of landslides identification.

Update on disaster reduction plans at each level, based on a survey in greater detail vulnerability in high-risk areas identified and planning material and financial resources required for disaster reduction.

Assess for the particular technical solutions aimed at protecting slopes with anti-erosion measures, designed to minimize slippage. Such as:

- Construction of gabions
- Control and protection Gully
- Reduction of angle slopes in scarps. Reforestation
- Terracing

Preparative

Orientate the people and entities on measures to be taken in hazard situations, in other to decrease the social vulnerability.

Perform activities of preparation and education of the population, with the aim of reducing the vulnerability of people, which maybe increased by the psychological impact of the disaster, especially in children, elderly and handicap peoples.

Response

Accelerate action collection and disposal of debris and existing solid waste in landslide hazard areas. Prioritize these actions in the municipalities of Manicaragua, Santa Clara, Remedios, Placetas and Camajuaní.

Building protections against landslides such as walls, gabions and terracing, along contour lines, among others. Prioritize these actions in the municipalities at risk.

Recovery

As conditions permit, the damage assessment and valuation, as well as the Environmental Impact Assessment are conducted, the latter is done by multidisciplinary teams trained in and according to the methodology established for this purpose.

- Assess damage, communicate and ensure the affected area to avoid increasing the damage area. Help victims in food, goods and in shelters.
- Collect debris affecting traffic especially more vulnerable road
- Do volunteer work to restore normalcy, help the sanitation and reconstruction where needed.
- Remove the debris, stones and accumulated soil and perform general cleaning.
- Perform the planting of crops are expected as soon given the conditions.
- If the condition permits, reconstruct the affected areas.
- Help the recovery of crops and other goods.

Acknowledgments

References

Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V. ,Reichenbach, P., 1991. GIS techniques and statistical models in evaluating landslide hazard. Earth surface processes and landforms 16, 427-445.

International Journal Geographical Information Science 18, 789-148.

Mora Castro, S. ,Vahrson, W.-G., 1993. Determinación "a priori" de la amenaza de deslizamientos utilizando indicadores morfodinámicos. Tecnologia ICE 3, 32-42.

Varnes, D.J., IAEG, 1984. Landslide Hazard Zonation: a review of principles and practice. UNESCO, Darantiere, Paris, 61 pp.

Francisco de la Caridad Viera Cepero

Environment Geology Department Vía blanca # 1002 e/ Línea de ferrocarril y Carretera Central. La Habana, Cuba.

e-mail: viera@igp.minem.cu

Luis Orlando Pichardo Moya

Environment and land use planning.CITMA Delegation at Villa Clara province.Candelaria #. 6 e/ Cuba y Colón. Santa Clara. Villa Clara.

e-mail: pichardo@dcitma.vcl.cu

Landslide risk assessment in the commune of Petit Goáve Republic of Haiti

Eberto Hernández, Luis Pichardo, Ida Pedroso, Darío Candebat, Nélan Sylvaince

Abstract In the present work a detailed study of the natural features in the areas of interest is done, delineating areas with greatest landslide hazard and factors that can catalyze these processes. We used the topographic data and data obtained through field trips. The relationships between different variables are performed using maps and databases.

The main result is the map of landslide risk for the commune of Petit Goáve, considering three hazard levels: high, medium and low. In addition, we provide a group of measures to be developed by all sectors of society. It will result in better forecast and risk management for decision making in economic, social and territorial matters, by authorities and the general public. A "Practical guide to landslide processes management", contextualizing the concepts, assessments and considerations to the study area, is presented.

Keywords Landslide, hazard, vulnerability, risk.

Introduction

Landslides are one of the processes that have caused more damage to the peoples of Central America and the Caribbean, have claimed thousands of lives, caused damage or destruction of ecosystems and engineering works, changes in geomorphology and landscape, psychological disorders, material damage, etc. However, few people are aware of these facts and their impact is easily forgotten over time, that is why is so important to look for alternatives to avoid or reduce such damage. To get knowledge about the laws and physical conditions for their genesis, its spatial distribution and expected impact, is the first action to be developed by people, exposed communities, local and national governments, with the aim of a proper management.

The mountainous regions of Haiti are very susceptible to landslides processes due to the presence of some of the most important conditions for its occurrence, such as topography, seismic activity, weathering processes, intense and prolonged rains in addition to the effects of human activities.

We have considered three levels of landslide hazard: low, medium and high for each one of the twelve communal sections in which the commune of Pettit Goaves is divided. In order to set the category of hazard we characterized passive factors or factors permanently present in each area as well as active or catalysts factors with potentiality to triggering these processes. The assessment of the levels of vulnerability in the section community 12 éme de Fouques was analyzed considering the physical, natural, social and economic elements. Results are presented in different tables and maps. A set of recommendations, that will allow at the short-, medium- and long-term to increase levels of resilience of the residents to this kind of process, is identified.

Landslides in the commune Petit Goáve had have a local effect, with little impact on the physical, natural, social and economic elements. Its occurrence could have a much greater negative impact if not properly treated, considering their potential impact, based on the land use planning as a guiding element and the progressive reduction of vulnerability.

Materials and methods

The study of the landslide risk in the commune Petit Goáve was conducted based on the "Methodological Guidelines for the Study of Landslide Hazard, Vulnerability and Risk at the Municipal Level", issued by the Environmental Agency (AMA) of the Ministry of Science, Technology and Environment of Cuba CITMA, on April 2009. (AMA, 2009)

It began with the identification and preparation of Haitian collaborators who would participate in the work, the explanation of the methodology used and its scope. Another step consisted in the study and analysis of the existing cartographic information that would allow the evaluation of different variables for hazard identification in twelve communal sections, specifying

the vulnerability study for community section 12 éme des Fouques.

Field trips were conducted in areas of the communal sections 12 and six that have been affected by landslides to find out the natural and anthropogenic conditions that give rise to the generation of these processes in each of the areas. The characteristics and types of landslides presented were evaluated.

Analysis and processing of existing information was evaluated with calculation programs and GIS. In the various communal sections, susceptibility levels corresponding to the geological, lithological, tectonic, land use, seismicity, conditions were defined; then the hazard was determined. The analysis of individual vulnerabilities: social, physical, economic, ecological and response capacity to the communal section 12, was done based on the information contained in databases and cabinet work. The landslide risk in the region was determined considering the areas with some hazard category and some level of vulnerability.

Objective

1. To assess the landslide risk to which Petit Goáve commune, in Haiti Republic, is exposed.
2. Provide theoretical and practical training to national working groups for the implementation of the methodology in other regions of the country with landslide hazard.

Physical and geographical characteristics

The Petit Goave commune is located southwest of Haiti in the Quest department, it has a population of 176 000 inhabitants in twelve communal sections, scattered in an area of 381.37 km².

Most of the territory is represented by mountainous areas with elevations reaching 1 200 m high, among which are small valleys. The largest settlements are located to the north and northwest portion of the commune along the coast length.

Geology

Lithologically the commune is represented in the northern part by deposits of sand and limestone; southeastward a large body of hard limestone rocks is located with embedded sandstones and deposits of magmatic rocks. Magmatic rocks are also found in the center and west of the commune, there are sequences of Cretaceous rocks composed of volcanogenic rocks fragmentary mixed with other of andesitic basalt composition and others. Correlations between these

sequences and combinations are highly variable alternating both vertically and horizontally; transitions between them are sometimes sudden and other gradual, in many cases it is practically impossible to establish boundaries between them. The most abundant rocks are: agglomerated tuffs, lavas and agglomerated lavas of andesitic, andesidacitic and dacitic, rarely rhyolitic, rhyodacitic and basaltic composition. Andesitic and andesitic basaltic tuffs, lavas and subordinated sedimentary rocks are found at the top. Tuff composition vary from medium to acidic calcareous rocks (limestone) are intercalated with these rocks. In addition, associated with this complex volcanogenic - sedimentary are hypabyssal bodies and dykes of varying composition. Extending with an approximate direction from east to west are found large deposits of alluvial materials resulting from erosion developed in the highest parts.

Tectonic features present in the study area show the evolutionary uniqueness of this area, limiting the lithological bodies with two sets of fundamental faults, extending in the direction E-W and another system of sub vertical faults with a NW - SE predominant direction. There are other fault systems with less representation associated with these, which shows the stresses the entire area is subjected because its geodynamic position, as well as tectonic events that have been developed at the regional level and proximity to structures or fault systems of major importance, fig. 1.

Fig.1. Tectonic map of the Petit Goáve commune

Results and discussion

For landslide hazard analysis, in the territory, geological, hydrological, terrain slopes and tectonics susceptibility was assessed. Heavy or prolonged rainfall and seismic events were considered as trigger factors.

Geological susceptibility

The geological susceptibility factors was established based on the information contained in the geological map of the Republic of Haiti, by identifying different lithologic sequences and their corresponding level of susceptibility to landslides. It was established that areas with very high susceptibility are in the center of the commune, extending in an E – W approximate direction, represented by deposits of alluvial materials, detritus rock with low values of shear stresses. Sandstones sequences found in the southern portion are highly susceptible. Limestones altered by weathering processes extending in a band with SE - NW direction, are of moderate susceptibility. Sequences with low susceptibility are found in the central portion formed by sedimentary volcanogenic rocks, tuffs with intense erosive processes on the surface. Across the north and south center are found the most stable sequences of hard limestone which are rated of very low susceptibility. The different levels of susceptibility assigned to each lithology are shown in fig. 2. It is important to consider that the effect of human activities in all areas has altered the natural conditions, increasing the chances of landslides or other potentially dangerous processes to occur.

A chart was used for the classification of geological units according to their landslide susceptibility, Modified from (Mora Castro S and Vahrson W 1993), establishing different lithologic groups according to their physical - mechanical properties.

Landslide susceptibility due to fault distance

Landslide susceptibility considering the distance to the tectonic fault as a factor that cause ground disturbance and trigger landslide processes was determined thanks to the study and analysis of the tectonic map of the region. The hazard areas were identified based on the distance to fault, defining three areas as shown in Tab. 1.

Susceptibility by distance to the river network

The existing river network in the territory is particularly dense in mountainous areas, with rivers and streams mostly intermittent. Those with permanent currents are of low discharges for most of the year, have V-shaped valleys and short courses. In flat areas the rivers have wider riverbeds, with large areas of sediment accumulation, margin erosion, with intense processes of siltation is predominant in them.

Three levels of susceptibility (low, medium and high) were established, depending on the distance to rivers and streams (100, 250 and 350 m, respectively). The areas located at a distance greater than 350 meters from any river channel are not influenced by this indicator and therefore its value in the analysis is zero,

while those located at a distance lower or equal to 100 m have the greatest influence. Those were rated with a higher susceptibility factor.
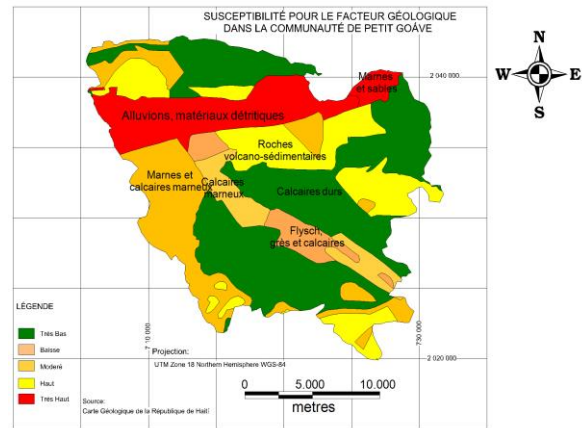

Fig.2 Landslide geologic susceptibility

Table 1 Landslide hazard by fault distance

Hazard level	Distance (m)
High	500
Medium	1 500
Low	2 500

Geomorphological susceptibility

The study of geomorphological characteristics of a region is one of the most important aspects for landslide analysis.

For evaluating this factor the digital terrain model (M.D.T.) was used. Five slope ranges were established with corresponding susceptibility values. Areas with slopes greater than 66.76° are distributed across the S and SE part of the commune and on the margins of most rivers, being the most susceptible.

It is important to consider that natural slopes are greatly altered throughout the region due to weathering processes catalyzed by human activity, within them, the extraction of construction materials, farming and roads and trails are activities that alter the natural geomorphology of the area.

Landslide hazard assessment

From the analysis of natural conditions described above, we found that the mountainous areas of the Petit Goáve commune have the greatest landslide hazard; these areas are present in all communal sections. Hazard is high where tectonic features are more complex i.e. steep and unstable slopes, soils and fractured rocks altered by weathering processes. In these areas, erosion and human activity act with

singular force. The hazard is also high on the margins of rivers where clay soils are found with little internal cohesion and there are steep gradients caused by bed erosion during periods of heavy floods, also in areas where water infiltration reaches out to the lower horizons, with the consequent change of the physical properties of soils and rocks. Areas with different levels of hazard are shown in fig. 3.
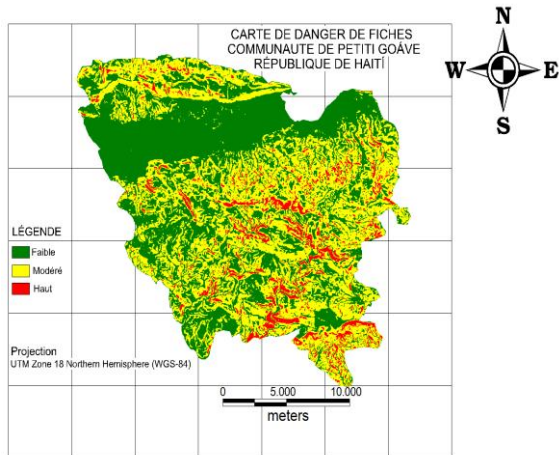

Fig. 3 Landslide hazard in Petit Goáve commune

The total area corresponding to different hazard levels is shown in Tab. 2.

Table 2 Area extension by hazard level in Petit Goáve commune

Hazard level	Área (Km^2)
High	26,74
Medium	169
Low	184,5

Vulnerability assessment

The determination of each of the vulnerabilities studied (physical, social, economic, ecological, for response capacity and total) was based on information provided by the Petit Goáve civil protection organization. The values were validated on field trips, research work and databases provided by the Ministry of Environment. Vulnerability was valued in the range from 0 to 1; zero for areas without vulnerability and one for areas with maximum vulnerability. Vulnerability values used for classification are shown in Tab 3.

All calculated vulnerability values correspond to the 12 éme des Fouque communal section, because it has been the most affected by landslides and other natural hazards. It was also used as a case study to facilitate the comprehension of the methodology to national working groups.

Total vulnerability by landslides (V_{ult}) is defined by the sum of each of the vulnerabilities discussed in section.

Vulnerabilities, determined for the communal section, show significantly high values. The fact that landslides have a local expression and are conditioned mainly by anthropogenic processes, highly variable in space and time, makes it necessary to pay attention to all and each vulnerability in order to promote a better resilience response of the State and private sector organizations, especially for those based in areas with medium and high hazard.

Table 3 Values adopted for vulnerability level classification

Vulnerability level	Vulnerability value
High	Larger than 0,51
Medium	0,26 − 0,50
Low	0 − 0,25

Vulnerabilities are listed as follows (in decreasing order of importance): response capacity, physical, economic, social and ecological vulnerabilities. This indicates the urgent need for establishing a management program throughout the community with the participation of the population. The behavior of different vulnerabilities is shown in Fig. 4.
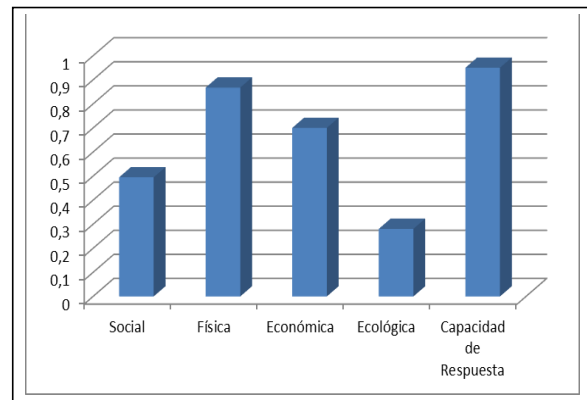
Fig. 4 Behavior of the study variables in the communal section 12.

A low hazard perception, the insufficient response capacity of institutions, the precariousness of housing stock, especially in rural areas, and the economic elements, are the highest priorities for achieving landslide risk reduction in the 12 éme des Fulk section.

Landslide risk assessment

As explained above, the risk is determined by the relationship between hazard and vulnerability. Even if

these two factors are usually separated, establishing an apparent autonomy, it is impossible the existence of hazard without the presence of vulnerability and vice versa. If there is not a predisposition to suffer damage when encountering a particular physical event, no hazard exists, just a natural, social or technological event without impact on society.

Therefore for calculating the landslide risk values, hazard and total vulnerability were associated. The risk values of section 12 were obtained qualitatively.

The association of present hazard and total vulnerability, in the communal section 12, results in predominantly medium landslide risk, being high in areas where the risk is high, totaling a spatial extension of 2,46 km².

Among the elements that increase risk levels in the communal section 12 are: poor soil quality in most of its areas (this factor is increased by the intensity and speed of acting climatic elements), deforestation, little conservative agricultural practices, the extraction of construction materials, the creation of unstable artificial slopes, the existence of a housing stock of bad constructions placed in hazardous areas, the poor hazard perception and low coverage of the health system. This points out to the need to work in a multitasking and multidisciplinary way to reduce the vulnerability levels present in the territory.

Recommendations for each phase of the disaster reduction cycle

Risk management has been considered in many cases as the basis of the development of society; its materialization involves hazard assessment and knowledge of vulnerabilities in each geographical area, work and economic activities as well as in each technological process. It considers the possibility of managing hazard uncertainty in a defined geographical area and time. Based on this a program of recommendations was elaborated for each of the phases of disaster reduction to be carried out in the communal section 12. Its aim is to ensure that actions should be implemented in optimum conditions of security for both infrastructure and population and those measures could be deployed during a real disaster situation.

Preventive phase

This phase comprises a set of measures to be implemented from the moment of planning for economic and social assimilation of the territory, is the most important phase to achieve a safe development from all points of view, should be implemented administrative, legal, social, sectoral actions in which all sectors of society, public and private get involved. The proposed measures are:

1. Define areas with medium and high hazard, as areas with limitations for constructions and little conservative agricultural practices, these areas should be a priority to take actions to reduce vulnerability.
2. Incorporate landslide risk management in all programs and projects carried out in the communal section.
3. Develop and implement training and preparation programs for the population of all social sectors.
4. Ensure stocks of medicines, food and other materials necessary to immediately face disaster situations.
5. Define alternative routes for accessing areas that might get isolated, this would ensure disaster management during the response phase.
6. Train and prepare members of civil protection bodies in topics that help understanding and coping with landslides.
7. Train and prepare the medical and paramedical personnel, from the professional and psychological point of view, to work in disaster situations

Response phase

1. After the occurrence of a landslide assess and determine as quickly as possible the technical condition of essential facilities to ensure the provision and supply of health services, water, electricity, foods, communications, radio and television signal, etc.
2. Evacuate population and resources from areas with landslides, fires, pollution, hazards.
3. Establish communication pathways affected with priority to essential facilities (hospitals, shelters for evacuees, food processing centers, etc.) and management centers.
4. Strengthen the check out and monitoring regarding the observance of sanitary, health and hygiene measures at the premises designated as shelters and centers for food processing. Similarly, proceed to the strengthening of phyto-sanitary and epizootiology surveillance and of the measures for medical, veterinary and phytosanitary securing in these areas.

Recovery phase

1. Establish priorities for the restoration of affected services and production activities, water supply, food processing and distribution to evacuees and victims, medical care and electricity supply.
2. Determine damage assessment, including environmental impact assessment, by the multidisciplinary teams created and trained for the purpose.
3. The construction and restoration of buildings, installations of all kinds and infrastructure being careful not to rebuild or create new vulnerabilities.

4. To clean and recover affected areas, take actions to repair or demolish affected buildings and facilities, using specialized forces and resources.

References

AMA (2009) Guía metodológica para el estudio de peligro, vulnerabilidad y riesgo por deslizamiento de terreno a nivel municipal. Agencia de Medio Ambiente. Ministerio de Ciencia, Tecnología y Medio Ambiente (CITMA), Habana.

Eberto Luis Hernandez Suros (✉)
National Center of Seismological Research. Department of Seismic Risk. Calle: 17 % 4 y 6, Rept: Vista Alegre, Santiago de Cuba, Cuba.
e- mail: eberto@citma.granma.inf.cu

Luis Orlando Pichardo Moya
Environment and land use planning. CITMA Delegation at Villa Clara province. Candelaria #. 6 e/Cuba y Colón. Santa Clara. Villa Clara.
E-mail: pichardo@dcitma.vcl.cu

Ida Inés Pedroso Herrera
Environment Agency (AMA).
E-mail: ida@ama.cu

Dario Candebat Sanchez
Department of Seismic Risk. National Center of Seismological Research. Calle: 17 % 4 y 6, Rept: Vista Alegre, Santiago de Cuba, Cuba.
E-mail: dario@cenais.cu

Nélan Sylvaince
Environment Ministry. Port Prince. Republic of Haiti.
E-mail: dr.nelan08@yahoo.es

The role of climate change on slope instability of the Central Andes during the last decades

Stella M. Moreiras, Iván Vergara

Abstract The main concern of this paper is to analyse how climate change is affecting slope instability in Central Andes (32º S). The focus is to elucidate which main mechanisms are promoting landslide activity in this mountain environment involving the highest peak of America. Climate change may promote landslides in many ways intensifying precipitations, shifting temperatures, increasing adverse effect of ENSO phenomenon among others. Unknown this fact coupled with poorly planned developments and population growth can drastically increase landslide-associated casualties, especially in Andean communities, where pressure on land resources exists.

Keywords landslides, climate variability, triggering mechanism, economic impacts

Introduction

The influence of climate change in slope instability has been referred worldly in the main mountain ranges as the Alps and the Himalayas; still it has not been properly evaluated in the Central Andes. Global warming, climbing of the zero degree isotherm, degradation of permafrost and above average rainfalls associated with current climate variability promote the occurrence of landslides in the broad sense. Which of these mechanisms are certainly forcing landslides in Central Andes is ignored as well as feeding mechanisms among them. For evaluating the coupled system climate change–landslides (CCL) we considered those events occurred along the Mendoza River valley during last decades.

Study area

At the latitude of study area, Central Andes are comprised by three different geological provinces in argentine territory: Main Cordillera, Frontal Cordillera and Precordillera, from west to east. The Main Cordillera, comprising highest peak such as Aconcagua, involves Cretaceous- Jurassic marine rocks and vulcanites. Permo-Triassic volcanic Choiyoi Group outcrops mainly in the Frontal Cordillera; while Paleozoic sedimentary rocks with Permian intrusives do in Precordillera range (Fig. 1). Even though, lithology and slope are main conditioning factors for landslide distribution, this link is not analyzed in this work.

An arid climate and high topography with a maximum peak of Aconcagua Mount 6,958 masl characterized this portion of Central Andes. However both parameters vary gradually longitudinal wise from west to east (Fig. 1). Topography of this mountain landscape decreases toward the eastern piedmont (700 m a.sl.) forcing precipitation behavior. While solid winter precipitation predominates in highest mountain areas, summer rainfall does in lower areas and valleys. Likewise, an average annual precipitation of 500 mm is measured in highest areas of the Andes diminishing until 200 mm in the Andes foothill where Mendoza city is established (see diagram on Fig 1).

Triggering mechanisms

A daily precipitation range of 6.5 to 12.9 mm has been determined for landsliding in middle elevations (1500 to 2700 m asl.) during South Hemisphere summer (Dec-Feb) when we use records of meteorological stations not farer than 10 km of affected locations. This low threshold could be partially explained by the reduced amount of annual precipitation (200 mm) and the abundant generation of debris in these mountain areas. Errors in determination could have resulted from impossibility of determine intensity of rainfall. Mountain meteorological stations measure 24 hours precipitation. Likewise, meteorological records are scarce in the region limiting a precise determination of the threshold values. Meteorological stations are located along the Mendoza river valley, but no data exists for remote highest areas where events have been reported as well.

Antecedent precipitation plays an important role. Mean values of accumulated rainfall reach to 28 mm whether a 5-day precipitation window previous to the

landslide events is taken in account. In fact, 50 debris flows induced by rainfall during 2013 rainfall were associated to 29 days of weather anomalies in the Central Andes (Moreiras and Sepúlveda, 2013).

Landslides are also associated to snowfall precipitation taking place during South Hemisphere winter in higher topography (See Fig 1). Greater slope instability is recorded in the following spring period associated to snow thawing (Moreiras et al., 2012). Herein, landslide triggering factors (rain /snow thawing) and temporal distribution (summer/spring) varies in the different ranges of the Argentinean Central Andes. Whereas debris flows and rockfall induced by rainfall are clustered in summer periods (December to February) along the valleys and lowest areas; debris flows and debris avalanches are consequence of snowmelt in highest areas of Main and Frontal cordilleras during spring (September-November).

Material and methods

Landslide records occurred along the Mendoza River valley (32ºS) during the last 50 years, were gathered. We analysed temporal and spatial distribution of historical events to elucidate any change in frequency. Available meteorological data (precipitation and temperatures) of local stations were analysed to determine threshold precipitation values (Tab 1). For correlation we used those records of meteorological station located not farer than 10 km. Radiosonde records taken in Santiago, Chile were used to detect changes in the altitude of the zero isotherm.

