2017 IPL SYMPOSIUM ON LANDSLIDES

29 November 2017
UNESCO Headquarters in Paris, France

Organized by
International Consortium on Landslides (ICL)

Sponsored by
The United Nations Educational, Scientific, Cultural Organization (UNESCO)

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Kyoji Sassa・