Many field sessions were carried out during last years to evaluate activity of landslides. We measured landslide parameters such as channel width, volume of deposits, banked deposits in bends along channel to estimate velocities, rate of streamflow and dimensions of cross sections. As well maximum size of mobilized boulders,
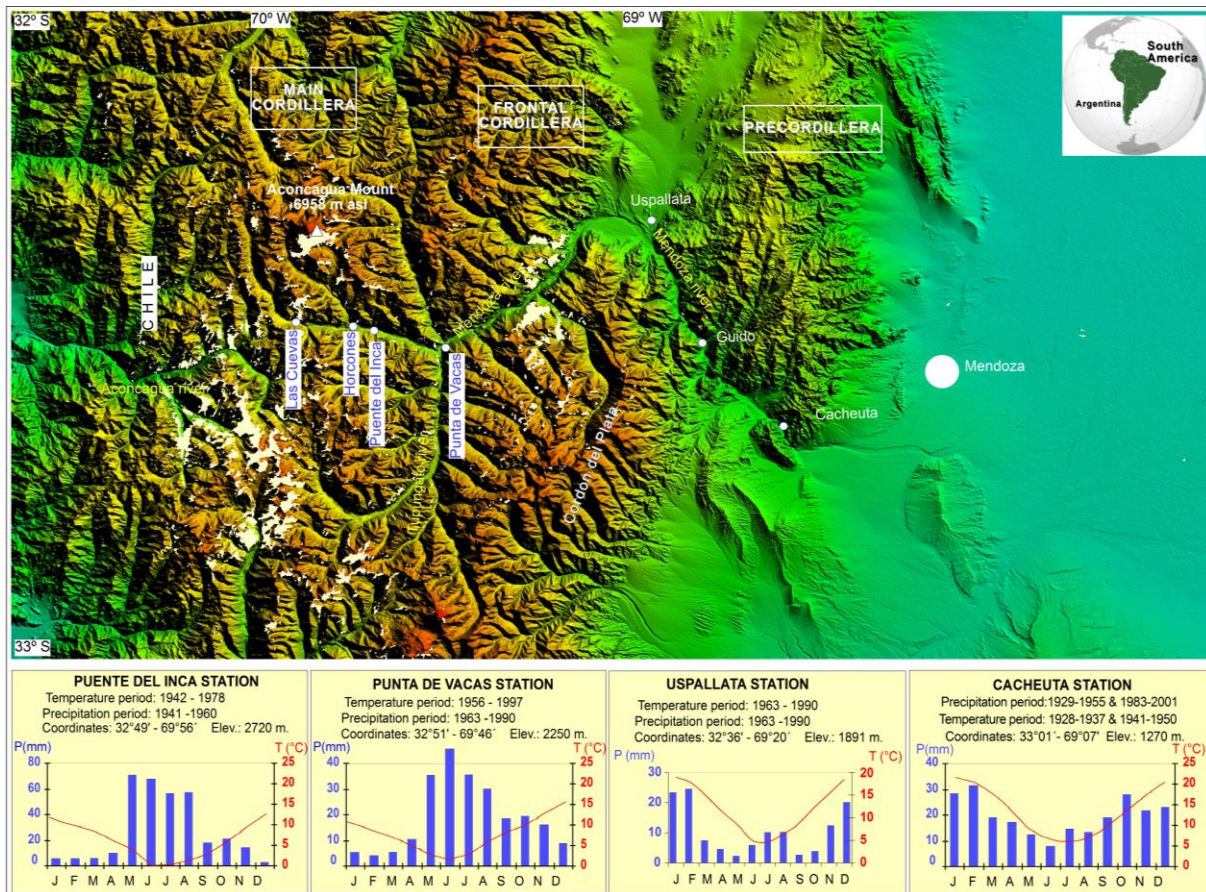

Fig.1: Shutter Radar Topography of the study area showing main geological provinces and villages located along the Mendoza River valley. Charts show mean annual precipitation and mean annual temperatures recorded in local meteorological stations in the measuring period indicated in each diagram.

matrix content of the deposits and sedimentary structures as lamination or imbrication were observed in the field.

Tab 1 Meteorological gauges analysed in this study. (SMN: Servicio Meteorológico Nacional, SRH: Secretaria Recursos Hídricos, EVARSA, AyE: Agua y Energía, DGI: Dirección Nacional de Irrigación).

Gauge	Lat (S)	Long (W)	Elev (m)	Prec record	Data source
Guido	32º 51'	69º 16'	1550	1957-2007	A y E - Evarsa
Uspallata	32º 36'	69º 21'	1880	1963 - 2007	SMN
Polvaredas	32º 47'	69º 39'	2350	1992 - 1997	Evarsa
				1983 - 2000	SRH
Punta de Vacas	32º 51'	69º 46'	2400	1955 - 1997	A y E - Evarsa
				1955 - 2005	SRH
Puente del Inca	32º 49'	69º 55'	2720	1941 - 1976	SMN
Horcones				2001 - 2006	DGI
Cristo Redentor	32º 83´	70º 08´	3829	1967 - 1984	SMN
Puente del Inca	32º 49'	69º 55'	2720	1941-1976	SMN

Shifting slope behaviour

Landslides as many other natural hazards are being modified by climate change. Main changes observed in landslides of the Central Andes are frequency-intensity relation (Moreiras, 2005; 2006), spatial distribution, altitudinal migration, and ambiguous/complex causes.

Frequency

Plot of temporal distribution of landslides occurred along Mendoza River valley show a markedly arise (Fig.2). In lower areas, landslides triggered by summer rainstorms have been triplicated during the last 50 years. Moreover, higher areas associated to permafrost degradation have become to be more prone to slope instability.

Intensity of landslides

Material mobilized by landslides has been increasing during last decade as well as their violence and associated impacts. Extraordinary occurrence of at least 55 landslide events triggered by convective rainstorms during a short period of 29 days in Mendoza river valley caused repeated trouble for traffic along the international road connecting Mendoza with Santiago, Chile (Fig. 3). A first set of events happened on 13th January, 2013 spatially gathered in Guido locality (1550 masl) located 12 km downstream Uspallata. Fifteen debris flows were generated in Guido where a granitic intrusive crops out, known for historical rock fall processes. On 7th February another cluster of debris flows was triggered by rainstorms in a western sector located 5 to 15 km from Uspallata village. During this month, mean monthly precipitation exceeded in 20 mm the historical mean value (40 mm) for this month.

During last summer (December 2015-February 2016), 23 danger debris flows impacted on the study area generating important economic losses to the region. A bridge of the International Road to Chile was taken away by a debris flow coming from the Soltera gully after an intensive rainfall.

Climbing collapses

Topography limits types of geomorphological processes. While rockfall and debris flows triggered by summer rainstorms are predominant in lower areas of the Andes; snowfall are frequent in higher steep zones. However, this topographic control is changing because of imminent current warming scenario. Then, tracks of snow avalanches are currently affected by debris flows.

The propagation of this new debris flow channels is driving a denser landslide spatial distribution in the higher areas.

Complexity on causes

The Godzilla El Niño events (December 2015-February 2016) drives 23 debris flows in the Mendoza River valley. However, triggering mechanisms were completely different for the three separated clusters of events. While daily debris flows were generated in December 2015 by the thawing of ice glacier in the Salada and Negro basins; 20 events were lately generated on 23th January 2016 by a daily intensive precipitation. However the most damaging events occurred when a damming landslide lake collapsed as consequence of 30 mm-rainfall being the highest precipitation recorded in Uspallata station since 1984.

Analysis of zero isotherm

Although global warming is widely accepted among the international research community, we analyzed the evolution of the zero isotherm in the last decades. We compared the elevation of zero isotherm based on geo-
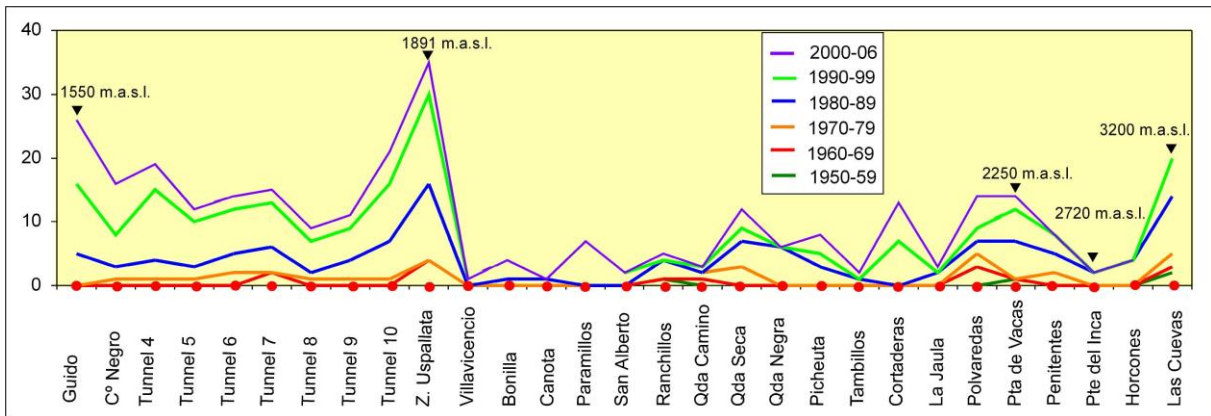
Fig .2: Number of events recorded per decades at different localities along the Mendoza River valley.
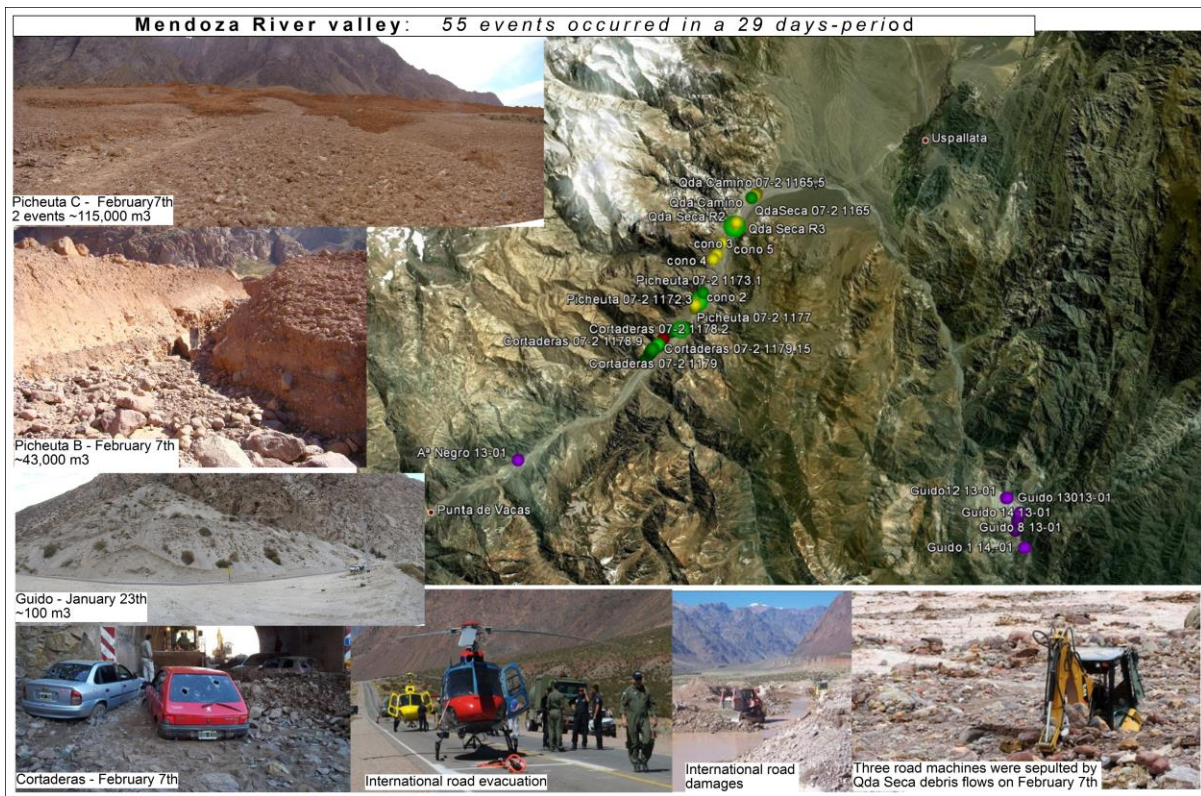

Fig. 3: Occurrence of 55 landslides triggered by convective rainstorms in the study area during summer 2013 that generated important damages to international road to Chile. Equipment and bulldozers were razed or covered by debris material. Tourists had to be rescued and a fatal victim resulted during this drastic events.

potential data and temperatures recorded by the radiosonde during South Hemisphere summer (DJF) and winter (JJA) (Fig 4).

According to our findings, the altitude of zero isotherm is roughly climbing since 1940. Still this arise is not very pronounced, from 4.380 to 4420 masl, any

change at this altitude compromises seriously the permafrost. Besides we could distinguish that geopotential and temperature values correlate very well during January, however a disengaged of these variables exist since 1976 for winter seasons.
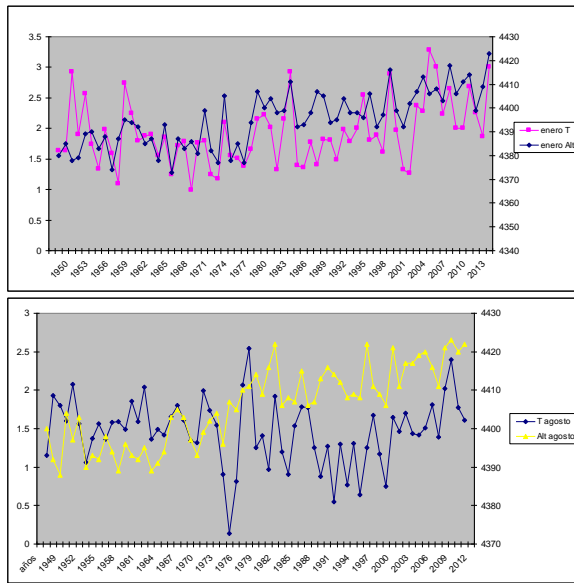
Fig. 4: Geopotential elevation and temperature of zero isotherm for studied area since 1942. Above graphic shows data of January and below graphic represents records measured in August.

Discussion and conclusions

Climate change is driving slope instability in the Central Andes. According to our results, landslide activity has been raising during last decades. Main explanation of this explosion is associated with intensified summer rainfall and global warming due to climate variability. In the Mendoza River valley precipitations above average values have being recorded during last year causing catastrophic debris flow in 2013 and 2015-2016. Besides, global temperature rising is reflected in roughly climbing of zero isotherm in the Andean hillslopes with a severe impact on ice degradation on rock glaciers. This phenomenon could be extrapolated to permafrost degradation in mountain areas.

Landslides in the Central Andes show new frequency-intensity relation, a denser spatial distribution, a progressive altitudinal migration as consequence of permafrost degradation and higher temperatures on hillslopes. Besides, interactions of more variables are associated to complex landslide causes in Mendoza River valley.

The extraordinary contribution of sediments mobilized by landslides has caused alarm in infrastructure and dams located downstream. In the present study volumes, thicknesses and speeds of catastrophic events recorded in the last Southern Hemisphere summer (December 2015-February 2016) were estimated.

References

Moreiras S M (2005) Climatic effect of ENSO associated with landslide occurrence in the Central Andes, Mendoza province, Argentina. Landslides Vol 2 (1): 53-59.

Moreiras S M (2006) Frequency of debris flows and rockfall along the Mendoza river valley (Central Andes), Argentina. Special Issue Holocene Environmental Catastrophes in South America. Quaternary International 158: 110-121.

Moreiras S M, Lauro C, Mastrantonio L (2012). Stability analysis and morphometric characterization of palaeo-lakes of the Benjamin Matienzo Basin- Las Cuevas River, Argentina. Natural Hazards 62 (2): 593-611.

Moreiras S M , Lisboa S , Mastrantonio L (2012) The role of snow melting upon landslides in the central Argentinean Andes. Earth Surface and Processes Landforms. Special issue on Historical Range of Variability. Guest editors: Ellen Wohl and Sara Rathburn

Moreiras S M, Sepúlveda S A (2013) The high social and economic impact 2013 summer debris flow events in central Chile and Argentina. Bollettino di Geofisica Teorica ed Applicata, Vol. 54, Supp. 2, 181-184.

Sepúlveda S A, Rebolledo S, Vargas G (2006) Recent catastrophic debris flows in Chile: geological hazard. climatic relationships and human response. Quaternary International. 158. 83-95.

Stella M. Moreiras (✉)
IANIGLA –CONICET. Geomorphology Group. Mendoza. Ave Ruiz leal s/n Parque Gral. San Martin s/n. Ciudad Mendoza. 5500, Argentina.
e-mail: moreiras@mendoza-conicet.gob.ar

Ivan Vergara Dal Pont
IANIGLA –CONICET. Geomorphology Group. Mendoza. Ave Ruiz leal s/n Parque Gral San Martin s/n. Ciudad Mendoza. 5500, Argentina.
e-mail: ivergara@mendoza-conicet.gob.ar

Climate change and soils

Aleyda Montoya

Abstract At present, there are many studies about the manifestations of climate change, how it affects us and how we must adapt using the available resources or upgrading some of them. There are many authors who are looking at the causes and effects, and have created a series of initiatives at national and international level that seek to contribute to the mitigation of the problem. When we talk about climate change, we also speak of greenhouse gases (GHG), and how the increase in the emission of these contributes to the problem. Within these gases, carbon dioxide (CO_2) is being studied with particular importance. Several actors are involved in the increase or reduction of the emission of this gas to the atmosphere. In the Carbon Cycle, the relationship between these actors can be observed and this is where the important role of the soil is appreciated. Based on this, we can say that in addition to being affected by changes in rainfall patterns (effect of climate change), soils can contribute to the mitigation of climate change, so the study of the interaction of soils with climate change should be given importance. This paper mentions both landslides and erosion problems caused by changes in rainfall patterns and soil degradation, the soil resilience and mitigation potential. Additionally, the paper presents some tools that can contribute to enhance the soil mitigation potential as well as some concepts that will allow the reader to understand the importance of preserving the soil not only from the food security point of view.

Keywords climate change, soil, mitigation, resilience

Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC), defined climate change in Article 1 as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is, in addition to natural climate variability, observed over comparable time periods". Meanwhile, the Intergovernmental Panel on climate change (IPCC, for its acronym in English) states that "climate variability refers to variations in the mean state and other statistics (such as standard deviations, statistics of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability)".

Another important concept related to climate change is the greenhouse effect. According to the International Research Center for El Niño phenomenon (CIIFEN, for its acronym in Spanish) the greenhouse effect is the "phenomenon by which certain gases (called greenhouse gases, GHG), which are components of the planetary atmosphere, retain part of the energy emitted by the soil being heated by solar radiation". The more greenhouse gases such as CO_2 are in the Earth's atmosphere, the higher the temperature of the planet. There is a consensus among the scientific community that climate change is a product of the increase in the emission of greenhouse gases; because of this, climate change policies are focused mostly on reducing emissions. The combustion of fossil fuels (coal, natural gas, and oil), destruction of forests, changes in land use, waste production, etc. contribute largely to the increase in CO_2 emissions, which is one of the most important greenhouse gases (GHG).

According to data presented by the Ministry of Environment and Natural Resources of El Salvador (MARN for its acronym in Spanish), the frequency of hydrometeorological events that exceed the country's annual average rainfall for the period 1997 to 2000 (1800 mm) has increased in recent years. According to them, global warming and climate change are responsible for this rise (see Fig. 1).

The Soil

There is evidence that the planet is undergoing a series of major environmental changes that impact natural resources; such changes are boosted by climate change. "Climate change finds soils with severe limitations to contribute to the mitigation of the environmental problems associated with the use of the territory" (Montico, 2010). These limitations are associated with, among other things, changes in land use, inadequate

management practices and the lack of knowledge that all this brings about the increase of the effects and impacts of climate change and the reduction of the soil's mitigation capacity. In El Salvador, the rise in the frequency of hydrometeorological events has increased the frequency and amount of landslides and has accelerated erosion processes. These generally affect the soil and can be seen as effects of climate change.
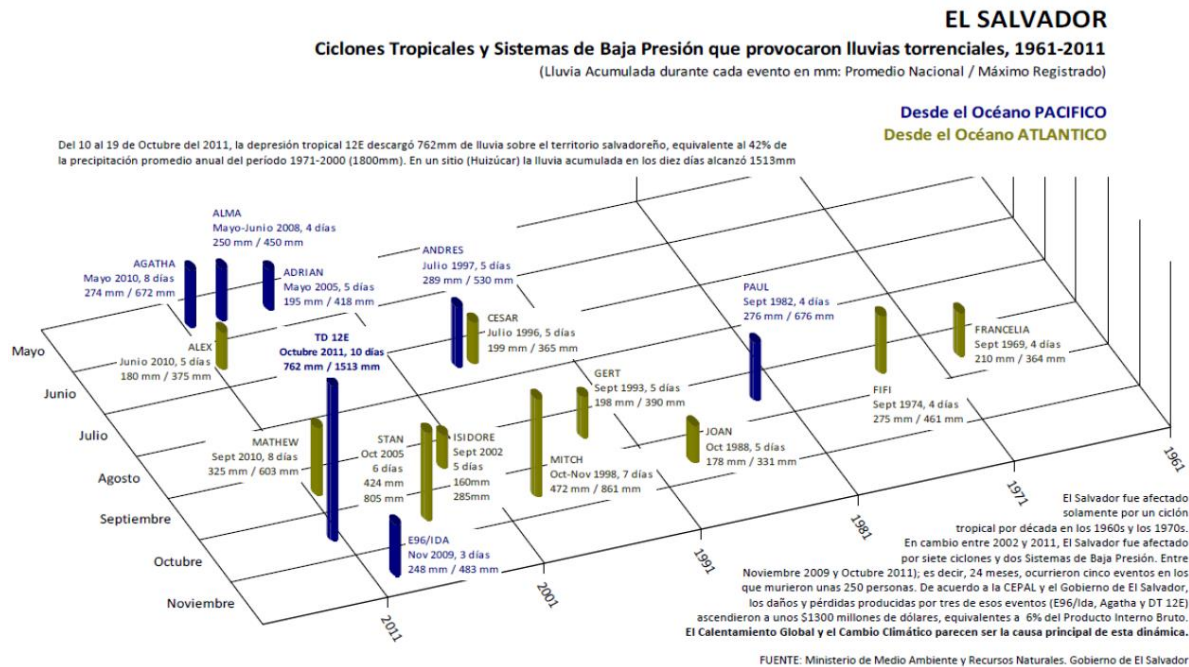

Fig. 1 Cyclones and tropical low pressure systems that have caused torrential rain between 1961 and 2011 (source: MARN)

Landslides

A landslide may be defined as a "movement of rock, debris or earth down a slope" (Cruden, 1991). There are many factors that can contribute to the triggering of these mass movements, among which we can mention: rain, earthquakes, volcanic eruptions, erosion, etc. All these factors alter the natural soil conditions.

In El Salvador and many countries, landslides can be observed in different places during the rainy season (from May to October in El Salvador) (see Fig. 2). Because one of the effects of climate change is rain of higher intensity for shorter periods, the number of landslides has increased over time.

El Salvador doesn't have a historical record of landslides, but there is information about landslides occurring along main roads during the events of 2010 and 2011. Table 1 shows the numbers of landslides and Fig. 3 shows the records of rainfall accumulation. For this case, we can see a direct relationship between the number of landslides and accumulated rainfall (Cruz Peraza, 2013).

Anthropogenic factors (of human origin or derived from human activity) also contribute to and largely condition the occurrence of failure surfaces and landslides that are responsible for most of the land use changes, changes in vegetation cover, waterproofing, etc.

Fig. 2 Landslide in San Francisco Street, Antiguo Cuscatlán, El Salvador, which occurred during an unspecified rainfall event in October 2010 (photograph taken by Alonso Alfaro on March 18th, 2011)

136

Tab. 1 Number of landslides for 2010 and 2011 (Cruz Peraza, 2013)

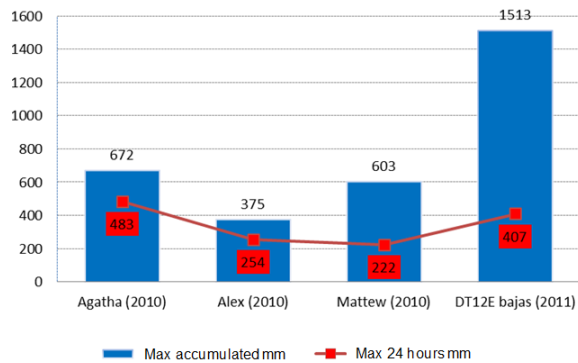| Event	Year	Number of landslides
Agatha	2010	528
Alex	2010	126
Mattew	2010	167
DT12E	2011	1158

Fig. 3 Rainfall accumulation during 2010 and 2011 (Cruz Peraza, 2013)

We must take into account that alterations in the soil caused by climate change do not determine the occurrence of new landslides; there must be a combination of the factors mentioned above for a landslide to be triggered. On the other hand, climate change alone can reactivate existing landslides. An adequate historical record of landslides becomes vital for development and land use planning.

Erosion

"Erosion includes detachment, transport and subsequent deposition of soil or rock material by action of the force of a moving fluid. Erosion can be generated both by water and by the wind" (Suárez Díaz, 2001) and occurs mainly because the soil loses its ability to absorb and store water. Some factors influencing water erosion are: rain, soil capacity, type of soil, slope, vegetation cover, soil use, etc.

The frequency of events related to water erosion has increased as long as the rain events become stronger and longer due to the effects of climate change. As an example, Fig. 4 shows a slope that suffered erosion problems in the Jardines del Pepeto community, Soyapango, El Salvador during the passage of Hurricane Ida in 2009. In addition, wind erosion has increased as the dry and rainless periods become more frequent and lasting, although this effect may also be attributable to climate change. The planting of certain crops, overgrazing (i.e. there is more cattle than the land can

support) and burning as a method of collection for sugar cane, etc. are some of the factors of anthropogenic origin that also bring about erosion and increase soil degradation.

Fig. 4 Erosion problem in the Tierra Blanca formation of the Jardines del Pepeto 3 community, Soyapango, El Salvador. It occurred during the passage of Hurricane Ida in 2009 (photograph taken by Aleyda Montoya on May 25th, 2011)

The modernization of agricultural practices (specifically, the use of pesticides) together with changes in climate have led to a higher rate of erosion and simultaneously a decrease in soil organic matter, which stimulates plant growth, maintains the soil structure, facilitates infiltration and water retention and reduce the evaporation (Imeson and Curfs, 2005) .

Finally, it can be concluded that although erosion and landslides may have a natural or anthropogenic origin, these have increased both in magnitude and frequency due to the manifestations of climate change. Therefore, it is necessary to take adaptation measures to reduce the problem and contribute in some way to mitigate the climate change.

The soil has a high resilience capacity but this will depend on the magnitude of the hazards and soil management. Soil conservation may contribute to mitigation, thereby increasing the spectrum of uses and helping reduce vulnerabilities. Once some damages to

137

the ground have been defined as a result of climate change, it is necessary to know the role of soil in mitigation.

The Carbon Cycle

To understand the contribution of soil to the mitigation of climate change, it is necessary to understand what the carbon cycle is about. The carbon cycle refers to the chemical transformations by which carbon is exchanged between the biosphere, lithosphere, hydrosphere and atmosphere of the Earth (see Fig. 5).
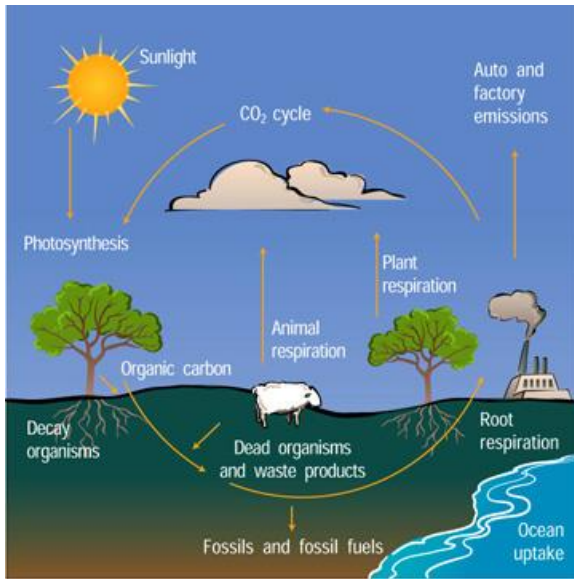

Fig. 5 Carbon Cycle (available at https://eo.ucar.edu/kids/green/cycles6.htm)

In this cycle, it can be seen that carbon retention occurs when it is absorbed from the atmosphere and stored in the soil. Through photosynthesis, vegetation captures atmospheric CO_2 and transforms it into organic C to be incorporated into the soil. Healthy soils are the largest terrestrial carbon stock, and can influence a reduction of emissions of greenhouse gases into the atmosphere, as long as proper management of the resource is made. The mismanagement of land and/or inadequate agricultural practices can increase the release of CO_2. For example, changing pastures and forests to crops and grazing have resulted in historical losses of soil carbon.

Therefore, practices of soil management to ensure the maintenance of soil carbon are appropriate to mitigate carbon emissions to the atmosphere. The production of fertile soil, rich in organic matter, must be sought, since the organic matter keeps vegetation, increases the ability of soil to retain moisture, helps resist erosion and desertification, thus contributing to

better withstand droughts and floods. Because of the above mentioned reasons and considering that it is the second world's largest carbon stock, organic matter plays a key role in the relationship between soil and climate change.

Vegetation and slope stability

The role of vegetation in protecting embankments and slopes is related to the following aspects (Gray and Leiser, 1982):

- interception: foliage and the plants' waste absorb energy from rain and prevent soil compaction through the impact of the drops directly on the surface.
- retention: physically, the root system holds the soil particles. Also, the vegetation parts above the ground function as sediment traps.
- retardation: on the surface, waste increases the coefficient of terrain roughness, thus reducing runoff velocity.
- infiltration: the roots and plant residues help maintain soil porosity and permeability.
- perspiration: the depletion of soil moisture by plants slows saturation and thus the occurrence of surface runoff.

In slopes and hillsides devoid of vegetation, erosion processes and soil instability are accentuated when the slope increases, so the challenge of contributing to the soil stability is not only limited to areas of land with little or no slope. To achieve this, solid technical criteria are necessary to ensure that a plant species actually protects and strengthens the floor properly.

Fig. 6a shows a landslide located at km 18.5 of the CA-01 East route in El Salvador. This area was also affected by erosion problems. In 2015, and as part of the applied control measures, the planting of vetiver grass was implemented. This type of grass is widely used in the country for its maintainability and the long size of their roots, which allow an effective erosion control. Fig. 6b shows the landslide-affected slope after it had undergone the plantation of the vetiver grass.

Although the effects of vegetation on slope stability are widely discussed, we cannot overlook the experiences that have shown that vegetation prevents erosion problems, creep and subsurface flows (Suárez Díaz, 1998). Depending on the type that is planted on the slopes, vegetation can serve to: absorb the humidity of the surface, increase the infiltration capacity, give consistency through the mechanical framework of its roots, etc. It should be clear that to define the appropriate type of vegetation to be planted on a slope, both the advice of an expert in slope stability and the expertise of an agronomist are required.

Organic agriculture

Organic agriculture is a production system that tries to make the maximum use of farm resources, with emphasis on soil fertility and biological activity. At the same time, it minimizes the use of non-renewable resources and the non-use of synthetic pesticides to protect the environment and human health (Andersen, 2003).

Fig. 6 a. Landslide located at the km 18.5 of the CA-01 East route in El Salvador. It occurred during the night of January 17th, 2009 (photograph taken by Yuri Rodriguez on January 5th, 2014). b. Control measure applied to the affected slope (photograph taken by Jorge Urrutia on December 17th, 2015)

How does organic agriculture contribute to the mitigation of climate change? Its aim is to restore the contents of soil organic matter (which can increase the capacity of carbon retention), reduce emissions of greenhouse gases (with reduced use of agrochemicals) and protect fragile vegetated soil surface. If this is achieved, the erosion and/or the susceptibility to landslides will be reduced. It is important to mention that this is not intended to make deforestation of land for agricultural use, but rather to change from conventional to organic agriculture.

Particularly in the case of El Salvador, organic agriculture has been encouraged through local initiatives and some international cooperation agencies as a mean of preserving the environment, maintaining the sustainable agriculture and limiting the exposure of farmers to agrochemicals. In August 2014, the

Government of El Salvador launched a line of credit to promote organic agriculture through the Ministry of Agriculture and Livestock (MAG, for its acronym in Spanish) and the Agricultural Development Bank (BFA, for its acronym in Spanish). With this measure, the government seeks to place El Salvador at the forefront of production technology.

In El Salvador, due to soil type and unplanned growth of urban areas, it is easy to find areas affected by erosion problems and/or slope instability. These areas have high population density and in many cases, the population has limited resources, so a comprehensive solution that solves the soil instability problems and contributes to the improvement of the economic situation of the population is urgently needed. It is essential to take advantage of the benefits of organic farming and all current promotion efforts carried out by the government and other institutions, both nationally and internationally.

Organic agriculture can be exploited in embankments and residential areas; it can become a complement to the works of gray infrastructure to leverage the skills and country experience. It will seek to provide stability to the ground so that it can withstand changes in rainfall patterns, reduce its erosion and at the same time, as already mentioned, contribute to the mitigation of greenhouse gases by increasing its carbon retention capacity.

Conclusions

- The soil should not be regarded only as a supplier of food security for the population but also as the cause of some disasters in El Salvador, so its management should consider both situations.
- It is difficult to determine a precise relationship between rainfall and slope stability, but an increase in rainfall results in an increase in the number of landslides.
- Erosion problems on slopes in El Salvador are further enhanced due to soil type (Tierra Blanca, see Fig. 4), so the impact of rain in these cases is greater.
- The resilience depends on the current conditions of the soil and the magnitude of hazards.
- By providing the ground with suitable organic matter content, the carbon retention capacity is increased, thus contributing to the mitigation of climate change.
- It is important to use all kinds of initiatives aimed at reducing the effects of climate change and consider using them in conjunction with other solutions.

References

Andersen, M. (2003), ¿Es la certificación algo para mí?, RUTA-FAO,Catherine Pazderka, Unidad Regional de Asistencia Técnica, San José, Costa Rica. (ISBN: 9968-866-30-X)

Cruden, D. M. (1991). A simple Definition of a Landslide, Bulletin of the International Association of Engineering Geology. No 43

Cruz Peraza, E. I. (2013) Carreteras más afectadas por eventos hidrometeorológicos extremos en El Salvador durante los años 2010 y 2011

Gray, D. H., & Leiser, A. T. (1982). Biotechnical slope protection and erosion control, Van Nostrand Reinhold Company, New York, United States of America

Imeson, A., & Curfs, M. (2005). La Erosión del Suelo, Land Care in Desertification Affected Areas From Science Towards Application, Colección de folletos: B, número 1

Montico, S. (2010). Impacto del Cambio Climático sobre los Suelos, Revista Agromensajes de la Facultad de Ciencias Agrarias Universidad Nacional de Rosario, Argentina.

Suárez Díaz, J. (2001). Control de Erosión en Zonas Tropicales, División Editorial y de Publicaciones Universidad Industrial de Santander, Colombia. (ISBN 958-33-2734-4)

Suárez Díaz, J. (1998). Deslizamientos y Estabilidad de Taludes en Zonas Tropicales, Ingeniería de Suelos Ltda, Instituto de Investigaciones sobre Erosión y Deslizamientos, Bucaramanga, Colombia

Aleyda Montoya (✉)

Climate Change Adaptation and Strategic Risk Management Department, Ministry of Public Works, Transportation, Housing and Urban Development, Carretera a Santa Tecla Km 5 ½, San Salvador, El Salvador,

email: aleyda.montoya@mop.gob.sv, aleydamontoya@yahoo.com

Risk as social construct: a comparative view from risk scenarios

Rosa Sánchez

Abstract. From the social sciences, elements have been provided to apply the concept of social construction of risk to concrete realities. Although this concept becomes relevant in analyzes related to disaster risk is also essential to make a reference to the link between modernity and risk from a sociological perspective, as well as to the contributions to the understanding of risk behaviors from an anthropological perspective. These approaches are complemented by the proposal to seek a comprehensive understanding of disaster risk, linking social behavior with the natural environment, and the social one.

Nevertheless, case studies are the ones that allow us to identify time and space dynamics that explain the construction of this environment and the way people, their systems, and their institutions contribute to this.

Methodologically, it is about considering three risk scenarios already built where recurring and periodic events (e.g. floods) and / or sudden events (e.g. landslides) are present: One with the occurrence of phenomena considered disaster, another with events that allow coexistence with the risk, and another one where appropriate public intervention make resettlements possible.

Furthermore, comparative analysis allows us to formulate some proposals on the use of concepts that seem to be adequate to show the aforementioned dynamics, such as risk transfer and housing atomization, among others. Finally, this kind of analysis contribute to the understanding of the dynamics, regulations and institutional discourses that end up being part of the social construction of risk attending at its limitations, dispersion or obsolescence.

Keywords risk, risk transfer, social construction of risk

Introduction

Guatemala's territory is described as "multi-threat" (FAO OMS, 2011), a term that is beginning to stand on its own based on two activities gathered by Central American actors involved in pilot projects on risk reduction management implemented with a single point of view (regional-national-local), and mainly oriented to the strengthening of local structures (CEPREDENAC-FEMID, 1998). Regarding the local dimension, it was discussed, at the time, the importance of communitarian involvement in order to identify the ongoing various threats in a specific territory suffering the impact of a particular event, the determining role played by local governments and the influence and repercussions of decentralization focused, at the time, in its potential on risk disaster management.

Vulnerability, being one of the risk components, has been mainly approached from the institutional point of view, building its own meanings in front of certain threats and their different manifestations; and in the last decades linking both –vulnerability and expression- to climate change and climate variability. Furthermore, various regional events have allowed for the advance of the gender and the disasters topics, as well for the achieving of a conceptual and practical development and its application in the field of public policies (CEPREDENAC-OIM, 2008, 2010).

Comparatively, investigation related to perception of risk and social risk construction has not had much development in the region despite the recognition of its analytical utility.

Social construction of risk

We use the concept of social construction of risk from the perspective that each form of social organization is willing to accept or avoid certain risks, and that, when investigated, the cultural bias that shape the way we perceive those risks cannot be disregarded; as stated by Bestard in the prologue to the work of Mary Douglas when he said that social groups use risk to control uncertainty and strengthen their social norms (Bestard, 1996). Nevertheless, in order to contextualize the cases included in this article, it is necessary to pick up the statement from Beck (1998) regarding the social production of risk in this advanced modernity, where the problems and conflicts arise from the production, definition and distribution not the risks produced on a technical and scientific basis.

If we are to approach risk perception as a cultural construct, it is important to add, as stated by García Acosta (2005), that conceptions of risk and disaster held at different moments of history, and their various consequent perceptions, come from the specific kind of society they originated from.

One of the risk conducts assumed, as explained by Douglas (1996), is expressed in the peoples' and groups decision of staying in areas that have been declared as hazardous, which define its condition of not been suitable for being inhabited. When it comes to Guatemala, this can be partly comprehended by the enduring and influence of a mythical and religious thinking.

As explained by Morini (2015), this way of thinking makes the network that weaves the events, up to a decision subject to the will of a divinity; being that, as a decision being defined from above it cannot be controlled from below. Approached like that, the social construction of risk in the analyzed cases show three types of dynamics that we consider contribute to explain, at a national level, housing atomization, risk transfer, and institutional vulnerability.

It is about proposing some elements in order to reflect on one of the concepts developed in the context of risk studies, understanding that one of the difficulties, as expressed by Briones Gamboa (2005), is to establish a conceptual frame fitted to the cultural context that is being subject of study

Risk scenarios

Landslide in the municipality of Santa Catarina Pinula

On October 1, 2015, a massive landslide occurred in Colonia El Cambray II (El Cambray II neighbourhood). According to official statements there was a slide of approximately 65,000 cubic meters of sediment (CONRED, 2016); as a result, 131 persons died buried, and approximately 76 houses were destroyed, as show in Fig.1. This area has been affected by the rise of the Pinula River, which is considered as the cause of instability in the mountainside, as well as the cause of the eroding of the plots and housings (CONRED, 2015)

Recurring flooding in *Barrio La Ciénaga* (La Ciénaga neighbourhood), Zone 2, municipality of Quetzaltenango

The neighbourhood is located in one of the lowest part of the basin. Natural elements defining this scenario consist of: three bodies of water, the rivers Seco Xequijel and Samalá; the so called *zanjones* (big ditches), part of the topography of the city, which explain partly the risk of *correntadas* (strong currents), flooding and landslides. Anthropic elements are associated to an accelerated urbanization, a poor man-
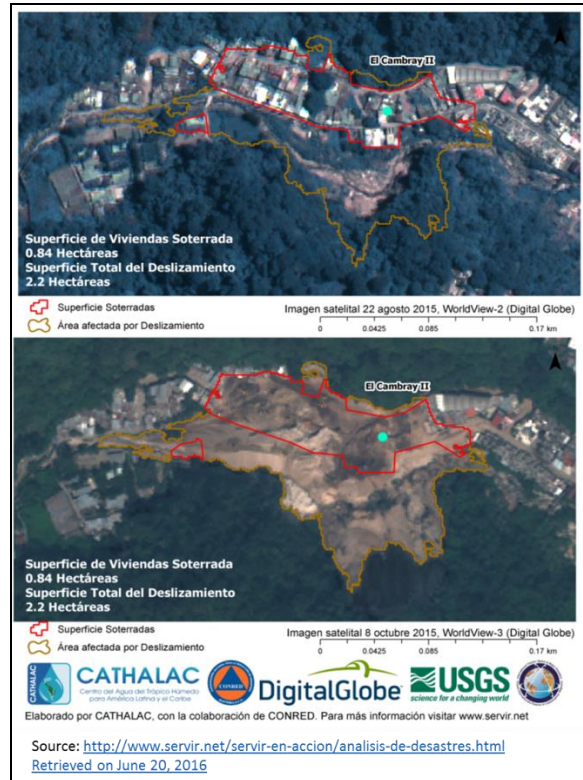

Fig. 1 Surface area of buried houses and total area of landslide in El Cambray II, municipality of Santa Catarina Pinula

agement of rainwater, sewage, and solid and liquid waste that explain the risk of flooding and landslides, as show in Fig 2.
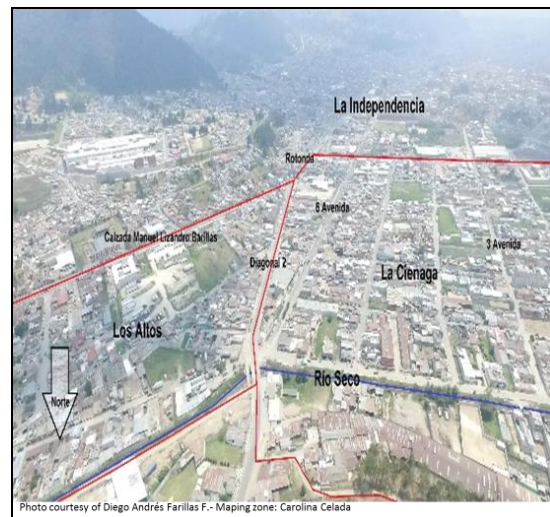

Fig. 2 Aerial photography shows the location of La Ciénaga, in an area of accelerated urbanization

Landslide in the municipality of Mixco, in the colonies La Asunción, Los Magueys, Los Olivos, Finca San Jerónimo and Anexo San José Buena Vista, zone 1

Official intervention, (CONRED, 2011), occurred as a reaction to a warning issued by the neighbours asking to investigate the causes of strong noises and damages in their houses, as well as damages in the streets. What was described by the neighbours as "a crack" was later confirmed as a landslide with a high speed of movement indicating the necessity of immediate evacuation, as show in Fig. 3.

The first survey of experts in the area, in addition to the information from the neighbors, confirmed the formation of a crevice going through the five neighborhoods, located in the urban area of the municipality. The actions that were taken include monitoring, house evaluation, road infrastructure, inter institutional coordination, as well as inter municipal and with the neighbors; urgent evacuation, use of economic emergency funds, and finally the relocation of the population to new houses built in an area considered as secure.

These three cases are relevant considering that, according to official statistics, 33% of the national territory is located in the classification of high risk of landslides and flooding; and 44% of the territory is on the classification of high probability of occurrence (CONRED, 2014).

In terms of population it is calculated that 62% live in territories with high risk of floods. In a classification by department, 15 out of 22 that make up the country (i.e. 68% of the departaments including Guatemala City and Quetzaltenango) are considered as of very high risk of floods and landslides.

Housing atomization

The term "land atomization" is used in agriculture to make reference to a process of succession of ownership rights, by the way of fragmentation of the surface of the land. Here it is used to explain how original owners progressively split their properties, either formally (legally) or informally, by adding new housing areas in the same plot or even new houses. All of this occurs within a single private property. These dynamics can be observed in the so called *asentamientos precarios urbanos* (urban precarious settlements) many of which appear because of the invasion of lands owned by the state.

These settlements begin with the invasion of areas with high percentage of slope (ASIES, 2003), this condition of the land makes necessary a process called "urban land production", which include cuts in the land that allow the beginning of constructions, which end up being progressively increased. Nonetheless, this
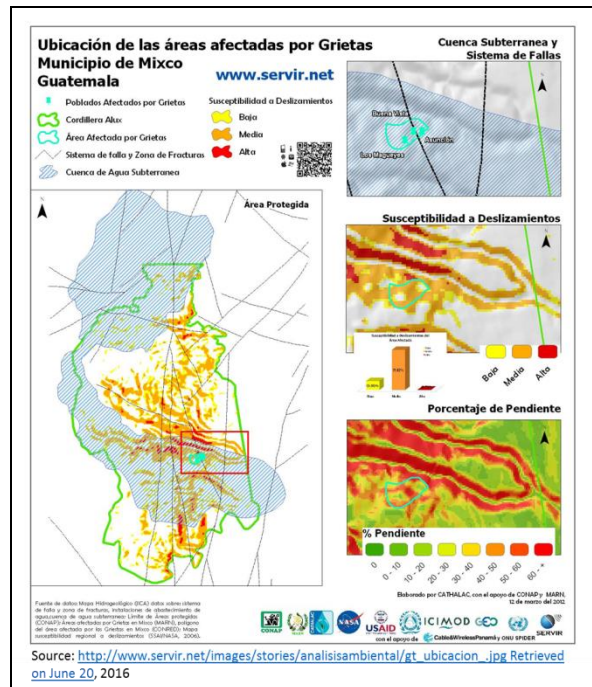

Fig. 3 Location of the areas damaged by the crevices, in the municipality of Mixco, landslide susceptibility and gradient percentages

housing atomization is not only observed in precarious settlements, but also on plain areas where the population have better possibilities of acquiring plots, even legally authorized and urbanized ones.

In the case of El Cambray III, this atomization can be documented by analysing the history of the three properties from where the housing developments Valles del Cambray I y II came from; including a residential area, La Pradera and one neighbourhood, Las Victorias. In this case, the splitting of the land can be traced to 1923, but others can be documented in the decades of 1980 and 1990. Part of the housing developments and new constructions can be traced analysing constructions permits, although and under registration must be acknowledge because many of those so called formal constructions or modifications may be done without attending such legal formalities.

This dynamic ends up being interrelated with what can be characterized as institutional vulnerability, being that, in this context, municipal governments suffer the lack of updated statistics about land occupation, but furthermore because every period that a new government is installed it faces risk scenarios already set up, in face of which, intervention is difficult; specially because of the characteristics of current regulations applying to private property.

Risk transfer

The term is used in the insurance field to make reference to the action of insuring a property in the face of probable future events, undesired but uncertain (accidents, fire, earthquakes, etc.), transferring the cost of replacement of a property or an investment to a second party. In our context, it is used to make reference to actions performed by human beings, who by performing them, with or without knowledge, transfer the risk to other people, outside or inside a single private property.

In two of the analysed cases, decisions can be documented of a selling of a property located in a risk area declared as uninhabitable or with evident signs of the impact in the construction caused by events prior to the selling; such as deterioration of the structure by the effect, over the years, of it being located in areas near the basin of the river or recurrent floods.

To acknowledge such risk, as previously identified, stimulate the decision to sell or rent a house. In any of the cases, whoever buys or rents the house is aware of the risk, but the decision falls in the field of the assumption of risk conducts, which in the case of the human settlements analysed can be explained by reasons of economic vulnerability expressed in the fact that access to housing market is prohibitive, or even the renting of rooms or houses because of the high prices, compared to the economic possibilities.

In the case of Barrio La Ciénaga, the risk scenario involves the renting and selling of houses. Being that in the area the usage of the land has changed, those who still live in it are owners who develop conducts that allow them to coexist with the risk; being those reasons of identity and belonging to the territory, or for being unable to buy or rent a house in areas relatively safer; taking in consideration that in recent years the territory affected by floods, in the municipality, is bigger by the year for reasons associated with the collapse of the sewage system; which in turn is explained by the accelerated process of housing development in absence of urban or land regulations.

The other vulnerability element present in this scenario is the one linked to the usage of the plots and properties bought or rented that, as of today, are used as mechanic workshops, spare parts shops that usually operate in the day. During night the area turns into what's called a *zona roja* (red zone).

It has been observed as well, as part of the process of risk transfer, the adding of a formal or informal construction to an original construction (private property) in a risk area, which in turn increases the structural instability of the added construction. The original owner places new families (population vulnerability) who in turn established new family cores that, since they cannot afford other housing options (economic vulnerability) set residence in the area, where the cost of rent is sensibly lower than in other areas of the municipality.

Institutional vulnerability

The case of Mixco illustrates a process that despite showing positives elements like the timely relocation of a population also shows what conceptually would be the institutionalization of an approach that, in theory, has been accepted by various institutions that will have competence in the topic of disaster risk. Nonetheless, we believe this institutionalization is still a pending task, which is why we think in terms of institutional vulnerability. But its analysis show elements that will allow to truly intervene risk, transfer it, in institutional terms, and achieve more permanent results when resettling population.

This process begins thanks to the perception of risk from the people that illustrate the way that social actors approach their every-day activities and notify about "big noises" and cracks in their houses and streets. From that alert, two dynamics take place, one based on time and one based on space, both coordinated. In summary, with the involvement of the population and inter-institutional support, structures and families that are a priority to be evacuated are identified. While the assessment of risk is conducted, dynamics to ensure the flowing of information and specific local monitoring systems are implemented: the installation of a radio base in a neighbourhood, instruments to observe the behaviour of the gap in the ground, a seismograph placed in the local church, a ground penetrating radar system (GPR) to determine the exact origin of the cracks, among others. Spaces of coordination with the population including its local social structures (Communitarian Council of Development, *COCODES*) are set in place, as is with the Ministry of Education for the establishment of temporary shelters; also a scientific institution is asked to issue a report that allow to demonstrate that not every instability can make an area to be considered as of high risk. All of this occurred in a 26-day time frame from the moment the crack was reported to the moment the report was requested and a 5-day time frame from the request of the report to its delivery.

Finally, it takes criteria like location of the inhabitants in the territory regarding the fissures in the structures, and the risk that these fissures represent for the population, in order to prioritize and finally decide the moving of families and achieve some form of voluntarily resettlement; for which, so far, there aren't any regulations in the country, situation that also demonstrates institutional vulnerability.

References

ASIES. (2003). Asentamientos precarios en la ciudad de Guatemala Segunda Parte [Precarious settlements in Guatemala City, Second Part]. Momento(6), 12. Retrieved on May 6, 2016from Asociación de Investigaciones y Estudios Sociales[Investigations and Social Sciences Association]:https://s3.amazonaws.com/asies-books/books/momento_6-2003

Beck, U. (1998). La sociedad del riesgo.[Society of risk] (J. Navarro, D. Jiménez, & M. Borrás, Trads.) Mexico, Mexico: Ediciones Paidós Ibéica, S. A. Retrieved on May 19, 2016.

Bestard, J. (1996). On M. Douglas, La aceptabilidad del Riesgo según las ciencias sociales (pág. 173) [Acceptability of risk according to Social Sciences (p. 173)]. Barcelona: Ediciones Paidós Ibérica, S. A. Recuperado el 14 de 5 de 2016

Briones Gamboa, F. (enero-junio de 2005). La complejidad del riesgo: breve análisis transversal. Revista de la Universidad Cristóbal Colón, III(20), 9-19. [The complexity of risk; breaf transversal analysis. San Cristobal Colon University Magazine III (20) pp. 9-19]. Retrieved on May 10, 2016, from http://www.ver.ucc.mx/revistaucc

CEPREDENAC-FEMID. (1998). Memorias Simposio Internacional Mitigación de Desastres: Una contribución al desarrollo sustentable de Centroamérica. Panamá. [International Disasters Mitigation Simposium Report: A Contribution to Sustainable Development in Centralamerica and Panama] Retrieved on May 22, 2016.

CEPREDENAC-OIM. (2008, 2010). Memorias. Género y Desastres.[Gender and Disasters Report] Guatemala, Colombia. Retrieved on el 18 de 5 de 2016

CONRED. (2011). Boletines y evaluación de riesgo. [Bulletin and risk assesment] Retrieved on May 18, 2016, from Coordinadora Nacional para la Reducción de Desastres [National Coordination for Disasters Reduction]: http://CONRED.gob.gt/www/index.php?option=com_co ntent&view=article&id=3712:expertos-realizaron-evaluacion-de-riesgo-en-mixco&catid=35&Itemid=1008

CONRED. (5 de octubre de 2015). Retrieved on May 15, 2016, from Coordinadora Nacional para la Reducción de Desastres   -CONRED-: http://www.CONRED.gob.gt/www/documentos/cambra y2/DCS_20151005_Informe%20situaci%C3%B3n%20act ual_0800hrs_Deslizamiento_Cambray_II.pdf

CONRED. (enero de 2016). Consideraciones sobre condiciones físicas asociadas al deslizamiento en el sector El Cambray II Municipio de San José Pinula Departamento de Guatemala.[Consideration on phisical conditions related to the landslide en the El Cambray III sector, Municipality of San Jose Pinula, Guatemala] (C. N. Desastres, Ed.) Revista Científica CONRED 1 [CONRED scientific magazine 1]. Retrieved on May 15, 2016, from http://www.CONRED.gob.gt/www/documentos/cambra y2/ConsideracionesCambray2.pdf

Douglas, M. (1996). En La aceptabilidad del riesgo según las ciencias sociales.[Acceptability of risk according to Social Sciences] Barcelona: Novagrafic, S. L.

FAO-0MS (2011). Los desastres requieren un enfoque multiamenaza. Boletin 116,1-3. Retrieved on 26/6/2016 http://www.paho.org/disasters/newsletter/index.php?o ption=com_content&view=article&id=468&Itemid=266 &lang=es

García Acosta, V. (septiembre-diciembre de 2005). El riesgo como construcción social y la construcción social de los riesgos.[Risk as social construct and the social construction of risks]Desacatos(19), 11-24. Retrieved on May 19, 2016.

Morrini, S. (2015). Il rischio. D Pascal Fukushima. Torino: Grupo Editoriale Mauri Spagnol.

Rosa Sanchez (✉)
23 avenue 31-80, zone 12, Guatemala 1012, Guatemala
rosa.sanchez.valle@gmail.com

Educational methodologies implemented in Latin America for landslide inventory and analysis

Rigoberto Moncada, Hiromitsu Yamagishi

Abstract This paper provides details and summarizes experiences in educational methodologies for landslide inventory mapping and characterization. Two different application cases are described in order to show the implementation of these methodologies. These educational approaches applied a varied set of tools such as aerial photographs, satellites images, digital elevation models (DEM) and geographic information systems (GIS). All of these tools allowed trainees, many at beginner level and some with a moderate level of expertise, to quickly start developing their own maps.

Experiences of the methodologies, applied in virtual and conventional classroom environments, are explained. The virtual seminar instructed with the Pan-American Center for Geographical Studies and Research (CEPEIGE) of Ecuador involved development of a landslide inventory component with learning topics such as: landslide geomorphology, aerialphoto identification, data digitalization, among others. Conventional face-to-face education was developed with the United Nations Education, Science and Culture Organization (UNESCO) Extreme Natural Hazards and Societal Implications (ENHANS) project. The objective of this multi-hazard project was to train key participants who would then replicate hazard assessment methodologies in their respective countries for different types of threats. In this project, landslide learning was approached with a modified procedure that stressed the importance of site characterization during landslide inventory. Target countries for landslide component were Chile, Ecuador and Peru.

Through these experiences, a consolidated program for landslide education is established for teaching basic tools for landslide identification and characterization at local scales, proposed for academic staff and professional specialists. This training can be a fundamental and low-cost input for other landslide studies. Subsequent educational activities will include training of trainers in order to attain a continuous socialization of the knowledge and skills for landslide mapping.

Keywords Aerial photographs, DEM, GIS, Landslide education, Landslide inventory mapping, Stereoscopy.

Introduction

In order to develop a detailed assessment of landslide hazard and risk for a specific study area, it is first necessary to identify the locations of mass movements in an inventory map. These location maps provide a clear picture of the geographic distribution and density of landslides in a zone and indicate the general characteristics of different parts of each landslide identified (such as scarps, cracks and main body). Combined with geologic and hydrologic information, they can reveal sections of a study region that are more prone to mass movements and should be target of more specialized research. Thus, they become an essential input for subsequent analyses and designs related to landslide prevention and countermeasure design.

However, landslide inventory maps can have difficulties in their elaboration. For example, the map can be hindered by the modification of topography due to weathering or infrastructural development, presence of vegetation cover and/or prevalence of rugged terrain, all of which either erase distinctive landslide features or impede access to zones for their examination. In addition, feature identification in large areas can be time and resource consuming. In situ and remote landslide recognition and classification require specialized skills for the development of reliable inventory maps.

To address all of the complications exposed above, a landslide inventory educational methodology has been formulated such as that these limitations can be mitigated. Use of remote sensing, stereoscopy and geographic information systems applied in this methodology allow to work with considerable extensions of territory, including places of difficulty access. These tools also provide a more general view of landslide sites in a way that can bypass obstructions such as vegetation and exogenous processes and still visualize landslide features. Combining new tools with fundamental skills of geologic, geotechnical and topographic surveying, objects detected in the office can be fully confirmed in site. By designing a program that teaches all the necessary proficiency for landslide inventory, the knowledge gap can also be closed and

implementation of these types of map becomes technically and economically feasible. This is especially important for landslide-threatened communities with limited resources, which can be assisted to apply inventory methodologies independently and reduce their reliance on external specialists. Therefore this methodology is targeted to government officials, community leaders, professional engineers, academic researchers and any representative related to disaster prevention.

Application cases of landslide inventory education methodology in Latin America

The projects "Hazard Geology Focusing on Landslides in Tegucigalpa" and "Strengthening and Capacity Building of Professional Techniques for the Control and Mitigation of Landslide in Tegucigalpa Metropolitan Area" developed by Japan International Cooperation Agency (JICA) experts in Tegucigalpa, Honduras as described by Yamagishi, Yagi & Sato (2014), can be mentioned as one of the earliest applications of this specific inventory methodology in Latin America. Yamagishi (2014), Hirota (2015) and Sato (2015) explain some of the first cases of application in the Honduran projects and provide details of successive steps after inventory, such as hazard assessment and detailed geologic mapping. For this paper, application cases of this methodology in other countries of Latin America are described. One important distinction of this type of methodology is combining both traditional techniques such as stereoscopy and modern GIS application, exploiting all available resources for executing the inventory.

Authors such as Guzzeti et al. (2012), Burchfiel (2012), and Colombo et al. (2005) provide explanation about landslide inventory development, relationship with hazard and risk maps and applications using GIS and other information technologies. This paper, instead, focuses on educational approach of the landslide inventory topic, first presenting successful cases and then synthesizing the most important details for an educational program that can be applied even with limited resources for Latin America. More details regarding the execution of the methodology are included in Moncada et al. (2016).

Hazard geology focusing on landslides in Tegucigalpa

To better understand the antecedents of the specific methodology discussed in this paper, the first application is briefly described. It was developed in the project "Hazard Geology Focusing on Landslides in Tegucigalpa" executed by JICA , the Japanese Society Promotion of Science (JSPS) and the Engineering Polytechnic University (UPI) of Honduras from 2012 to 2014. During the duration of this project both professional engineers (from disaster prevention agencies and universities) and undergraduate students were trained in aerial photograph interpretation and contour map analysis in order to develop an inventory map for the city of Tegucigalpa. They also learned how to transfer their inventory to digital format, editable in GIS. The map generated was limited to inventory only and has been used as input for the subsequent project mentioned before. Fig. 1 and Fig. 2(left) show inventory activities and a sample of this inventory map respectively.

In addition of creating a landslide inventory map for all Tegucigalpa, the learning process developed during this project set the bases for resulting applications and improvements of the landslide inventory educational methodology focused on aerial photographs, contour maps and GIS applications mentioned in this article. Specifically, students were guided and corrected by the Japanese project experts in order to develop their own methodological document which narrated all the steps for their inventory mapping. The document was called: "Manual Para Elaboración de Mapa de Inventario de Deslizamientos de Tierra, Caso de aplicación: Ciudad de Tegucigalpa"; in English: "Landslide Inventory Map Elaboration Manual, Application Case: Tegucigalpa City" (UPI-JICA, 2014). Fig. 2 (right) shows the cover of this document. This manual was and is currently being used as reference textbook for the following training activities described.

Fig. 1 Training activities developed during JICA_JSPS-UPI Project

CEPEIGE course

The first example outside of Honduras of how this methodology was applied is that of a virtual course provided by the Pan-American Center for Geographical Studies and Research(CEPEIGE) of Ecuador in 2014. The title of this course was "XLI International Courser of Applied Geography: Geomorphology and Landslide Risk Management in Latin America". The international course was integrated by different training components, including risk management and basic landslide concepts, and the inventory methodology was applied in the topic "Identification, Cartography and

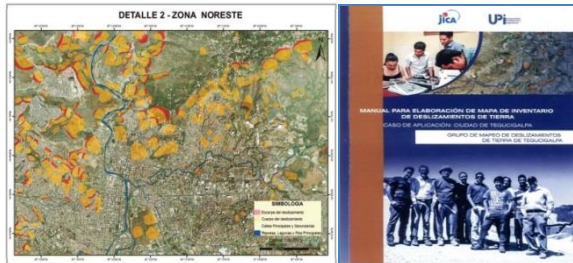Monitoring of Unstable Terrain", which was imparted from September until December, 2014.

Fig. 2 Landslide Inventory Map developed for Tegucigalpa-North East Zone (left) and cover of Landslide Inventory Map Elaboration Manual, Application Case: Tegucigalpa City (right)

This international course targeted professional civil engineers, geologists, geophysicists, geographers and university professors and researchers of several Latin American countries such as Ecuador, Argentina, Peru, Colombia, Chile and Dominican Republic. As a result of having participants well-versed in the skills necessary for inventory mapping, training of this component was divided into two phases: 1) Inventory Theory 2) Research Project.

First, participants were trained in topics such as landslide classification and typology, landslide maps, topographic features interpretation, inventory techniques, GIS applications and landslide block monitoring. During these initial sessions participants applied their knowledge using information of their respective localities. Then, for their final research project, participants chose a landslide site in their vicinity, proceeded to collect all necessary data, performed inventory analysis and put into practice all the skills acquired in the course to make a landslide inventory report and a preliminary hazard analysis to deliver as a final product. Fig.3 and 4 show examples of landslide inventory maps generated by different participants. Final report and mapping delivered by course students demonstrated the effectiveness of the training methodology for inventory, even with limited resources and time.

With assistance of virtual education platforms it was possible to further develop participants´ knowledge and skills using comment boards and videoconferences for more complete feedback with the instructors. Flexibility provided by this virtual modality permitted access to this education to greater number and diversity of participants, and in a longer period of time that allowed developing each learning objective fully. On the other hand, limitations of this approach included that a moderate percentage of participants did not complete their course and instructors were not able

to go together with participants in their inventory confirmation visits at each site.
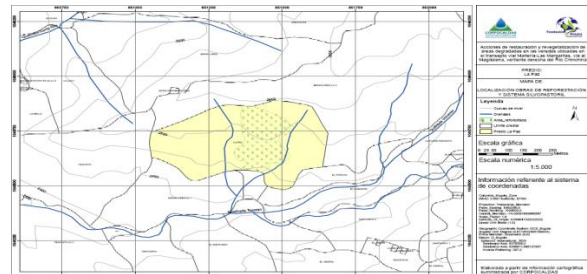

Fig. 3 Landslide feature identified over topographic map

Fig. 4 Landslide inventory map examples over satellite images

UNESCO ENHANS Project training

A second experience that has been applied for inventory education in Latin America is that of the landslide inventory component of UNESCO project called Extreme Natural Hazards and Societal Implications (ENHANS). Particularly speaking the project involved was that targeting South American countries of Chile, Ecuador, Peru and Uruguay from 2015 to 2016. The purpose of project ENHANS was the preparation of key officials in disaster management-related institutions in topics such as hazard assessment, risk assessment and resilience. For hazard assessment, the landslide component focused on inventory mapping to at least attain preliminary hazard mapping with aid of geology specialists in the target countries (except for Uruguay).

The key members selected for this training had a similar profile to those of the virtual course mentioned before (geologists, geographers, geophysicists, hydrologists, etc.), but included more government officials and disaster reduction management specialists rather than academic researchers.

Initially ENHANS Project started with introductory meetings at each of the different target countries in order to present the project to stakeholders. Landslide

component was introduced in the meetings at Santiago (Fig.5 left) and Quito (Fig.5 right) on April 2015 and at Lima on September 2015. This way the landslide component established the scope of the inventory methodology and the general details of how it would be implemented and by what means it could benefit the work of officials and decision-makers in the target countries.

Fig.5 Preparatory Ceremonies of UNESCO ENHANS Project in target countries, for example Santiago (left) and Quito (right)

Due to time constraints, training in the landslide inventory component was limited to one week per classroom (in person) learning session for the target countries. In the case to be exposed next, that of inventory instruction in Peru, the training was developed in November, 2015 and additional sessions are expected by the end of 2016.

Landslide inventory workshop was adapted to a shorter amount of time and, with the opportunity to execute site inspections, it was done this way: First, landslide inventory concept and techniques (such as stereoscopy) were introduced and preliminary applied to a nearby target area (Fig.6). For this training the neighboring site of Chosica was selected and some additional maps were developed for the region of Huancavelica. Then, initial inventory data identified remotely was used to define a field inspection activity at Chosica executed at the middle of the workshop. Feedback provided by this field inspection was used to enhance inventory and provided some initial insight for hazard mapping. Finally, all the inventory information was combined with GIS and DEM data to generate landslide location maps. An important advantage of working with government officials is that they must adhere to regulations and a Multinational Mass Movement Hazard Assessment Guide for the Andean Region (Proyecto Multinacional Andino, 2007) could be utilized to generate standardized mapping and inventory.

For UNESCO Project case, the complete extent of methodology was also divided in two phases, albeit differently than CEPEIGE course due to a vital objective of the project: preparation of key officials who then can replicate this methodology in their respective communities. Therefore the first phase consisted in

preparing a leading group of officials in landslide inventory mapping (as explained above) and for a second phase, this leading group will be supervised by the instructors so they can teach using the same methodology (adapted to their necessities) to new officials and then continue this replication autonomously.

Fig.6 Use of stereoscopes during training

Training has yielded successful results with officials participating being able to generate their inventory maps (Fig.7 and 8), refined by field visits (Fig.9) and establishing a draft for future pilot workshops initially assisted by specialized instructors as guides.
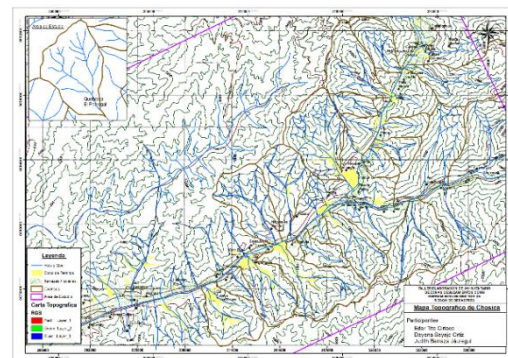

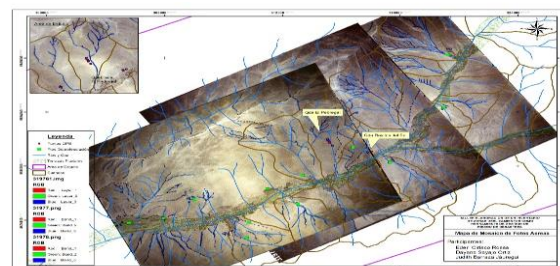Fig.7 Landslide inventory map over topographic maps of Chosica

Fig.8 Landslide inventory map of Chosica with aerial photographs used as data source.

Fig.9 Field visit at Chosica during training

Landslide inventory methodology developed from application cases

As a result of the necessity identified and the experiences described in this paper a more general landslide inventory methodology can be derived, as a base model to be duplicated and adapted, taking into account the conditions in Latin American countries. This way landslide inventory mapping can be executed in more places, by more officials, researchers and professionals and at different scales (local and regional) so landslide disaster management can be significantly improved. The details of this methodology are explained next.

Learning objectives

The main objective for the methodology is for all participants to able to generate by the end of the training a landslide inventory map that accurately reflects field conditions, by correct interpretation of landslide topography. More specifically participants must attain the following:

- Learn to use the tools related with aerialphoto interpretation and GIS that allow landslide topography identification.
- Recognize the basic principles of landslide classification
- Apply identification and classification tools to generate a landslide inventory map both individually and in group.
- Validate and enhance inventory through field visits of landslide sites
- Develop the preliminary basis of the creation of hazard, vulnerability and risk maps for landslides
- Acquire the capabilities to share the inventory methodology with collaborators

Summary of the procedure

The procedure necessary to reach the objectives is summarized in the outline of Fig. 10. The steps are

repeated in two main phases, which are an initial course to develop the necessary skills and a pilot course by the participants that graduated from the initial course that allows them to apply these skills in the socialization of knowledge by becoming trainers. This second phase, the pilot course, can also be used as initial course for other all-new participants. In any case all trainings done with a pre-defined study area of interest, and participants must analyse it by identifying and collecting all the necessary information of this area.
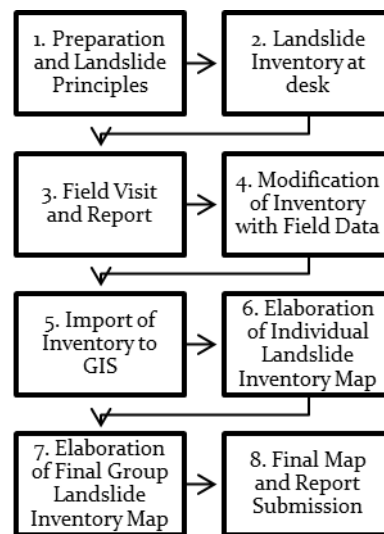

Fig. 10 Summary of landslide inventory methodology procedure

Conclusions and recommendations

- Training activities in all of the cases presented were able to successfully teach participants how to use available information for the development of landslide inventory maps. Therefore both conventional classroom education, as that in UNESCO ENHANS Project, and virtual classroom education, as that of the CEPEIGE landslide inventory module, can be applied to impart this methodology.
- Selection of the appropriate participants for the training is vital for its success. For the two cases exposed, both groups had already significant background and experience so training could be imparted in a week or a couple of weeks when time was very limited. If less favourable profiles are among those selected, training should take more time, but can also be successfully implemented like in the case of JICA projects in Honduras, such as JICA_JSPS project which was able to generate a

complete methodology manual with undergraduate trainees.

- One of the most important aspects of this training is the capacity to execute an adequate field visit and report of the landslide sites. So instructors are encouraged to visit the field directly with participants. For virtual courses, it is recommended a more rigorous inspection of field reports by instructors.

- In addition to landslide inventory maps, developing the capacities to form new trainers is one of the fundamental points of the methodology exposed. With adequate selection of junior instructors and thorough evaluation of them, a replicable model can be created. If an editable web database is available, such as that of the JICA project in Honduras, replication of this methodology can help to complete landslide information voids much faster, involving the collaboration of several trainees.

- Other important advantage of this methodology is that maps can be worked at a local scale, with a detailed inventory. If new instructors are able to work together with community leaders and local disaster professionals, this model can be applied to communities difficult to access by government authorities and help them strengthen their landslide hazard component independently.

- Important aspects to continue improving of this methodology include: evaluation for junior instructors, customized methodologies for different data and equipment available depending on target region and design of a simplified version for local emergency committee representatives with few or none engineering or scientific background.

Acknowledgments

References

Burchfiel, P. (2012). Visualizing Landslide Hazards: Methods for Empowering Communities in Guatemala through Hazard Mapping. Master's Theses. Paper 4187.

Colombo, A., Lanteri, L., Ramasco, M. and Troisi, C. (2005). Systematic GIS-based landslide inventory as the first step for effective landslide-hazard management. Landslides, 2(4), pp.291-301.

UPI-JICA (2014). Manual Para Elaboración de Inventario de Deslizamientos de Tierra. Caso de aplicación: Ciudad de Tegucigalpa. Agencia de Cooperación Internacional del Japón (JICA). Tegucigalpa. ISBN: 978-99926-701-1-8.

Guzzetti, F., Mondini, A. C., Cardinali, M., Fiorucci, F., Santangelo, M., & Chang, K.-T. (2012). Landslide inventory maps: New tools for an old problem. Earth-Science Reviews, 112(1–2), 42–66. http://doi.org/10.1016/j.earscirev.2012.02.001

Hirota, K. (2015). Landslide and geology education in Honduras, as activities of Japan International Cooperation Agency senior volunteer. Journal of the Japanese Landslide Society, Vol. 52, No. 4, pp. 36-42.

Moncada, R. & Yamagishi H. (2016). Landslide Inventory Educational Methodology Derived from Experiences in Latin America. Landslide Dynamics: ISDR-ICL Landslide Interactive Teaching Tools (LITT) (in press)

Proyecto Multinacional Andino: Geociencias para las Comunidades Andinas. (2007). Movimientos en Masa en la Región Andina: Una guía para la evaluación de amenazas. Servicio Nacional de Geología y Minería, Publicación Geológica Multinacional, No. 4, 432 P., 1 CD-ROM.

Sato, G. (2015). Investigation and Mitigation of Landslide in Republic of Honduras as Japan´s International Cooperation Program. Journal of the Japanese Landslide Society, Vol. 52, No. 4, pp. 1-7.

Yamagishi, H. (2014). Integrated Disaster Prevention Maps and Landslide Hazard Maps using GIS –Examples of Shikoku and Central America Honduras-. Journal of the Japanese Landslide Society, Vol. 51, No. 2, pp. 24-29.

Yamagishi, H., Yagi, H. and Sato, G. (2014) Landslide Hazard Mapping of Tegucigalpa, Honduras-Capacity Building by JICA-JSPS Project of 2012-2014. Proceedings of World Landslide Forum 3, 2-6 June 2014, Beijing, pp. 712-715.

Rigoberto Moncada (✉)

Central American Technological University, Faculty of Engineering, , Zona Jacaleapa, Tegucigalpa, Honduras.
e-mail:rigoberto.moncada@unitec.edu

Hiromitsu Yamagishi

Asian Institute of Spatial Information, Shiroishi-ku, Hongodori 2chome kita 3-10, 003-0025, Japan
e-mail: hiromitsuyamagishi88@gmail.com

The social construction of risk and landslides in Tuxtla Gutiérrez, Chiapas, México 2016

Jorge Paz, Raúl Gonzales, Elisa Sandoval, Mario Gómez

Abstract: Actually the paradigm prevails that disasters are natural, situation that limits the vision and the management of them. In the case of disasters by landslides in the south of the city of Tuxtla Gutiérrez, they have become a recurrent situation associated with heavy rains and seismic activity. The limited view of the authorities continues focusing on the emergency and to the study of phenomenon. In this case, is proposed the methodology for the construction of vulnerability and risk mapping of landslides to level blocks, whereas variables available in the general census of population, and by automates processes by applying the advantages of geographic information systems.

Keywords Landslides, mapping, risk, vulnerability.

Introduction

The growth accelerated and without order of the urban center, produced the occupation in slopes without considering the intensity of the slope (more than 35°) or the instability of the terrain. Another aspect is the occupation of apparently inactive old slope, with the absolute lack of knowledge of this. In the case of the city Tuxtla Gutierrez, Chiapas, México, it recorded growth occupied area ranging from 133 hectares in 1892 to 13.600 hectares in 2010. In terms of population, growth was 7000 inhabitants in 1982 to 537.102 in 2010. This mean an increase of more than 100 times in land surface occupied and an increase in population 76 times. This occurred in a period of 118 years according to the available date.

The city is on river valley with east-west orientation (17,5 Km), in some parts, it is narrow (1,8 Km) and in others it is wide (3,5 Km). The disorganized urban growth causes the occupation of a significant part of the northern and southern slopes delimiting the valley. In contrast to the South slope, the North is stable, formed by limestone rock and it corresponds to the Animas Plateau. The southern slope is constituted by sides of the karstic Copoya Plateau. The landform is subjected to intense weathering and erosion processes.

Certain materials detach from the margins and accumulate in its surroundings (colluvium). For this reason this slope is considered unstable. The plateau contains of a sequence of limonite, shale-sandstone and limestone-sandstone. This addition to the slope, drainage density, regosol type soil and the constant change in the use of land to urbanization, are determinants for the occurrence of landslides.

On the other hand, Chiapas is a State governed by the action of the tectonic plates of Cocos, North America and Caribbean, by what is intense and frequent seismic activity. In addition, by placing in the inter-tropical zone of the planet, it receives abundant rainfall and is often affected by different cyclones causing concentration of rainfall in very short periods of time. These factors (seismicity and heavy rains) are considered detonators of landslides.

There is an inventory of 31 events, 12 of which are prior to 2006 (year in which the registration was initiated) and 19 from 2006 to 2015. Everyone associated with the margins of karstic Copoya plateau (Fig. 1), in addition to a map of threats by landslides (Paz-Tenorio et al., 2012).

This research proposes the construction of vulnerability mapping and risk landslides given variables available in the general population and housing census, cartography free digital (both published by INEGI, 2011) and field trips.

Landslide

According to the classification of Varnes (1984), in the study area there are three types of landslides. Topples or falls occur in the highlands that coincide with the circuses of erosion of the tableland. Rotational landslides take place in the high and middle lands, mainly in urban areas or where agriculture/livestock is practiced. Flows, into specific sites with possible connection to ancient riverbed of surface currents, also coincide with areas where the original vegetation has been replaced by residential areas.

Subject and methodology

Bibliographical and cartographical review was made. The local studies on the subject are scarce and stand out for their contributions; Muciño-Porras et al. (2005), Membrillo-Ortega and Paz Tenorio (2006), Mora Chaparro et al. (2007), Martinez-Villar (2012) and Espi-
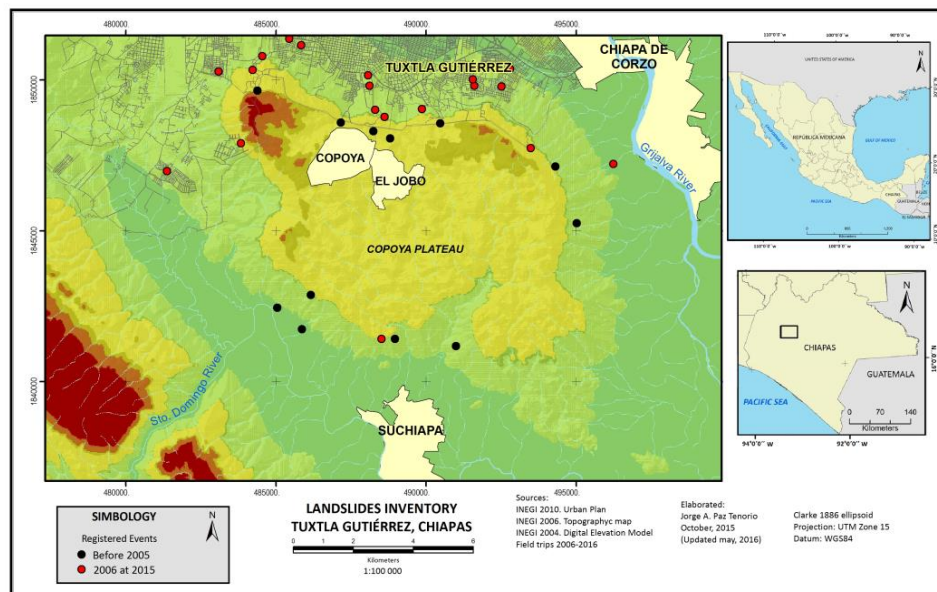
Fig. 1 Inventory of events

ritu-Tlatelpa (2012). In cartographic aspect, the digital cartography of the INEGI (2011) and the Census of population and housing 2010 were used. The map of hazards prepared by Paz-Tenorio et al. (2012) is used as the basis for delimiting the area of high and very high risk, and performs operations with the 12 variables present in the human settlements.

From this map, it is estimated that 13% (76,975 inhabitants) of the city's total population (537,102 inhabitants) living in these areas of high and very high risk. Here same concentrates 14.5% (23,968) of the total number of houses (165,206); distributed in 1,041 (13.2%) city blocks, being the total of city 7,837.

Finally, the geospatial analysis was carried out using ESRIs Arc Map version 9.3 and the data obtained were validated with a visit to the area.

Global Vulnerability and risk estimation

The digital cartography, incorporated into a system of geographic information (GIS), allows the manipulation of attributes associated with each of the traits represented. Aguirre-Gómez (2009) mentions that, while landslides are complex and result from interaction of multiple factors, both natural and human, it is feasible to manipulate these interactions through the use of GIS, which lets you create scenarios from specific unstable slopes, or zoning potential areas of instability.

As a result of destructive events that have occurred in Chiapas territory (Paz-Tenorio et al., 2011), have proliferated studies and assessments of vulnerability and risks, whose execution and results are accompanied by absence of data that hinder or preclude rigorous predictions, especially at the local scale (Villafuerte-Solís and Mansilla, 2010).

Landslides are the major hazard, combined with the vulnerability of populations, determines the risk. Throughout history, this hazard has caused a considerable number of disasters in various parts of the world. Alcantara-Ayala and Murillo-García (2008) have performed few of the works that include vulnerability and risk maps in México.

Murillo (2013), designed this type of cartography for the municipality of Pahautlán, Puebla. As a unit of analysis, defines "units of slope" delimiting areas based on riverbeds and lines of part water. Derived maps scale is 1:200.000.

In the case of vulnerability applies the approach Spatial Analysis of the Vulnerability (SAVE), which uses three fundamental concepts for understanding the vulnerability for activities interactions, these are: location, spatial relationships and spatial pattern.

In relation to the risk of landslides, Murillo (2013) is based on the conceptual proposal of Varnes (1984), which defines it as the probability of some degree of damage due to a landslide. Murillo divided into two areas obtained maps, the first focused on the population and the second to the equipment and infrastructure.

154

In the Atlas of risk factors of the Motozintla basin in Chiapas, Novelo-Casanova et al., (2013) presented vulnerability maps at two scales of approximation: 1:50,000 for the basin and 1:15,000 for the city of Motozintla. Vulnerability was classified into four categories: environmental vulnerability applied at the basin scale, and structural, socio-economic and global vulnerability at the city level. The Atlas presents four maps nationwide which identify equal number of drivers of risk.

Municipal Atlas of risks of Tuxtla Gutiérrez (H. City Hall of Tuxtla Gutiérrez, 2012), in Chapter 6, called "Identification of hazards, vulnerability and risks to disturbing phenomena of Natural origin", classified the risks in two large groups: phenomena hydro-meteorological and geological phenomena.

In the first group, mass movements are divided into landslides, downfall and flows. Neither the author of the classification of the registered movements nor the numerical scale of the maps were specified. The document concludes with a generic chapter for the identified hazards and vulnerability. This chapter is called "Synthesis of the degree or level of risk, hazard and vulnerability due to disturbing phenomena in the municipality of Tuxtla Gutiérrez".

Despite the unstable conditions of the southern slope, any previous urban development plan to 2001 identifies this risk, so it is considered that the population, housing, systems, roads and other public and private buildings have a vulnerability of origin, as established Romero (Maskrey, 1993).

The urban chapter of 2007 (H. City Hall of Tuxtla Gutiérrez, 2001 and 2007), is limited to classify "problematic soils", without issuing any clear recommendation, and nor refers to issues already reported in 2005.

For purposes of estimating the global vulnerability, is considered the experience of the methodology for the design of the vulnerability maps in the Atlas of risks of the municipality of Tuxtla Gutiérrez (H. City Hall, 2012).

Global Vulnerability (GV) consists of the sum of the vulnerabilities physical (PV), Demographic (DV) and socioeconomic (SEV), once multiplied by the respective weighting (Tab. 1, Fig.2, and Fig. 3). The concept of SEV is related to access to health, education and goods and public services.

It is conceived to risk as a continuous, dynamic, and changing in time and related to the development process. This process is a social construction, receiving influence and feedback of social, economic and political

$$GV = 0.5PV + 0.25DV + 0.25SEV \quad [1]$$

Where PV refers to the housing conditions and considers three variables x_i

$$PV = \frac{\sum_{x=1}^{3} x_i}{3} \quad [2]$$

DV refers to the conditions of the population y_i.

$$DV = \frac{\sum_{y=1}^{3} y_i}{3} \quad [3]$$

The SEV concept is related to access to health, education and goods and public services z_i

$$SEV = \frac{\sum_{z=1}^{6} z_i}{6} \quad [4]$$

Fig. 2 Interaction of hazard, vulnerability and exposure to risk

Table 1 Variables considered in the estimation of vulnerability

| VT	L	Indicator
Physical	1	% Homes with a single bedroom.
	2	% Homes without any good (radio, TV, refrigerator, washing machine, car, computer, phone, cell phone or internet)
	3	% Homes with dirt floors.
Demo-graphic	1	%Population density
	2	% Population under 12 years
	3	% Population older than 60 years
Socioeconomic	1	% Population of 6 to 14 years old who do not attend school
	2	% Population 15 and over without secondary completed
	3	% Population without medical coverage
	4	% Homes without refrigerator
	5	% Homes without piped water
	6	% Homes undrained

VT = Vulnerability Type, L = Level
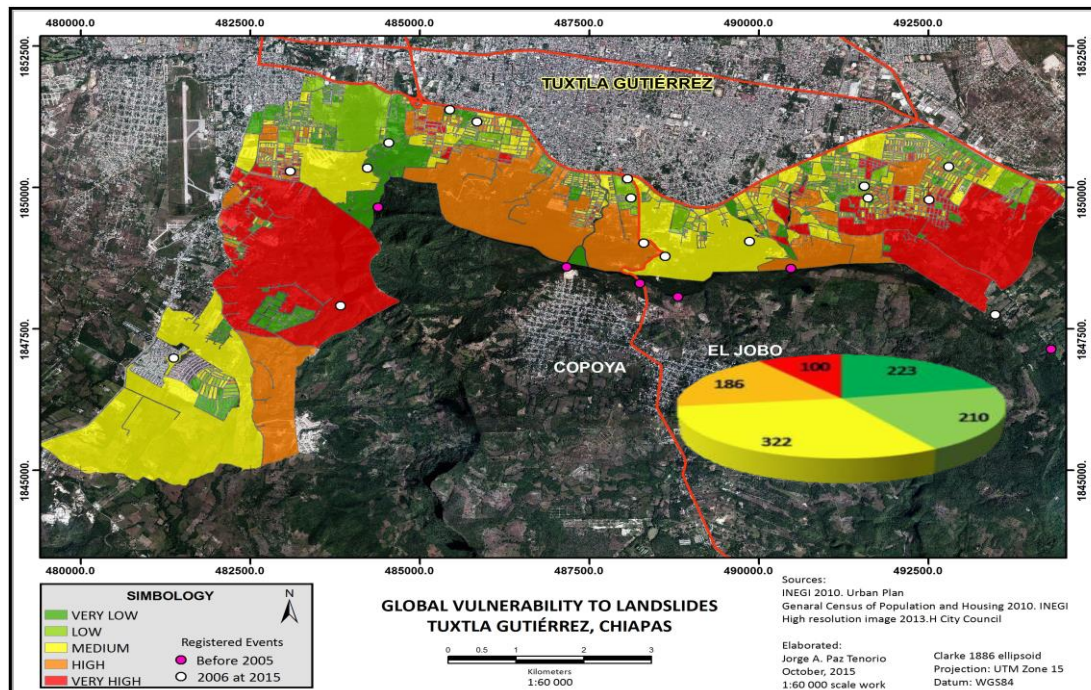
Fig. 3 Global Vulnerability show the distribution of blocks by Global vulnerability level

dynamics, that is to say, individual or collective, deliberate decisions (UN, 2009) (Fig. 4, Tab. 2).

Table 2 Distribution of habitants, homes and blocks by level of risk, Tuxtla Gutierrez, Chiapas

Level/ Unit	Habitants	Homes	Blocks
Very Low	4557	1920	198
Low	22237	7663	306
Medium	23065	7085	272
High	18304	4922	181
Very High	8812	2378	84
Total	76 975	23968	1041

Results and discussion

Results have been obtained new and interesting which for this area is not available. The veracity and precision of the same can be questioned, as well as the validity of the employed census databases. However, the methodological proposal for the preparation of cartography is the remarkable thing for a study that is as complex as it is the estimation of the vulnerability (V) and risk (R) before landslides, within a context where the risk is socially constructed.

The application of different processes of spatial analysis and geostatistical through geographic information systems such as the interpolation, the Morans I index and the index called "G general Getis-Ord", important information about the behavior of the spatial distribution of the studied phenomena. On the one hand, the values of urban block have a grouped distribution pattern, but also high values of V and R, are also targeted. The 12 variables chosen to V provided sufficient evidence to establish levels of V and R. This, in combination with data on the map of hazard from landslides (Paz-Tenorio et al., 2012) shows interesting results that explain its holistic manifestation in situations that predisposing the disaster by landslides.

Conclusions and recommendations

In a State as Chiapas, where levels of poverty and marginalization are among the most critical in the country, is understandable that the authorities do not bet a culture really preventive to diversity of hazard that coexist in a territory of otherwise complex in the natural, social, economic and political fields. As the reported events, the approach continues to be emergency care.

Rapid urbanization and the growth of urban areas to slopes (some of them are part of ancient landslides), is carried out studies without restrictions, which may be an additional ingredient to the vulnerability before this and other hazards such as floods and earthquakes.
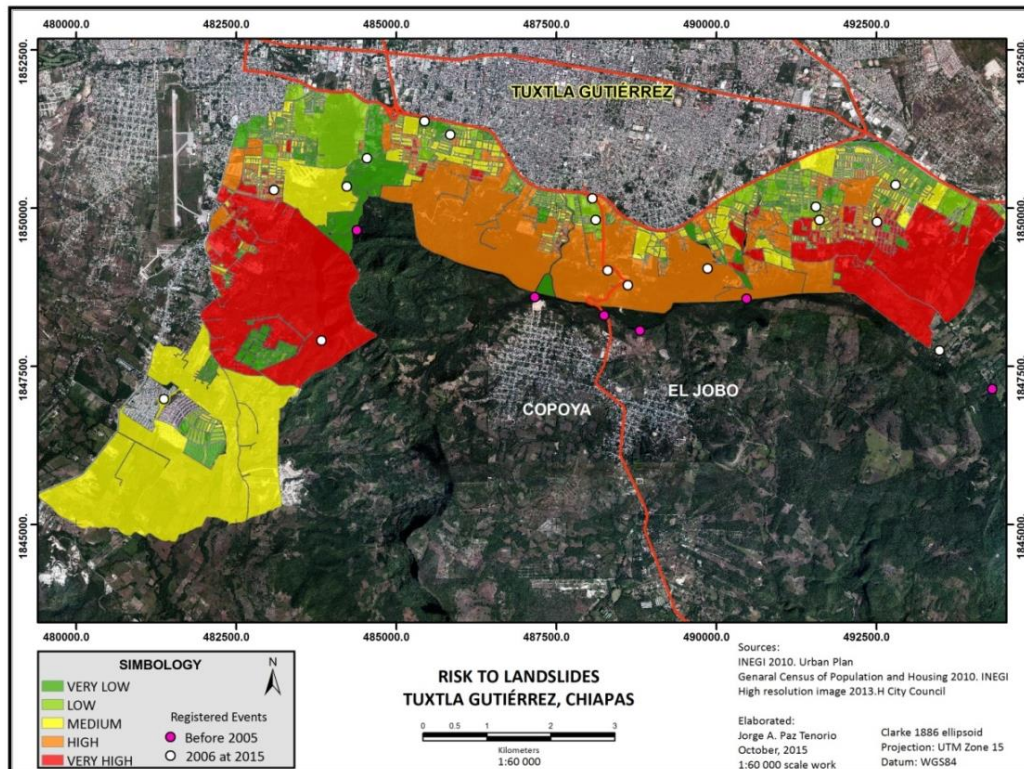
156

Fig. 4 Risk from landslides

It is convenient to update the database used from the population count INEGI in April 2015, and whose data even to 2016 may or not available.

Digital cartography produced by INEGI, which is available for free, allows you to associate census data to level urban blocks, something that greatly strengthens the results and their analysis. The shape format is compatible with great amount of both commercial software and free, enabling you to use and update of cartographic bases derived from this research by interested users.

It is convenient to add variables such as demographic, adults, elderly, disabled, in addition to measuring the institutional vulnerability from the way in which the inhabitants of this area perceived to institutions and authorities responsible for civil protection.

Studies of land use planning and urban development to Tuxtla Gutiérrez plans, consider the characteristics of rock and soil from the flanks surrounding karstic Copoya plateau, since these slopes are unstable in nature.

The academic and institutional links should be encouraged, articulated and maintained so that strong research will allow the guidance of residents, the coordination of institutional action and the strengthening of its credibility. Remember the case of the opinion of eviction in Lomas of Orient (Government of Chiapas, 2011) State Civil protection and annulled by specialists from CENAPRED in a technical note (SEGOB, 2015)

References

Aguirre-Gómez. R. (2009) Conceptos de Geomática y estudios de caso en México, Instituto de Geografía/UNAM. Colección Geografía para el siglo XXI: Serie Libros de investigación, México D.F. (ISBN: 970-32-2976-X). 331p.

Alcántara Ayala, I., Murillo García, F. (2008) Procesos de remoción en masa en México: hacia una propuesta de elaboración de un inventario nacional. Investigaciones Geográficas (Mx). (ISSN: 0188-4611). 47-64p.

Espíritu-Tlatelpa, G. (2012) Movimientos de masas y sus implicaciones en el ordenamiento urbano. El Sudcaliforniano; Ciencia, Innovación y Tecnología para el desarrollo de México. Año 4 No. 102. La Paz BCS. México. 22 de abril (ISSN 2007-1310). 1p

Gobierno de Chiapas. (2011) Dictamen de Identificación de Riesgos (Col. Lomas del Oriente), Instituto de Protección Civil para el Manejo Integral de Riesgo de Desastres, Chiapas. 18 de enero. 26p.

H. Ayuntamiento Municipal de Tuxtla Gutiérrez. (2012) Atlas Municipal de Riesgos. SEDESOL.

H. Ayuntamiento Municipal de Tuxtla Gutiérrez (2001) Carta Urbana. Escala 1:125 000, proyección UTM zona 15. 1 mapa, color.

H. Ayuntamiento Municipal de Tuxtla Gutiérrez (2007) Carta Urbana. Escala 1:125 000, proyección UTM. 1 mapa, color.

Instituto Nacional de Estadística y Geografía (2011) Censo General de Población y Vivienda 2010. URL: www.inegi.org.mx/sistemas/TabuladosBásicos/Default.aspx?c=27302&s=est. [abril 13, 2016]

Martínez-Villar, J. R. (2012) Vulnerabilidad social por remoción de masas en Tuxtla Gutiérrez. Caso Cueva del Jaguar. Tesis de Licenciatura. Universidad de Ciencias y Artes de Chiapas- Marzo 2012.

Membrillo-Ortega, H. y Paz Tenorio, J.A. (2006) Deslave en la carretera Tuxtla Gtz-Villaflores. Informe Técnico. INEGI . Chiapas. septiembre. 13p.

Maskrey, A. (1993) Los Desastres No Son Naturales, Red de Estudios Sociales en Prevención de Desastres en América Latina. 134p.

Mora-Chaparro, J.C., Carrera, M., García-Diego, A.M., Escobedo, S., Figueroa, H.N., Hernández, V.M., Sol, L.L., (2007) Reporte de observaciones geológicas en la ciudad de Tuxtla Gutiérrez, Chiapas. Informe técnico. Instituto de Protección Civil para el Manejo Integral de Riesgos de Desastre. 26p.

Murillo García, F. G. (2007) Análisis y Cartografía de Riesgo de Desastre por Procesos de Remoción en Masa en el Municipio de Pahuatlán, Puebla. Tesis de Maestría. UNAM. México.

Muciño Porras, J. J., Domínguez Salazar, F.F. y Villalvazo Báez, M. (2005) Informe técnico del problema de deslizamiento en las colonias Lomas del Oriente y la Cueva del Jaguar. Informe. Tuxtla Gutiérrez, Chiapas. 11p.

Naciones Unidas (2009).Terminología sobre reducción del riesgo de desastres. Estrategia Internacional para la Reducción de Desastres. UNISDR. Ginebra, Suiza.

Novelo-Casanova, D., Oropeza-Orozco, O., Figueroa-Maheng, J.M. (Coords) (2013) Atlas de Factores de Riesgo de la Cuenca de Motozintla, Chiapas. UNAM/IG/IGG. México.

Paz-Tenorio, J. A., Gómez Ramírez, M., González Herrera, R. y Domínguez Salazar, F.F. (2011) Los procesos de remoción en masa en Chiapas; una revisión de los últimos cinco años (2006-2011). Lacandonia Revista de Ciencias de la UNICACH Año 5, vol 5 num 1 junio. pp 113-122.

Paz-Tenorio, J. A., Gómez Ramírez, M., González Herrera, R., Murillo Sánchez, M.E. Domínguez Salazar, F.F. (2012) Mapa de Amenazas por Procesos de Remoción en Masa en la ciudad de Tuxtla Gutiérrez, Chiapas. VIII Reunión Nacional de Geomorfología. Guadalajara, Jal. Septiembre.

Secretaria de Gobierno SEGOB (2015) Visita técnica de seguimiento al proceso de inestabilidad de laderas que afecta a las Colinas lomas del oriente y cueva del Jaguar, municipio de Tuxtla Gutiérrez, Chiapas. Nota técnica. (25 de febrero) Centro Nacional de Prevención de Desastres, México. pp 24.

Naciones Unidas (2009). Terminología sobre reducción del riesgo de desastres. Estrategia Internacional para la Reducción de Desastres. UNISDR. Ginebra, Suiza.

Varnes, D.J. IAEG Commission on Landslides and other Mass-Movements, (1984) Landslide hazards zonation: a review of principles and practice. The UNESCO Press, Paris 63p.

Villafuerte Solís, D., Mansilla, E. (Coords), García Aguilar, M.C., Basail Rodríguez, A. y Angulo Barredo, J. (2010) Vulnerabilidad y riesgos en la Sierra de Chiapas: Dimensiones económica y social. UNICACH. Tuxtla Gutiérrez, Chiapas. (ISBN 978-607-7510-40-6) 240p.

Jorge Antonio Paz Tenorio (✉)
Universidad de Ciencias y Artes de Chiapas, 1° Av Sur Poniente no. 1460, col. Centro, CP.29000. Tuxtla Gutiérrez, Chiapas, México
jorge.paz@unicach.mx

Raúl Gonzales Herrera
Universidad de Ciencias y Artes de Chiapas, 1° Av Sur Poniente no. 1460, col. Centro, CP.29000. Tuxtla Gutiérrez, Chiapas, México
ingeraul@yahoo.com

Elisa Mercedes Sandoval Sierra
Universidad del Valle, Calle 17ª # 3e – 33 Pitalito, Colombia
elisaeg0792@hotmail.com

Mario Gómez Ramírez
Universidad Veracruzana, Facultad de Economía, Av. Xalapa Esq. Ávila Camacho s/n, Xalapa, Veracruz, México
mariogomez@uv.mx

Unstable zones in the highways and roads of Panama

Eric Chichaco

Abstract The instability of slopes and embankments in Panama, particularly on highways and roads, is a serious problem, especially in the western region, because of geological, topographical, climatic and tectonic features, combined with bad designs and lack of maintenance of embankments and drainage systems. In the history of Panama, landslides have occurred usually generated by seismic activity (moderate to high magnitude), by torrential rain (heavy-short and/or long), and due to excavations and cuts in contact areas of complex geomechanical behavior (e.g., Corte Culebra or Gaillard Cut, Panama Canal and roads). Some of these have caused deaths, injuries and/or economic losses, affecting the country's socio-economic system and producing environmental losses. This vulnerability to landslides in different scenarios commits us to improve engineering practices in all existing and planned works through the systematization of the hazards, and with the help of susceptibility maps and zoning of unstable areas.

Keywords instability, slopes, embankments, hazards, vulnerability, landslide, susceptibility maps

Introduction

In Panama, landslides on unstable slopes along highways and roads, although not as widespread as in other countries of the region, are a major hazard and a consequence directly associated with rapid population growth in vulnerable areas, without any land use planning. Due to weather conditions in Panama (hot and humid), the rocks are strongly weathered, and fine-grained residual soils often include planes of weakness. The topography and tectonics of the country have contributed to roadblocks and other forms of instability along roads. However, the poor design of drainage systems and/or their maintenance is considered to be the main factor (Willenfors and Arnio, 1993).

Although the higher elevations and slopes have a greater angle in western Panama, rocks and soils are less weathered and eroded than those to the east. The main trigger of landslides on highways and roads in Panama is precipitation (intense-short rain and/or prolonged). Despite the absence of accurate historical data of landslides triggered by earthquakes, the year of 1991 and 2003 were periods of intense seismic activity that caused major landslides.

Geological and geotechnical aspects of landslides along roads and paths in Panama

The main geological and geotechnical aspects of landslides on roads in Panama include:
1. Shallow landslides in residual soils (falling soil, rocks and trees): these can be fast (i.e., a few m/s) or slow (i.e., some mm/year) and are accelerated during the rainy season.
2. Rotational landslides in soils: occur in weathered clayey soils (saprolite), mainly. Eventually, rock fragmentation occurs. The break is fast and occurs during or after heavy rainfall (> 100 mm/d). Fig. 1 shows a rotational slide in a cohesive, highly plastic soil on the Panamerican Highway.

Fig. 1 Rotational slip in the Panamerican Highway, Tole, Chiriqui province (photo taken by Ministry of Public Work, Panamá in 2001)

3. Flows in fine-grained soils: occur in water-saturated soils during or after heavy rains.
4. Translational landslide in soils and rocks: take place in contacts between clayey soils and more

competent rock or soil. The break is fast and occurs during or after heavy rainfall (> 100mm/d).

5. Fall or rockslide: characterized by a fast break and occur during or after heavy rainfall (> 100 mm/d) (Willenfors and Arnio, 1993).

6. Debris flows: occur in saturated pyroclastic rocks (critical period may be <1 hour). When dry, fractures in soil/rock with high permeability are produced.

7. Detachment and overturning of dry soils.

The last two cases are less frequent on highways and roads in Panama.

Other aspects of landslides in the highways and roads of Panama

The most frequent landslides usually occur in slopes greater than 40°, especially in thin soil horizons (usually <0.6 m), clays, agglomerates, tuffs and very weathered and/or fractured basalts/andesites. In urban and rural areas of human occupation, landslides are generated in places without proper channeling of surface water, in areas of geological faults and geological contact walls of the valley, in the courses of rivers, and in sites with groundwater levels at the surface. Roads and paths in these places are usually affected.

In the Central Cordillera, characterized by the mountainous and hilly areas of volcanic origin, landslides are conditioned by geology, slope steepness and the presence of geological faults (see Fig. 2). On the other hand, landslides in the Panama Canal (at key points such as the Gaillard Cut, or Culebra) have occurred in areas of geomechanical contact (shales and basalts) and have disrupted the access to some sites.

Fig. 2 Road slip at Chiriqui-Bocas del Toro conditioned by the presence of geological faults and poor design of drainage system (photo taken by Eric Chichaco in 2012)

Design of embankments, water control and corrective measures for the stabilization of slopes

In the western region (Fortuna road-Chiriqui Grande), roadblocks have occurred on steep slopes (50° - 70°). Most of these cuts were made in the saprolite horizon, which is a potential rupture surface (almost all landslides are translational).

As for the control of water, mainly on roads, there are several factors that may contribute to landslide occurrence. For example, the lack of proper drainage of surface water (poor design), or a bad sizing (usually very small), allows water to infiltrate and saturate the unstable mass. In addition, the inadequate maintenance and cleaning of drainage systems is also aggravated by the accumulation of gravel, sediment, vegetation and industrial and domestic waste.

In the case of rockslides and certain types of agglomerates, gabion walls were built with satisfactory results. Geotextiles, geonet 3D, shotcrete, abutments and other controls are used in the highways and roads of Panama.

Recognition of landslides in the field: intrinsic and external indicators

Topographic indicators (relief)

Part of the Panamanian territory is composed of ridges, hills, and mountainous areas, as a result of its volcanic and tectonic origin. These are favorable conditions for landslide occurrence.

Geological and soil indicators

In Panama, igneous rocks (volcanic and intrusive), sedimentary, and very few outcrops of metamorphic rocks are present. Most of these rocks were formed in the Tertiary, some in the Quaternary, being the green Cretaceous shales the oldest. The high degree of weathering and fracturing of the rocks, the geological faults, and the intense tectonic activity in the geological past, make Panama a country vulnerable to landslides.

Hydrogeological indicators

There are many regions in Panama with shallow groundwater levels. This favors the reduction of resistance by the generation of pore pressure, increasing the weight of the soil and accelerating the weathering of rocks and soils. This produces moisture and poor drainage in those areas and water filtration can be observed on the faces of the slopes.

Land use indicators

Land use is one of the main indicators, since the Panamanian population tends to settle in areas most vulnerable to landslides. Construction in areas of

shallow water table, in artificial fillers, deforested areas and mainly on steep slopes and roadsides and paths are common.

Precipitation indicators

In Panama, two seasons are distinguished from the meteorological point of view: the dry season and the rainy season. The rainy season begins in May, extending until November or December, with annual minimum average of 1,000 mm and annual maximum average of 7,000 mm. It is considered the main external factor triggering landslides in our country. Landslides triggered by rain are related to the intensity, duration and distribution of rainfall. Fig. 3 shows a significant slide in the Trans-Isthmian Highway triggered by rainfall.

Fig. 3 Cebo Curve at Transistmica road, Quebrada Ancha, Province of Colon (photo available at www.laopinionpanama.com in 2012)

Seismic indicators

The Isthmus of Panama is located in the Panama Microplate, a seismically active area surrounded by the Caribbean plates (north), Cocos (southwest), Nazca (south), and the North Andean Block (east). Both the movement of the plates as well as local geological faults originate an annual average of 2000 earthquakes, the majority with epicenters in the sea. The maximum seismic intensity reached in the Modified Mercalli (MM) scale in Panama has been IX.

Vegetation indicators

Deforestation and burning are anthropic practices (among many others) affecting the highways and roads in Panama. They are made primarily for housing construction, infrastructure, agriculture and livestock purposes. All the indicators have been described by Chichaco (2005). These morphodynamic indicators are used in landslide hazard zoning models to define the landslide susceptibility of the studied region and to create susceptibility maps.

Landslide Triggers in Panama

Seismic activity

Seismic events usually have a moderate to high magnitude on the Richter scale, and greater than VI on the Modified Mercalli scale-MM (see Fig. 4). In the Isthmus of Panama, both the movement of the plates as well as geological faults have historically generated several earthquake-triggered landslides. The magnitudes of these earthquakes range from Mw=4.5 (e.g., in the slopes of Baru Volcano, Boquete, Chiriqui Province) and Ms=7.9 (e.g., along the ridges and mountains to the northeast of Panama City), according to Chichaco (2012).

Fig. 4 Landslides on fault planes because of the December 25, 2003 earthquake, Mw=6.2 in Puerto Armuelles (taken by Eduardo Camacho in 2003)

The rocks most affected by landslides triggered by seismic activity are sandstones and shales (due to the loss of shear force), and moderately weathered surface clay soils (due to the reduced shear force as a result of cyclic loading). The seismicity in Panama Microplate from 2013 to 2016 can be seen in Fig. 5.

In the chronology of earthquakes listed as triggers for landslides, there are no clear reports of events affecting roads and paths in Panama (see Tab. 1).

Rainfall (intense and/or prolonged rainfall)

Periods of intense and/or prolonged rainfall in the rainy season have led, through history, to major landslides in Panama City, mainly in the District of San Miguelito, as well as on highways and roads, and other mountain areas of the Republic. The intense precipitation has mainly caused rotational landslides and flows in the highways and roads of Panama (see Fig. 1 and Fig. 6)
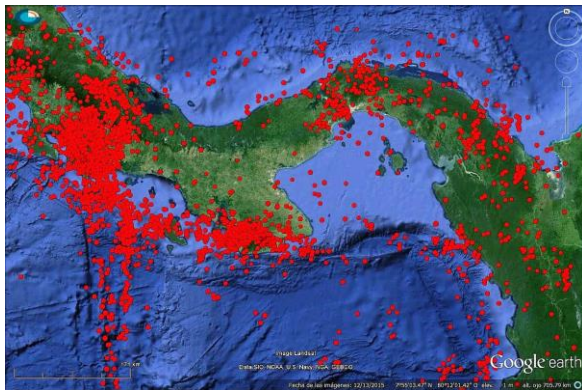
Fig. 5 Seismicity in Panama Microplate (photo courtesy of the Geoscience Institute, University of Panama)

Fig. 6 Aerial view of the slide at Villa Esperanza in October 1992 (photo taken by Jaime Toral in 1992)

Table 1 Chronology of earthquake-triggered landslides in the last 133 years in Panama (after Chichaco, 2016)

Date	Magnitude	Intensity (Mercalli-Modified Scale-MM)	Epicentral Area
September 7, 1882	7.9	IX Las Cruces; VIII-IX Colon and Miguel de la Borda; VI-VII Panama City; V-VI Azuero Peninsula	Off the coast of Colon, Caribbean Sea
October 1, 1913	7.5	VIII Tonosi VII Penonome; V Panama City	South of Azuero Peninsula, Pacific Ocean.
July 17, 1934	7.7	IX Puerto Armuelles; VIII David; VII Bocas del Toro and Sona; VI Azuero Peninsula; V Panama City	Charco Azul Bay, Chiriqui Province
July 13, 1974	7.3	VIII Jaque; V Panama City	Darien Province, Panama-Colombian border
July 11, 1976	7.1	VIII Jaque; VII La Palma; VI Bayano; V Panama City	Darien Province
April 22, 1991	7.6	VIII Changuinola and Guabito; VII Almirante, Bocas del Toro City e IColon island; VI Chiriqui Grande; V Volcan, Boquete	Valle de Limon, Costa Rica
July 30, 2002	6.2	VII Puerto Armuelles, Limones and soroundins; VI David, Paso Canoa, Concepcion, Alanje and Dolega; V-VI Boquete and Volcán; V Almirante and Changuinola	South of Burica Peninsula, Pacific Ocean
December 25, 2003	6.2	VII Puerto Armuelles, Los Potreros, San Andres, Progreso and San Bartola; VI-VII Divala, Gariche, Limones; VI David, Alanje, Gualaca, Dolega, Concepcion, Boquete, Horconcitos; V Almirante, Changuinola, Bocas del Toro island, Chiriqui Grande, Remedios, Tole, Las Lajas, Cañazas, Santiago and Coiba island	North of Puerto Armuelles
May 4, 2006	4.5	VI Bajo Boquete, Jaramillo Abajo; V Los Naranjos, Bajo Quiel	High Lands, Boquete
July 5, 2008	5.2	VI Los Plancitos, La Vaquita, La Victoria; V las fincas; IV Puerto Armuelles	Panamá-Costa Rican border

Conclusions

Highways and roads in Panama have been affected by landslides of various types: rotational slides in residual soils, translationals slides in soils and rocks, falls or rockfalls and debris flows. These events are related to high and steep areas, geology, geological faults and high water tables. Landslides have heavy rainfall as the main trigger, with no involvement of seismic activity.

Even though earthquake-triggered landslide events are not usual in Panama, the classification after Balder et al. (2016) will improve total seismic hazard assessment, especially for mountain regions. The main problems of stability and damage in many Panamanian highways and roads are caused by poor design of drainage systems and/or maintenance, and accumulation of industrial and domestic waste.

References

Balder Havenith H., A. Torgoev, A. Braun, R. Schlögel and M. Micu (2016). A new classification of earthquake-induced landslide event sizes based on seismotectonic, topographic, climatic and geologic factors. Geoenviromental Disasters **3:6** DOI 10.1186/s40677-016-0041-1

Chichaco, E. (2016). Landslides caused by earthquakes in Panama. Geosciences Institute. Internal Publication. Panama.

Chichaco, E. (2012). Landslides: Effects Assessment and Risk Management. Part I: Landslides and its effects. Lessons Learned from Latin America and the Caribbean. UNESCO and CYTED. Panama.

Chichaco, E. (2005). Landslides in Panama. Volume 1: Geodynamic Risks in Mining Activities, Ibero-American Science and Technology for Development (CYTED) and Center for Scientific and Technological Research (CICYT), Polytechnic School of the Coast (ESPOL). 1st Edition 2005, Imprenta Mistral, Guayaquil, Ecuador.

Willenfors, P., Arnio, T. (1993). Problems with Roads in Tropical Regions. Survey of two damaged roads in western Panama. Master of Science Thesis. Department of Soils & Rock Mechanics. Royal Institute of Technology, Stockholm.

Eric Chichaco (✉)

University of Panama, Geoscience Institute and Faculty of Engineering, (Campus Octavio Méndez Pereira, La Colina, El Cangrejo, Bella Vista & Campus Harmodio Arias Madrid) Panama City, Panama

e-mail: echichaco@yahoo.com

Modeling of landslides triggered by rainfall in the Colombian tropical and mountainous terrains

Edier Aristizábal, Edwin García, Hernán Martínez

Abstract Although landslides triggered by rainfall are common in tropical and mountainous basins, few studies have been applied to the case of tropical regions. New studies on forecasting, real-time monitoring and critical rainfall thresholds have become essential tools for the implementation of early warning systems. A conceptual and physically based model called Open and Distributed Hydrological Simulation & Landslides -SHIA_Landslide- (*Simulación HIdrológica Abierta*, or SHIA, in Spanish) was applied on a basin located in tropical and mountainous terrains of Colombian Andes to estimate the landslides caused by rainfall occurred on September 21th, 1990. The model is supported by geotechnical and hydrological features occurring on a basin-wide scale in tropical and mountainous terrains. SHIA_Landslide is a significant contribution that offers a new perspective with which to analyse shallow landslide processes by incorporating a comprehensive distributed hydrological tank model coupled with a classical analysis of infinite-slope stability under saturated conditions. To compare results effectively, the model SHALSTAB was applied using similar values for the parameters involved in SHIA_Landslide. SHALSTAB has been widely applied in engineering practice for shallow landslide susceptibility assessment. SHALSTAB, similarly to SHIA_Landslide, simulates the fluctuation of a perched water table lying above a slope-parallel impermeable layer controlled by rainfall. The results obtained by both models are compared with a landslide inventory presented during the event. Finally, by using a ROC (Receiver Operating Characteristics) analysis, it is possible to show a good performance of the model suggesting that SHIA_Landslide and SHALSTAB are able to simulate the physics involved on landslides triggered by rainfall in tropical and mountainous terrains. However SHIA_Landslide shows a considerably higher hit ratio without a considerable increase in false alarm rate, specificity and accuracy.

Keywords Rainfall triggered landslides, tropical environments, mountainous terrains, hazard assessment, SHIA-Landslide.

Introduction

Human and economic losses generated by landslides occur every year in all countries; however, its impact varies considerably according to the local geological conditions and socio-economic vulnerability (Harp et al., 2009). Although landslides are part of the natural and continuous geomorphological cycle, its occurrence in recent decades has been closely tied to world population growth and consequent urban expansion on susceptible slopes to this type of processes. The urban population of developing countries has increased by 5 in 40 years and continues to increase rapidly (UNFP, 2007). Estimation made by Varnes (1981) indicates that 89% of deaths, due to landslides, are located in countries around the Pacific Ring of Fire. Data presented by Sidle & Ochiai (2006) pointed out that in Latin America; Brazil presents the largest number of landslide victims, with an average of 88 fatalities per year.

Although the occurrence of landslide has affected the Colombian Andes for a long time, specific studies on this subject arise only from the 80's (Shlemon 1979). These studies essentially evaluated landslide susceptibility through methodologies based on morphological criteria (Chica, 1987; Ingeominas 1990, García, 2004). Few studies considering rainfall as a triggering factor have been carried out in Colombia. Early studies appear at the beginning of the 90's in Colombia (Paz & Torres, 1989; Castellanos & Gonzalez; 1997; Terlien, 1997; Echeverri & Valencia, 2004; Moreno et al., 2006).

Aristizabal & Gómez (2007) found a close relationship between precipitation and landslide occurrence, with a bimodal seasonal cycle with maxima during May and October, and minima during January and July. Aristizábal et al. (2011) analysed critical rainfall thresholds for landslides forecasting in the Aburrá Valley by empirical procedure. Recently, physical based models (e.g. SHALSTAB, SHIA_Landslide) have been used for the study of the susceptibility to shallow landslides (Aristizabal et al. 2015a, 2015b). Shallow landslides triggered by rainfall,

usually called soil slips, have a planar slip surface (Figure 1). These landslides are characterised by their shallow thicknesses (0.3–2 m), which are much smaller than their flow lengths, and by the slip of the surface fault parallel to the slope and the escarpment's small area (Anderson & Sitar 1995). This paper presents the results and discussion of the application of SHIA-Landslide and SHALSTAB models to the La Arenosa catchment located in Colombia. The obtained results show that the model is effective to be used on tropical mountainous watersheds, which are subjected to high rainfall intensities.

Figure 1 Aerial view of shallow landslide triggered by rainfall in Medellín (Colombia) in September of 1987 with more than 500 casualties (Photo: El Mundo Newspaper).

Hazard and vulnerability in the Aburrá Valley - Colombia

The Aburrá Valley, with an area of 1,326 km² and a length of 65 km, is located in the northern Central Cordillera of the Colombian Andes (Figure 2).

Its climatic conditions are typical of tropical environments, with an average temperature of 22 ° C and relative humidity of 70%. Precipitation has a bimodal distribution, with rainfall peaks during May and October. The mean annual rainfall varies from 1,400 mm in the central part and 2,700 mm in the north and south of the valley.

Currently, the Aburrá Valley has an estimated population of 3.3 million inhabitants, distributed in 10 municipalities as presented in Table 1. Population growth has been extremely fast; in a century the valley's population has increased 30%. Since 1950, thousands of immigrants have occupied areas exposed to natural disasters, and even over areas that had been affected by major events.
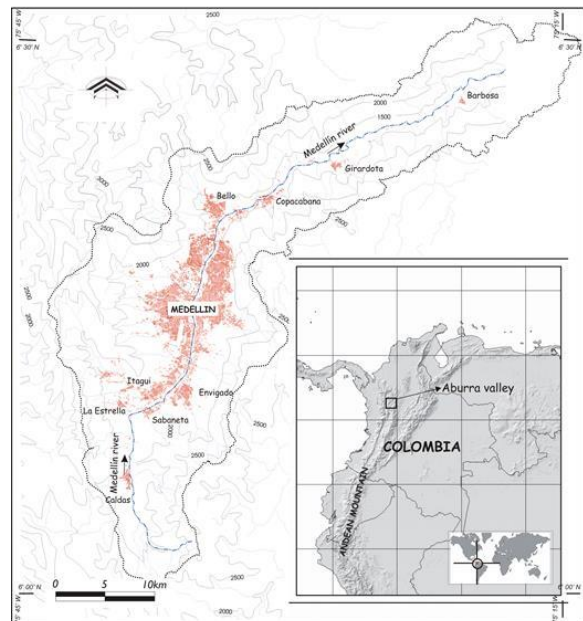
Figure 2 Location of the Aburrá Valley. Red colour represents urban development.

Table 1 Population and population growth in the Aburrá Valley (Data from DANE, 2007).

Cities	Population in 1951	Population in 1973	Population in 2005
Medellín	385.189	1´151.762	2´223.078
Bello	34.307	129.173	371.973
Envigado	28.797	73.057	175.240
Itaguí	20.151	103.898	230.272
Sabaneta	----------	16.518	44.820
Barbosa	15.507	22.271	42.537
Caldas	12.431	33.630	67.537
La Estrella	8.698	23.619	52.709
Girardota	10.956	17.879	42.744
Copacabana	10.720	29.997	61.421
TOTAL	526.756	1´601.804	3´317.166

The Aburrá Valley has been affected by a large quantity of disasters, most of them with a magnitude between small (<10 deaths) and moderate (10 – 100 deaths). According to Aristizabal & Gomez (2007), a total of 6750 disasters were registered in the Aburrá Valley during the period 1880 – 2007. In this inventory, floods represent 42% of disasters and rainfall triggered landslides represents 35%. It means that approximately 80% of the natural disasters that occurred in the Aburrá Valley are related to hidrometerological conditions that are precisely the triggering factor of both floods and landslides in this area of Colombian Andes. Table 2

presents the distribution of different types of landslides in the municipalities of the Aburrá Valley.

Table 2 Main landslides occurred in the Aburrá valley (Aristizábal & Yokota, 2006). Landslides in 1954, 1974, 1987, and 2012 have been the deadliest disasters.

Landslides	Date	Place	Deaths
Mudflow	18/06/27	Rosellón (Envigado)	22
Mudflow	12/07/54	Media Luna (Santa Elena)	>100
Debris slide	25/06/73	La Manguala (S.A. Prado)	13
Mudflow	29/09/74	Santa Domingo (Medellín)	>70
Landslide	04/02/75	Medellín	18
Debrisflow	20/10/80	San Antonio (Medellín)	>18
Debris slide	23/11/84	Santa Maria (Itagüí)	10
Mudflow	27/09/87	Villatina (Medellín)	>500
Complex rotational slide	31/05/08	El Socorro (Medellín)	27
Complex rotational slide	16/11/08	El Poblado (Medellín)	12
Complex rotational slide - debris flow	05/12/10	La Gabriela (Bello)	84

According to partial results showed by Aristizabal & Gomez (2007) using the DesInventar database, the disasters recorded have left a tragic toll of 1,390 deaths during the last century, most of fatalities were generated by landslides (74%) and flash floods (13%).

Study area

The "La Arenosa" catchment was selected for the implementation of the models. The basin is located 160 km to the east of the Aburrá Valley, with an extension of 9.91 km². Elevation ranges between 1,000 and 1,900 m.a.s.l. The geology consists of residual soils from granodiorite rocks covered in the gently sloping areas with slopes and fluviotorrential deposits.

A short duration, high intensity rainfall event impacted the basin of La Arenosa on 21 September 1990. In less than 3 hours a precipitation of 208 mm fell within the study area, triggering many landslides. During this event, the population was strongly affected, 20 people were killed and 260 had to be evacuated, 27 houses were destroyed and 30 others were damaged. Total losses were estimated at more than US $ 6 million (Hermelin et al., 1992).

Physically-based models implemented in the analysis

SHIA_Landslide model

SHIA_Landslide is a conceptual and physically based model for the prediction of rainfall triggered shallow landslides in tropical environments and complex terrains (Aristizábal et al, 2015a). It is a model program for computing positive pore pressure changes and attendant changes in the factor of safety due to rainfall infiltrations using a hydrological module coupled with an infinite stability slope geotechnical module. The model is supported by geotechnical and hydrological aspects occurring over a wide basin scale. The model analyses shallow landslide processes by incorporating a full and comprehensive distributed hydrological tank model that includes water storage in the soil and a geotechnical and classical analysis under saturated conditions.

SHALSTAB model

The approach developed by Montgomery & Dietrich (1994), called SHALSTAB model has been widely applied in engineering practice for shallow landslide susceptibility assessment. SHALSTAB, similar to SHIA_Landslide, simulates the fluctuation of a perched water table lying above a slope-parallel impermeable layer controlled by rainfall. However, SHALSTAB is based on the coupling of a steady-state hydrological model and an infinite-slope-limit-equilibrium slope stability analysis (Figure 2).

Comparison of the results by ROC analysis

To have a balance analysis, a quantitative performance evaluation of these models was accomplished through GIS-based, map overlay operations, and by calculating Receiver Operating Characteristic (ROC) values. (Fawcett, 2006)

The SHIA_Landslide model predicted 77% of observed unstable areas as well as 76% of observed stables areas (Tab. 3). In contrast, the model erroneously predicted 93% of unstable grid cells provided for the model when actually landslide did not occur over them, and as stable 0.52% stable grid cells

provided for the model where landslide indeed occurred.

Table 3 ROC analysis of SHIA_Landslide simulation for La Arenosa rainstorm event

Classifier	Area (m^2)	Percentage (%)	
		Total	Partial
Unstable areas			
True Positive	168.900	1.71	76.98
False Negative	50.500	0.51	23.02
Stable areas			
True Negative	7´306.700	74.06	75.68
False Positive	2´338.500	23.70	24.22

Aristizabal et al. (2015a) applied the model SHALSTAB for the rainstorm event of La Arenosa. Table 4 shows the ROC analysis for this model. Clearly model performance will increase as the hit rate (true positive) increases more quickly than the false negative rate.

Table 4 ROC analysis of SHALSTAB simulation for La Arenosa rainstorm event

Classifier	Area (m^2)	Percentage (%)	
		Total	Partial
Unstable areas			
True Positive	198.700	2.01	90.60
False Negative	20.700	0.21	9.40
Stable areas			
True Negative	5´595.700	56.49	57.80
False Positive	4´090.900	41.30	42.2

Most of physically based models that show high levels of prediction, also overestimate landslide occurrence. SHIA_Landslide was quantitative compared to SHALSTAB. SHIA_Landslide shows a much better performance in terms of unstable grid cells correctly classified. However, SHIA_Landslide results also show that more cells are predicted to be unstable than are observed.

Conclusions

Considering research scopes, both SHIA_Landslide and SHALSTAB can be useful frameworks for investigations on how a catchment system would likely respond in the short and long term to a rainfall perturbation from its current state. These models make possible to evaluate responses of tropical residual soil slopes under rainfall conditions. The knowledge of the processes, which govern slope stability conditions and evolution, could

help in arranging proper tools for hazard analysis and risk management.
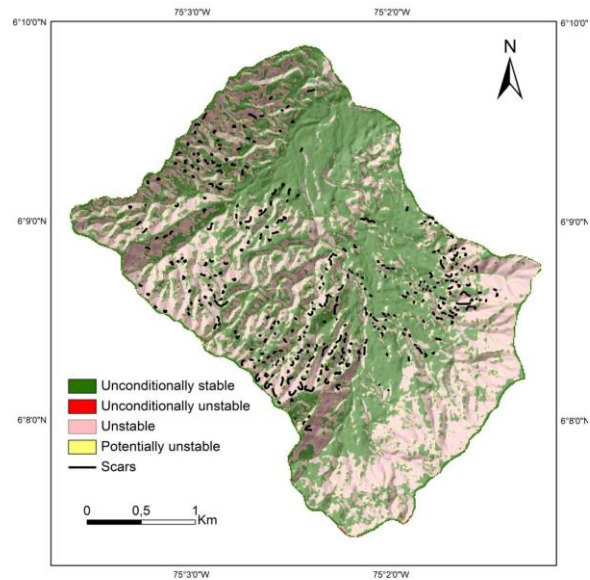
Figure 2 Areas with landslide occurrence triggered by the September 21st 1990 rainstorm simulated by SHALSTAB using q=90 mm/h.

References

Anderson A, & Sitar N (1995) Analysis of rainfall-induced debris flows. J Geotech Eng 121:544–552

Aristizábal, E. & Yokota, S. 2006. Geomorfología aplicada a la ocurrencia de deslizamientos en el Valle de Aburrá. Revista Dyna 149. Pág. 5-16.

Aristizabal, E.; Gonzalez, T.; Montoya, J.D.; Velez, J.I.; Martinez, H. & Guerra, A. 2011. Análisis de umbrales empíricos de lluvia para el pronóstico de movimientos en masa en el Valle de Aburrá, Colombia. Revista Escuela de Ingeniería de Antioquia, No. 15, Pag. 95-111.

Aristizábal, E. & Gómez, J., 2007. Inventario de emergencias y desastres en el Valle de Aburrá: originados por fenómenos naturales y antrópicos en el periodo 1880-2007. Revista Gestión y Ambiente, Vol. 10 No 2. Pág. 17-30.

Aristizabal, E., García, E. & Martinez, H. 2015a. Susceptibility assessment of shallow landslides triggered by rainfall in tropical basins and mountainous terrains. Natural Harzards, inpress.

Aristizabal, E., Velez, J., Martinez, H. & Jaboyedoff, M. 2015b. SHIA_Landslide: a distributed conceptual and physically based model to forecast the temporal and spatial occurrence of shallow landslides triggered by rainfall in tropical and mountainous basins. Landslides, inpress.

Castellanos R. & González, A. 1997. Algunas Relaciones de Precipitación Crítica –Duración de Lluvias que Disparan Movimientos en Masa en Colombia. 2ed. Panamerican Symposium on Landslides – ABMS, Vol. 2. Río de Janeiro. Pp. 863 – 878.

Chica, A. 1987. Geología y geotecnia en terrenos inclinados, modelo para la elaboración de planos geologico-geotecnicos. Magazine Fac. De Minas, Universidad Nacional de Colombia 119, 27-32.

DANE – Departamento Administrativo Nacional de Estadística. 2007. Censo General de 2005. www.dane.gov.co .

Echeverri, O. & Valencia, Y., 2004. Análisis de los deslizamientos en la Cuenca de la quebrada la Iguaná de la ciudad de Medellín a partir de la integración lluvia-pendiente-formación geológica. Dyna, Universidad Nacional de Colombia pág. 33-45

Fawcett, T. (2006). An introduction to ROC analysis. Pattern Recognition Letters, 27, 861-874.

García, H. 2004. Evaluación de la susceptibilidad a los movimientos de masa usando sistemas de información geogràfica y redes neuronales artificiales. Disertación de Maestrìa, Universidad de Brasilia, Brasilia

Harp E.L., Reid M.E., McKenna P.J. & Michael J.A. 2009. Mapping of hazard from rainfall-triggered landslides in developing countries: examples from Honduras and Micronesia. Engineering Geology, in press.

Hermelin, M., Mejía, O. & Velasquez, E. 1992. Erosional and depositional features produced by a convulsive event, San Carlos, Colombia, September 21, 1990. Bulletin of the International Association of Engineering Geology 45, 89-95.

Ingeominas, 1990. Zonificacion de aptitud del suelo para el uso urbano costado occidental de Medellín. INGEOMINAS. 91pp.

Montgomery, D. R. & Dietrich, W. E. 1994. A physically based model for the topographic control of shallow landsliding. Water Resource Research 30. Pág. 1153-1171.

Moreno, H., A., Vélez, M., V., Montoya, J., D. & Rhenals, R., L., 2006. La lluvia y los deslizamientos de tierra en Antioquia: análisis de su ocurrencia en las escalas interanual, intranual y diaria. Revista Escuela de Ingeniería de Antioquia, No 5. Pág. 59-69.

Paz, C. I. & Torres A. M., 1989. Precipitación y su influencia sobre algunos deslizamientos ocurridos en las laderas del Valle de Aburrá. Tesis pregrado, Universidad Nacional de Colombia. 174 pp Scheidegger, A. E., 1998. Tectonic predesign of mass movements, with examples from the Chinese Himalaya. Geomorphology 26, 37-46.

Shlemon, R., 1979. Zonas de deslizamientos en los alrededores de Medellín, Antioquia (Colombia). Publicaciones Geológicas Especiales del Ingeominas. 45 pp

Sidle R.C. & Ochiai H. 2006. Landslides: processes, prediction, and land use. Water Resources Monograph 18. American Geophysical Union, Washington D.C.

Terlien, M.T.J., 1997. Hydrological landslide triggering in ash-covered slopes of Manizales (Colombia). Geomorphology 20. Pág. 165-175

UNFP (United Nation Population Fund), 2007. Estado de la Población Mundial 2007: liberar el potencial del crecimiento urbano. Informe de la UNPF, Pag. 108.

Varnes, D.J. 1981. Slope stability problems of Circum-Pacific Region as related to mineral and energy rsources, Am. Assoc. Pet. Geol. Studies Geol., 12. Pág. 489-505

Edier V. Aristizábal Giraldo （✉）

National University of Colombia at Medellín, Department of Geosciences & Environmental Engineering, Medellín, Colombia

e-mail: evaristizabalg@unal.edu.co

Edwin F. Garcia Aristizábal.

Universidad de Antioquia UdeA, Department of Civil & Environmental Engineering, Medellín, Colombia.

e-mail: edwin.garcia@udea.edu.co

Hernán E. Martinez Carvajal

University of Brasilia, Department of Civil & Environmental Engineering, Brasilia, Brazil.

National University of Colombia at Medellín, Department of Civil Engineering, Medellín, Colombia.

e-mail: carvajal@unb.br

Electric Resistivity Tomography in landslide and infrastructure characterization in El Salvador

Alonso Alfaro

Abstract Electrical resistivity tomography test is based on the principle of electric current transmission through the soil and the drop of potential. According to electricity properties, the electric current moves from the anode (positively charged electrode) to the cathode (negatively charged electrode) generating electric potential lines perpendicular to the flow lines or flow paths. The magnitude of that electric potential is directly proportional to the intensity of the current, a variable previously known, and inversely proportional to the resistance of the medium through which current passes; which is the unknown variable to be determined by the test.

The uses of this branch of geophysics in the task of those institutions that are responsible for monitoring and maintaining infrastructure is wide-ranging. Electric tomography allows us to infer not only the stratigraphy of the place where it is performed, but it identifies the existence of voids, or the presence of water, situations that may be harmful to landslides and to certain infrastructure components.

In this paper some of the experiences made by the Department of Climate Change Adaptation and Risk Management of the Ministry of Public Works of El Salvador (DACGER) in the use of electrical tomography will be exposed. Specifically, the use of the given technology in landslide characterization will be discussed, as well as the use in the assessment of deteriorating sanitary infrastructure.

The limitations of technology are also exposed. How this situation can be overpassed by other geophysical test or other technologies will also be debated.

Keywords Monitoring, Geophysics, Electric Resistivity Tomography

Introduction

Electrical tomography test is one of the most developed methods in the geophysics field. While it has it origin in the exploratory process for extractive industries such as oil and gas, the actual usages range from Soil Characterization to archaeology (AGI, 2016).

However, the usage of this technology has no limits but creativity and the proper understanding of the methodology and its inherent limitations. This document begins with a short explanation of the Electric Resistivity Tomography test methodology and its limitations. After this introductory section, we present two uses given to electric tomography in everyday task at the ministry of public works In El Salvador: firstly for landslides monitoring, and secondly for drainage infrastructure assessment.

Electrical tomography test on a glance

The science behind it

Electrical tomography test is based on the principle of electric current transmission through the soil and the drop of potential. As any other electric current, current introduced in soil produces a magnetic field following the right hand rule: since the voltage introduced in the soil is already known properties of the conductive mean can be inferred.

According to electricity properties, the electric current moves from the anode (positively charged electrode) to the cathode (negatively charged electrode) generating electric potential lines perpendicular to the flow lines or flow paths.
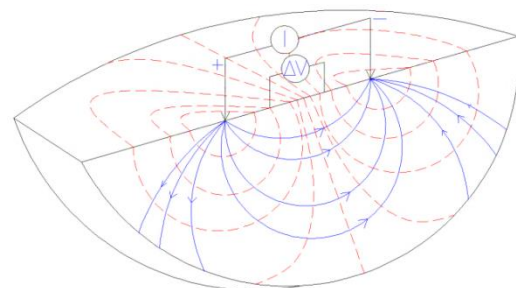

Fig. 1 Electric flow and potential distribution in soil. Notice that the reading is not a perfect vertical slice, but the average of a semi sphere portion of soil.

The magnitude of that electric potential is directly proportional to the intensity of the current, a variable previously known, and inversely proportional to the resistance of the medium through which current passes; which is the unknown variable to be determined by the test. The field arrangement needs the positioning of an array of regularly spaced electrodes, connected to a central control unit. Resistivity data are then recorded via complex combinations of current and potential electrode pairs to build up a pseudo cross-section of apparent resistivity beneath the survey line. The depth of investigation depends on the electrode separation and geometry, with greater electrode separations yielding bulk resistivity measurements from greater depths. There are various ways of arrangement of positively and negatively charged electrodes. Similarly, the other electrodes which serve for voltage measurement may have different arrangements. Different arrangements commonly used are presented on Fig. 2.
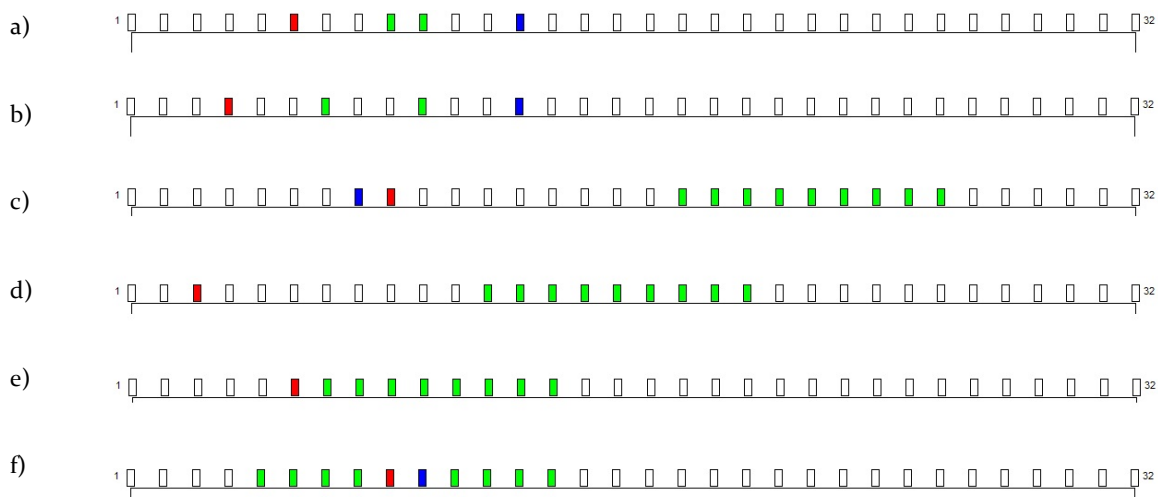
Fig. 2 Usual configurations of Electric Resistivity Tomography test. Red and Blue indicate electricity injection points; green indicates where potential is measured. a) Schlumberger, b) Wenner, c) Dipole-dipole, d) Pole-dipole, e) Pole-pole, f) Schlumberger Inverse.

Electric Resistivity Tomography measures resistivity. Resistivity, measured in $\Omega \cdot m$, is the mathematical inverse of conductivity. It is a bulk physical property of materials that describes how difficult it is to pass an electrical current through the material. Resistivity measurements can be made with either an alternating current (AC) or a direct current (DC). As resistivity measurements are frequency dependant, care must be taken when comparing resistivity values collected using different techniques.

Clay materials, metallic oxides, and sulphide minerals are the only common sedimentary materials that can carry significant electrical current through the material itself. As such, the resistivity of most near surface materials is primarily controlled by the quantity and chemistry of the pore fluids within the material. Any particular material can have a broad range of resistivity responses that is dependent on the level of saturation and the concentration of ions. (Surface Search Inc, 2011)

The advantages of multi-electrode tomography test over conventional resistivity method are notorious: they extract the range of true resistivity from the inverted resistivity models, and there is large density data coverage for better resolution and less time for data acquisition at the same time. The geophysical anomaly is directly seen and demarcated from the 2D resistivity models directly. Data processing is based on an iterative routine involving determination of a two-dimensional (2D) simulated model of the subsurface, which is then compared to the observed data. Convergence between theoretical and observed data is achieved by least squares optimization. The extent to which the observed and calculated theoretical models agree is an indication of the validity of the real resistivity model, indicated by the final root-mean-squared error between the proposed model and the readings (Terradat, 2014).

Experiences in the ministry of public works

Landslides

The Electric Resistivity Tomography was acquired by the ministry of public works having in mind the characterization of landslides sites. Consequently, the

first use given to the equipment happened during the characterization process of a landslide occurred in the kilometer 18. 5 of the Sal-38, route also known as CA-1A.

Thanks to Electric Resistivity Tomography we were able to discover properties that may have been impossible to find without the use of geophysics. While the presence of water in the soil mass was already known, the amount of it and its path in the whole soil mass remained ignored. The solution given to the landslide needed this information in order to stabilize it. Without the Electric Resistivity Tomography the technical solution would have been more subjective.

The Electric Resistivity Tomography interpretation allowed us to identify where the water was concentrated, by pointing out the section in the soil

mass with a leaser soil resistivity, once identified, the technical solution to control the landslide required the precise building of sub superficial drainages. The landslide occurred in the SAL 35-n route (also known as CA-1A Route) took place during the night of January 16th 2009. More than 80,000 m³ of soil mass moved about 5 m towards the highway shoulder. The landslide continued to move during several months on a decreasing speed. A full description of other steps given in order to stabilize this landslide is given in (Alfaro et al, 2013).

A compilation of the One of the Electric Resistivity Tomography profiles obtained in the landslide is presented on Fig. 3.
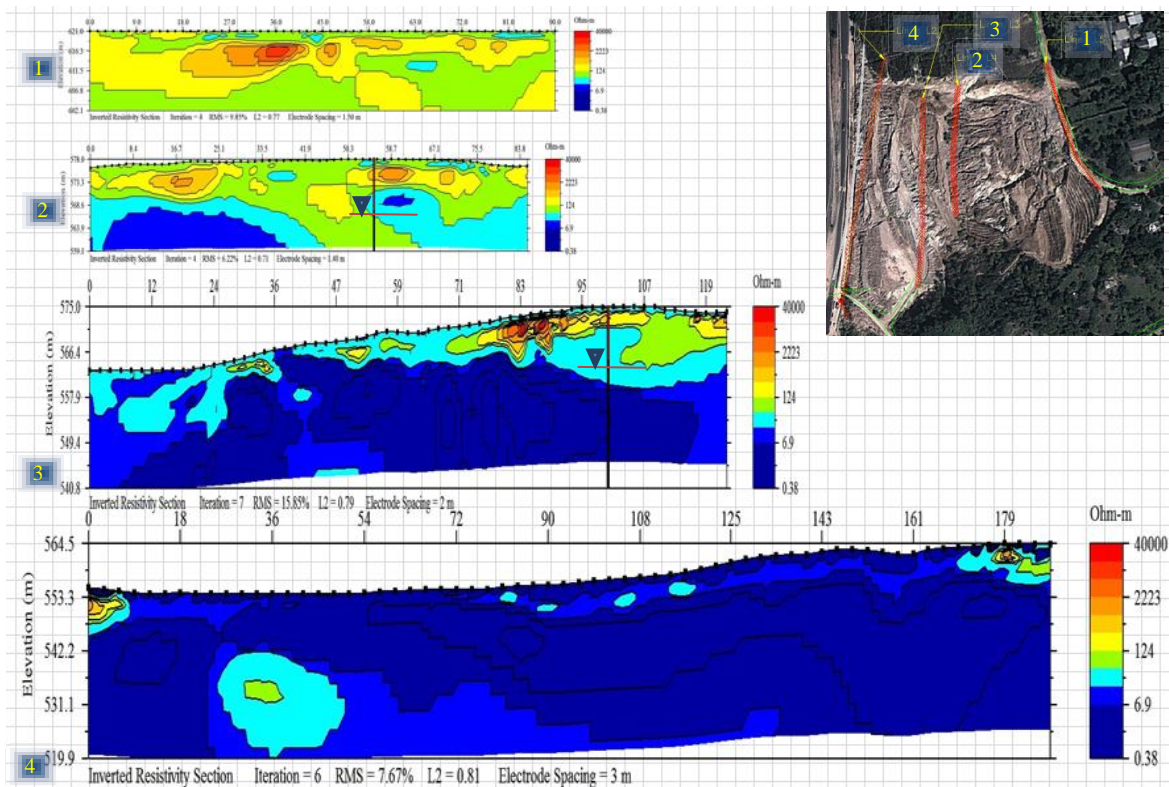
Fig. 3 Compilation of Electric Resistivity Tomography profiles, adjusted to maintain the vertical and horizontal scales. Source (DACGER, 2012)

Due to the relatively large size of the investigation site, four Electric Resistivity Tomography sections were performed. In these six profiles it was determined that the groundwater level follows the surface level. Unfortunately, since many land movement works took place in the site, it was difficult to follow the groundwater level using recurrent Electric Resistivity Tomography tests. Though, thanks to the initial Electric Resistivity Tomography test the sub soil

drainage was planned, and hence, it was possible to induce an increase in the groundwater level depth.

Non-landslide uses of Electric Resistivity Tomography

Nevertheless the original use given for Electric Resistivity Tomography was linked to landslide characterization, everyday requirements of this ministry allowed us to think about potential uses of the

technique. In the majority of these cases, the lack of Geophysics techniques would have meant longer test processes or, in the worst case scenario, a significant amount of lost information.

The cases presented next show two different kind of application given to Electric Resistivity Tomography. The first one consists in the usage of Electric Resistivity Tomography in the sewage structural assessment performed in the upper parts of the city of San Salvador. The second one is related to an on-going research that tries to evaluate the settlement of the main building of the school of medicine of the University of El Salvador.

Colonia Escalón neighbourhood drainage system

The studied zone is an area which drainage systems ages back to 1950´s. This area has been designated as critical for the urban drainage system of the northern part of Colonia Escalón neighborhood, in accordance with the Drainage Division of DACGER. As an illustration of this, several drainage collapses have occurred near the investigated area.

In the tests performed in this area, we had and extra condition to be considered. This is why having in mind how the test works and its limitations. Since the test was performed in the middle of urbanized area, the heterogeneity of resistivity properties in the area was important. At the same time, same resistivity reading could mean different situations. For instance, if we had an important case of scouring, but whit the presence of water, we would have a low electric resistivity area, on the other hand, if this area is dry we will have void, an though, a high electric resistivity area.

The info given by the Electric Resistivity Tomography test was supported by the info produced in parallel by a Closed Circuit Television System equipped remote controlled devise. The CCTV Equipment looks for minor cracks in the pipes and gives us a real time situation inside the pipes. If there is evidence of scouring or leakage the data provided by Electric Resistivity Tomography would be ratified. However, this ratification does not deliver us from performing additional exploratory tests, such as SPT. Additional surveys have not been done at this time.

One of the profiles that can be considered as suitable for presenting is depicted on Fig. 4.
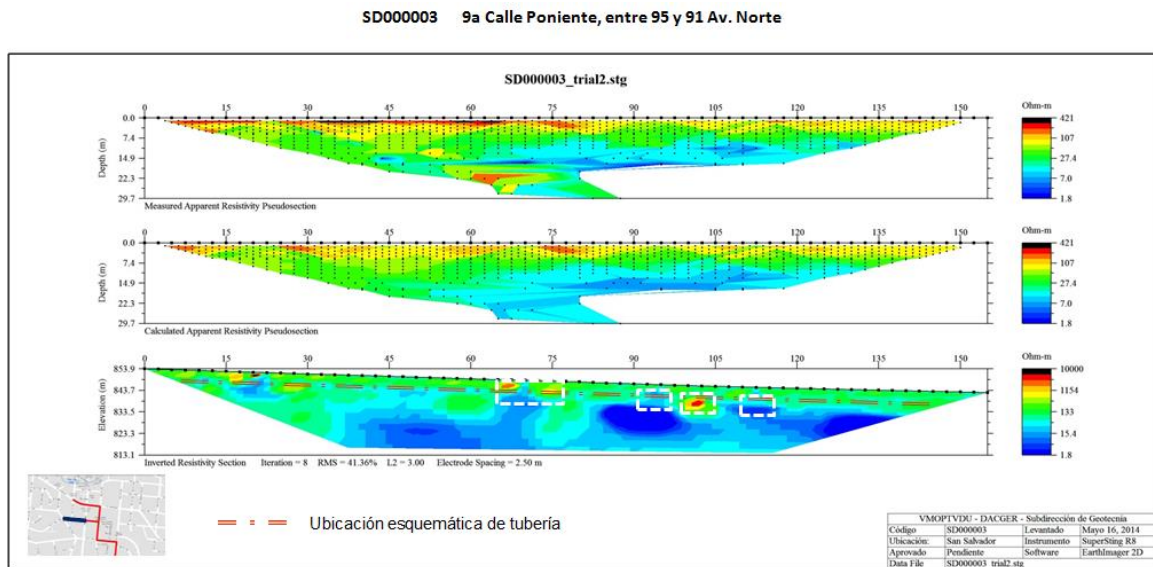
Fig. 4 Resistivity section in colonia Escalón neighborhood. The upper profile indicates the reading acquired in the test, followed by the generated model and the correspondent resistivity section (DACGER, 2014).

In this profile an upper layer of medium electric resistivity was found. However, a slight variation of lower resistivity allows us to identify the already known presence of the 16" diameter pipe. Beneath that layer we found a low resistivity segment, approximately at 833 meter above sea level. This low resistivity may be caused due to natural presence of water. In this resistivity scheme, lower values start at 2 ohm-m and go up to 5000 ohm-m.

Additionally to these layers, there are four notable points; two of them indicate the presence of segments of pipe with a high resistivity level, while the other two indicate the presence of points with low resistivity.

These points indicate transversal pipes and the presence of leakages respectively.

Universidad de El Salvador school of medicine building case

The main building of the school of medicine is a forty years old seven stories reinforced concrete building. The building is structurally divided in three sections. The middle section presents a minor settlement if compare with the other two. The profiles produced by the Universidad de El Salvador department of geophysics are presented in Fig. 5.

Beneath the basement level there are more than 30 compartments or chambers thought to be designed in order to collect the water coming from sub terrainwater flow identified in the place. Consequently, these cham-
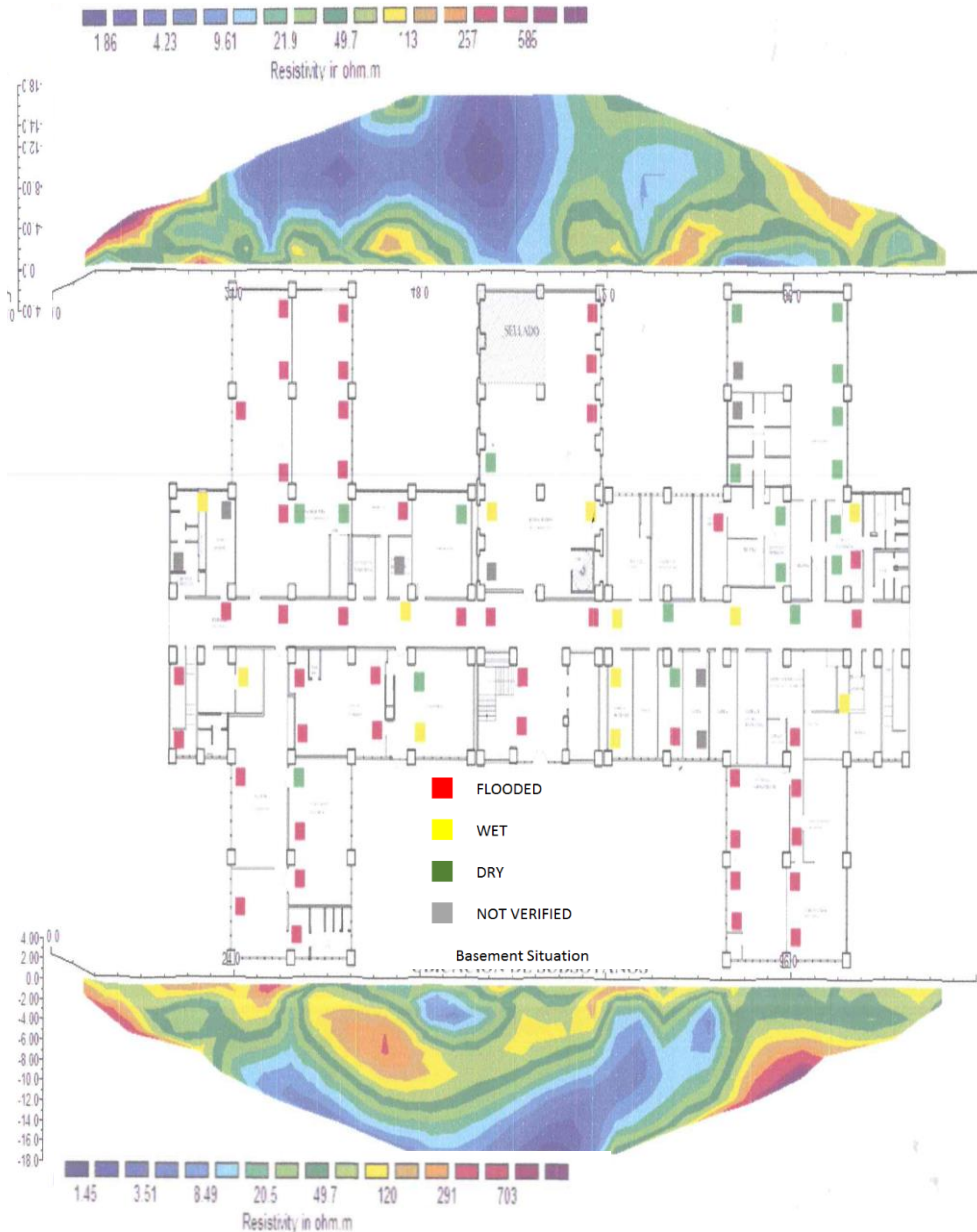
Fig. 5 Electric Resistivity Test profiles at School of medicine. (UES, 2016)

175

bers are filled with water all year long, giving and ideal location for the appearance of *aedes aegypty* mosquitoes.

Since there is no register of the initial location of the water flow, Electric Resistivity Tomography tests have been performed in order to locate it and catch the water before it reaches the building.

It is important to note that the western part of the building, section that corresponds to the upper part of this figure, presents a shallower presence of water, according to the low resistivity registered. The existence of sand with relatively high water content was found at about 5.5 m depth.

While the solution to this situation is still not formulated, more geophysics tests and other surveys will be done.

Conclusion

Electric Resistivity Tomography is an effective tool for monitoring and evaluation of landslides. However, the interpretive process is limited by the overall experience achieved by the users and site limitations. Nevertheless, if conditions are given, Electric Resistivity Tomography could also be used as a semi-permanent way to monitor groundwater level. Since applications can vary greatly, in order to have the best results, a high level of experienced has to be gained. Accordingly, this experience must be specific to each possible use. It is necessary that the Ministry of Public Works and other Salvadorian institutions to do more Electric Resistivity Tomography tests, similar to those presented in this document, in order to achieve a higher level of experience.

References

AGI (2016) About Us AGIUSA URL: https://www.agiusa.com/about-us [Last accessed: May 14th 2016].

Alfaro, A.; Cortés, D.; Calderón, S. ; Kuraoka, S.; Montoya, A. (2013) Identification of Sliding Plane and Effectiveness Study of Drilled Sub-Surface Drains in a Landslide. Primer Congreso Centro Americano Y Del Caribe de Deslizamientos, Tegucigalpa.

DACGER (2014) REF. MOP-DACGER-SG-009/2014 INFORME TÉCNICO: Ensayos de Tomografía de Resistividad Eléctrica en zona norte de Colonia Escalón, San Salvador, San Salvador. Ministerio de Obras Públicas Transporte Vivienda y Desarrollo Urbano. El Salvador.

DACGER (2012) REF. MOP-DACGER-SG-2012 INFORME TÉCNICO: Ensayo de Tomografía de Resistividad Eléctrica en zona de deslizamiento de Km 18.5 de la Ruta CA-1A Este, Delgado, San Salvador. Ministerio de Obras Públicas Transporte Vivienda y Desarrollo Urbano. El Salvador.

Surface Search inc. (2011). Electrical Resistivity Tomography (ERT) URL: http://surfacesearch.com/page11/page3/page4/page4.html [Last accessed: May 15th 2016].

Terradat (2014). Electrical Resistivity Tomography (ERT) URL: http://www.terradat.co.uk/survey-methods/resistivity-tomography/html [Last accessed: May 16th 2016].

UES (2016) Perfiles de resistividad Eléctrica, Departamento de Geofísica, Universidad de El Salvador.

Alonso Alfaro (✉)

DACGER, Ministry of Public Works, San Salvador, El Salvador

e-mail: alonso.alfaro@mop.gob.sv

Landslide susceptibility mapping adopting AHP method

Hiroshi Yagi

Abstract Scale of landslide susceptibility map (LSM) varies according to the objectives. Analytical Hierarchical Process (AHP) method is suitable for LSM of middle scale, 1/20,000 – 1/50,000 by aerial photo interpretation to nominate landslide-prone area. Landslide hazard mapping for implementation of landslide prevention work or installation of observation equipment requires ground truth and comprehensive evaluation combined with AHP.

Keywords landslide susceptibility mapping, scale, objectives, AHP, ground truth

Introduction

Landslides are one of the severest natural hazards that have to be addressed in relation to the development activities. However, planning, design and construction of development projects are often implemented without proper assessment of potential hazards, thereby triggering numerous landslide hazards due to slope instabilities during and after badly managed construction work or urbanization without proper planning. In order to minimize risk to infrastructure and human lives, Landslide Susceptibility Mapping (LSM) is required so that safe or least hazardous areas could be selected for urban or infra-development. Landslide susceptibility mapping is based on the assumption that landslides occur as a result of similar geological, geomorphologic and hydrological conditions that led to past and present landslides.

Mapping scale, method & objectives of LSM work

Before performing landslide susceptibility mapping, it is necessary to clarify the mapping scale considering the objectives of the LSM work. This is because the method adopted for LSM is determined according to a geographic extent depending on the intended application of the mapping results. Basic concept of identification of scale and objectives of the susceptibility mapping is generally categorized as follows:
- National scale: 1:100,000 - 1:1,000,000, national development planning of infrastructure

- Regional scale: 1:50,000 - 1:200,000, regional development planning of infrastructure
- Medium scale 1:20,000 - 1:50,000, urban & road development planning
- Large scale 1:5,000 - 1:20,000, urban development planning & implementation of disaster prevention work

Landslide inventory map is enough for national or regional level planner to know the landslide susceptibility of the targeted areas and it is also known as landslide zoning map in scale of 1:100,000 – 1:1,000,000. It is usually compiled from the inventory maps of the middle scale LSM prepared by aerial photo interpretation (NIED, 1998). However, hazard susceptibility mapping of small scale less than 1:50,000 is not feasible for engineering projects or disaster prevention work. If data on slope gradient and geological information are superimposed onto the inventory maps in scale of 1:50,000 or more, processed by GIS using wide grid size of DEM, the planner can realize the susceptible zone to be avoided when they make the development plan. Because it can be prepared quickly and conveniently, covering wider area.

Landslide susceptibility maps in the range of about 1:20,000 - 1:50,000 should be prepared for urban development planning or feasibility assessment for road alignment decision using GIS method. The medium scale LSM is practical method because most of study materials available in Honduras or other Central American countries such as topographic maps, aerial photographs and engineering geological maps are prepared in this scale. LSM of the middle scale refers to an arithmeticmethod of portraying the spatial variation in the susceptibility of slope to failure, assessing landslide factors such as micro topography relating to landslide reactivation through aerial photo interpretation. And it´s prepared on the basis of criteria system based on ranking of each slope facet.To quantify susceptibility ranking of slope, a weighting or rating system is used and range of landslide susceptibility rate obtained isto be categorized into some qualitative levels in terms of relative instability,high, moderate or low etc.

Large scale LSM is desirable, if high resolution digital elevation model (DEM) of 10m grid or more is available and field investigation in the study area is implementable. Objectives of the large scale LSM is

detection of high hazardous area from the aspect as follows; designing of countermeasure work for slope disaster, prioritization of prevention work for high risky infrastructures and determining the residential areas where need further monitoring for landslide.

Middle scale landslide susceptibility mapping combined with aerial photo interpretation and AHP

Landslide inventory map of the middle scale prepared by interpretation of aerialphotographs is the most basic way to know landslide prone area spatially, because old landslides are often reactivated by equilibrium change of slope stability due to erosion or artificial cutting. However, it is a matter of discussion for geotechnical engineers concerning to landslide management and control to presume which landslides will be reactivated in the near future. There are too much landslides to be checked in the field. So more detail qualification system to evaluate the slope stability in larger scale is required, using aerial photo interpretation.

Aerial photo interpretation is actually a cheap and effective method for landslide susceptibility assessment study. However, it requires for the geotechnical engineers much experience and formalization of evaluation, keeping quantitative identification of landslide. In this context, an expert system using AHP method to assess landslide susceptibility of the middle scale by aerial photo interpretation was developed based on the interview and brainstorming among experts on the photo-interpretation and reconnaissance study on landslide (Yagi et al.,2009), focussing on topographic features of landslide and location of landslide affecting its stability of slope.

What is Analytical Hierarchical Process (AHP)?

The Analytical Hierarchical Process (AHP) method, developed by Saaty (1980) decomposes the process of subjective decision of a person into a hierarchical structure of simple and independent factors and expresses the process qualitatively. It decides relative importance between two factors as a pair-wise comparison as follows; equal, weakly, strongly, much strongly. And it decides the weight for each factor and assigns it to each factor by each landslide. Consequently, AHP is a method for formalizing decision-making based on attributing factors that vary personally. So it is a key point to select which factors are important and attributing to your decision.

In a case of landslide hazard susceptibility assessment, the first step is to nominate important factors to cause slide from geomorphological aspects. The second step is to decide the relative importance of the factors. Subsequently, it can evaluate relative landslide potentiality of reactivation assigning weight for each factor.

Topographic features as attributing factors

Landslide inventory mapping is the most usual step of hazard assessment (Soeters and Westen 1996). Micro topography on landslide mass had been also focused on (Kienholz, 1978). Six geomorphological factors were selected as evaluating criteria in this study from views points of geomorphological evolution, landslide activity and destabilizing possibility, based on the brain-storming among the landslide researchers of Japan Landslide Society. They are as follows; 1) Sharpness and clearness of micro-topography formed by landslide, 2) Fragmentation of a primary block into sub-blocks, 3) Profile of landslide mass and toe part, 4) Erodibility of toe part of landslide mass, 5) Water collectability from upper slope of landslide crown, 6) Land cover, artificial change and habitation on landslide mass. Criteria of 1) and 2) represent stability due to landslide evolution those of 3) and 4) are stability factors attributed from conditions of landslide toe part, respectively.

Sharpness and clearness of micro-topography formed by landslide

Sharpness and clearness of such micro-topography on a moving block and a main scarp are checked as the factor of the susceptibility evaluation. Micro-topographies such as scarps, cracks, steps, hollows and ridges formed in and around a crown or landslide mass represent its recent ground motion from the aspect of geomorphological evolution, because micro-topographic features are easily subject to erosion and become rounded and unclear with the lapse of time (Fig. 1). For example, main scarps of old landslide are usually eroded and show rounded because the old landslides are dormant. If the landslide is active, those micro-topographies will be densely distributed and will be very sharp and clear.
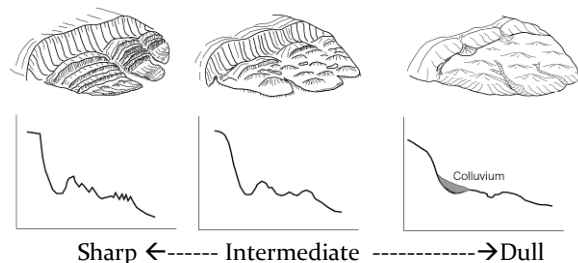

Sharp ←------ Intermediate -----------→Dull

Fig. 1 Schematic view of sharpness and clearness of micro-topography as evaluation criteria of AHP (Yagi et al., 2009)

Fragmentation of a primary block into sub-blocks

Rock mass of landslide is subjected to be fractured with retrogressive or progressive movement inside the original rock mass. Subsequently it is prone to be divided into the secondary or tertiary sub-blocks (Fig.2). Such fragmentation of the primary landslide mass also indicates recent activity and continuity of gravitational movement from the views point of geomorphological evolution. Consequently such fragmentation is adopted as an evaluation criterion of landslide susceptibility.
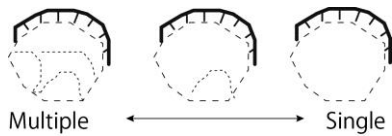
Fig. 2 Schematic plane view of fragmentation of landslide block

Profile of landslide mass and toe part

Geotechnical engineer usually checks howmuch driving force is remained within a landslide mass. Topographic profile of a landslide mass and toe part directly reflects its stability low or high. Thus the profile of landslide mass and toe part is chosen as one of criteria of susceptibility evaluation (Fig.3). If a steep and top-heavy profile at the toe part affects stability of landslide wholly, high score should be allocated to it.
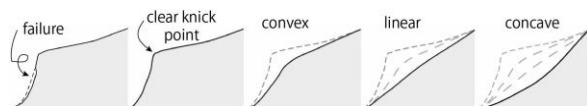
Fig. 3 Schematic profile of landslide mass and toe part

Erodibility of toe part of landslide mass

Under-cutting of a toe part of landslide easily breaks stability of a dormant landslide. If a river course shows incised meander and a toe part of the dormant landslide is located in an undercut slope, it is subject to sever erosion and is prone to be reactivated (Fig. 4). So erodibility of toe part of landslide mass is nominated as the evaluation criterion of landslide susceptibility.
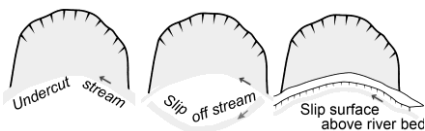
Fig. 4 Schematic plane view of erodibility of toe part

Water collectability from upper slope of landslide crown

Movement of landslide is prone to be controlled by ground water condition. Landslide occurs if driving force derived from slope materials becomes bigger than resistant force along a slope. Resistant force is reduced by ground water pressure, so stability of a slope much depends on inflow of water to the landslide mass. Then water collectability from upper slope of landslide considering slope concavity of water catchment (Fig. 5). It is chosen as the attributing factor for landslide reactivation.
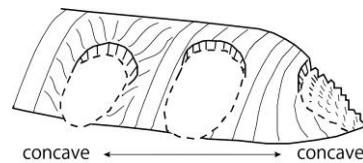
Fig. 5 Schematic view of water collectability

Land cover, artificial change and habitation on landslide mass

Human activity or habitation on landslide slope sometimes affects stability of the slope due to irregular cutting of slope or infiltration of living drainage if proper urban planning and designing is not done before development. Integrated attention and observation to such land-cover pattern shown in Fig.6 should be paid as the contributing factors for landslide reactivation.
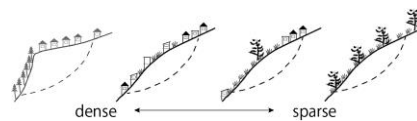

Fig. 6 Schematic view of land cover and habitation

Weighting system for susceptibility assessment of landslide

As mentioned above, the AHP method decomposes the process of personal decision into a hierarchy of simple and independent criteria such as Level II and Level III in descending order, and expresses the process qualitatively by each hierarchical level. That of Level I is comprehensive final decision.

Hierarchical level II of landslide susceptibility

Matrix of attributing factors as weighting criteria of hierarchical Level II, which consists of: sharpness and clearness of micro-topography formed by landslide, fragmentation of a primary block into sub-blocks, profile of landslide mass and toe part, erodibility of toe part of landslide mass, water collectability from upper slope of landslide crown, land cover, artificial change and habitation on landslide mass was decided by a series of pairwise comparisons (Tab. 1). Each number of a cell shows the relative important level of the objective i to the objective j, allocating odd number according to

the relative importance bybrain storming among skilled engineers with much experiences about landslide interpretation of aerial photos. They are as follows:

- 1: Objectives *i* and *j* are of equal importance
- 3: Objective *i* is important than objective *j*
- 1/3: Objective *i* is less important than objective *j* (inverse number of 3)

Erodibility of toe part shows big number for other attributing factors, because engineers usually pay much attention to condition of the toe part.

Table 1 Matrix of a series of pair-wise comparison of attributing factors of level II for landslides distributed along the river

Hierarchical level III

Example of an important factor at a hierarchical level III in a case of toe part erodibility is shown in Tab. 2. This case depends on combination of stream scale and slope type, undercut slope or slip-off slope, considering position of slip surface. Where a big stream is facing to undercut slope, higher score will be given, compared to the slip-off slope facing to the relatively small stream (Tab.2).

Table 2 Example of pair-wise comparison of attributing factors of level III, Erodibility of toe part

Weighting system

The weight coefficient for hazard susceptibility is calculated, multiplying the weight of hierarchical level II and level III. The score in Tab. 3 is percentage of each weight coefficient for the total, respectively. Among the attributing factors of level II, erodibility of the toe part is highly weighted. And higher score is given to the undercut slope facing to the big stream in level III.

Consequently, landslides of high potentiality of reactivation usually occur along main streams of big rivers, where the landslides have undergone toe erosion due to under cutting by the strong streams.

Table 3 Weight and score of AHP for landslide susceptibility assessment

Checking each decision criterion of level III for each attributing factor of level II by aerial photograph interpretation for each landslide block is implemented in order to assess landslide susceptibility by AHP.Fig7 is an illustrated weighting system at hierarchical level III allocating score to each criterion according to its slope condition.Such simplified image evaluation system that is originated from expert system is accessible for com-
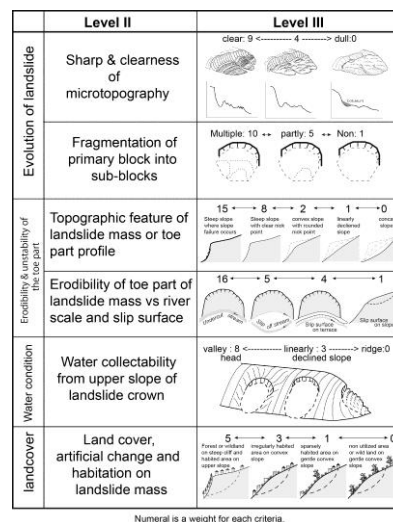

Fig. 7 Schematic illustration of weighting system for landslides locating along the river courses

mon geotechnical engineers to detect highly susceptible area among many coherent and dormant landslides.

Improved weighting system for Tegucigalpa

There are many active landslides in Tegucigalpa. Two thirds of them are located along Choluteca River and its tributaries (UPI-JICA, 2014). The most known one is Berrinche landslide that is located on the left bank of Choluteca River and was caused by Hurricane Mitch. Meanwhile, Tegucigalpa valley is surrounded by steep wall composed of thick welded ignimbrite or basalt sheet overlying the Cretaceous sedimentary soft sediments (See Fig. 8). Such geological/geomorphological feature is called "cap rock structure" that is prone to cause landslide due to top-heavy profile and viscous/fluid property of underlying stratum. Such types of landslides are called block glide or spread, respectively. Infiltrated water from upper lava sheet usually springs out along the discontinuity between the lava sheet and sediments. Pediment slope develops on the soft sediments along the foot of the volcanic rock wall and many dormant landslides are also detected on the slope of the pediment hill. Some landslides such as Reparto and Bambu, areas are very active though they are not facing to major streams.
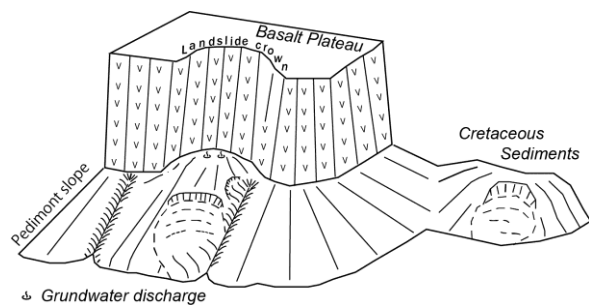

Fig. 8 Schematic geological and geomorphological model of a hilly land in marginal part of Tegucigalpa city

Then water derived from the lava sheet is presumed to activate those landslides. Furthermore, non-planned urbanizations proceed on the hilly area where capacity of living drainage is not enough.

Consequently, another set of evaluation factor is prepared for such hilly area (Tab. 4). The factor attributing to erodibility of toe part of landslide mass is replaced to that of geological and geomorphological setting (Fig. 9), expecting that development activity without proper planning affects the stability on the slope. According to change of the attributing factor, a series of weight and score is also alternated because relative importance among the factors is different on a new chart. They are schematically illustrated in Fig. 9.

Table 4 Matrix of a series of pair-wise comparison of attributing factors of level II for landslides in the marginal part of Tegucigalpa valley
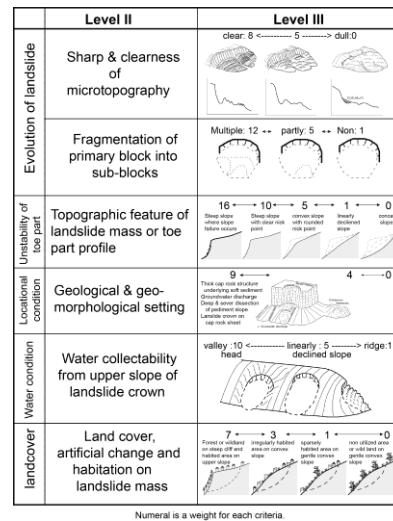

Fig. 9 Schematic illustration of weighting system for landslides locating on hilly slope

Landslide hazard mapping of large scale combining ground truth and aerial photo interpretation

Middle scale landslide susceptibility mapping in scale 1/20,000 to 1/50,000 using aerial photo interpretation is suitable to distinguish landslides that appear to be active or dormant. However, it is difficult to detect a landslide block under a critical condition causing movement only by aerial photo-interpretation.Concrete planning or designing of prevention work for landslide block or installation of observation equipment for reactivation of landslide should be done for critical landside block by priority. To solve this issue and to make LSM more practical at the site, landslide hazard map of large scale in scale of 1/5,000 to 1/20,000 combining ground truth and aerialphoto-interpretation is proposed, if high resolution DEM of more precise

than 10 m grid or aerial photo in scale of approx. 1/10,000 are available. A contour map super-imposed on an orthophotograph is preferable to plot in situ ground deformation.

Weighting and score system of AHP for landslide hazard evaluation of level II consists of micro-topography (Micro-topo) caused by landslide, slope profile of landslide mass, geology consisting of landmass (Geo_setting), water condition and land use and cover. Information on Micro-topography, geology, water condition and land-cover are observed by ground truth at the site respectively. Aerial photo interpretation can also detect topographic features on micro-topography and profile of landslide mass. Tab.5 shows a matrix of a pair-wise comparison between attributing factors of level II above mentioned.

Table 5 Matrix of a series of pair-wise comparison of attributing factors of level II for landslides assessment of large scale combining aerial photograph interpretation

	Micro-topo	slope profile	Geo_set ting	water conditi on	land use/ cover	Geo-Mean	Weight	Score
Micro-topo	1	1	1	1	3	1.25	0.24	24
slope profile	1	1	3	1	3	1.55	0.30	30
Geo_setting	1	0.333	1	1	1	0.80	0.15	15
water condition	1	1	1	1	1	1.00	0.19	19
land use/ cover	0.333	0.333	1	1	1	0.64	0.12	12
						5.24	1.00	100

Tab. 6 shows an evaluation list by each factor. Score of evaluation for each factor of Level II is allocated the highest number among those of Level III consisting of the factors of level II, based on result of ground truth.

Concluding remarks

Scale of landslide susceptibility map (LSM) varies according to the objectives of the projects. Landslide inventory of small scale is useful for national planning. AHP method is suitable for LSM of middle scale, 1/20,000 – 1/50,000 by aerial photo interpretation to nominate landslide susceptible area. Landslide hazard mapping of large scale for implementation of landslide Concrete planning or designing of prevention work for landslide block or installation of observation equipment for reactivation of landslide should be done for critical landside block by priority. To solve this issue and to make LSM more practical at the site, landslide hazard map of large scale in scale of 1/5,000 to 1/20,000 combining ground truth and aerial photo-interpretation is proposed, if high resolution DEM of more precise than 10 m grid or aerial photo in scale of approx. 1/10,000 are available. A contour map super-imposed on an orthophotograph is preferable to plot in situ ground deformation. Prevention work or

installation of observation equipment requires ground truth and comprehensive evaluation combined with AHP.

Table 6 Weight and score of AHP for landslide hazard and assessment of large scale

Score List for Susceptibility Evaluation				Block No.		
Level II		Level III		1	2	3
Microtopography	24	tilting of houses or ground	24			
		step on ground	20			
		crack on ground or wall	18			
		fissure on ground or wall	15			
		no signs	0			
profile of landslide mass	30	steep slope with slope failure	30			
		steep slope with clear nick point	20			
		convex slope	10			
		linerly decline slope	5			
		concave slope	0			
Geological setting	15	Collvium(Landslide debris)	15			
		Tertiary sediments	10			
		Hard rock	5			
Water condition	19	Spring water on slope	19			
		Spring water at the toe part	15			
		piping on the slope	15			
		natural darin of surface water	10			
Landcover	12	sprawl urbanization	12			
		scattered spral	8			
		wild land or forest	5			
total	100					

Score of evaluation for each criterion of Level II is allocated the highest number among those of Level III consisting level II.

References

UPI-JICA, (2014): Manual Para Elaboración de Inventario de Deslizamientos de Tierra. Caso de aplicación: Ciudad de Tegucigalpa. Agencia de Cooperación Internacional del Japón (JICA). Tegucigalpa. ISBN: 978-99926-701-1-8

Kienholz H (1978) Maps of geomorphology and natural hazards of Grindelward, Switzerland, scale of 1:10,000, Arctic and Alpine Research, 10,169-184

NIED（1998）Landslide maps, series 1 "Shinjo and Sakata" and explanations for the landslide maps. Technical note of the National Research Institute for Earth Science and disaster prevention No.69 (in Japanese and English abstract)

Saaty, T L (1980) The Analytic Hierarchy Process, New York, NY: McGraw-Hill Book Company, 265p.

Soeters R and Westen C J (1996) Slope instability recognition, analysis and zonation. Turner A K and Schuster R L (eds). Landslides: Investigation and Mitigation, Transportation Research Board, National Research Counsil. Pp. 129-177, National Academy Press, Washington D.C.

Yagi H, Higaki D and Japan Landslide Society (2009) Methodological study on landslide hazard assessment by interpretation of aerial photographs combined with AHP in the middle course area Agano River, Central Japan. Journal of Japan Landslide Society, 45(5), 8-16. (in Japanese and English abstract)

Hiroshi YAGI （✉)
Yamagata University, Faculty of Art, Science and Education Address, Kojirakawa Yamagata and 990-8560, Japan
e-mail: yagi@e.yamagata-u.ac.jp

UNAH

UNIVERSIDAD NACIONAL
AUTÓNOMA DE HONDURAS

www.ihcit.unah.edu.hn
E-mail: ihcit@unah.edu.hn
Phone number: +504 2235-3030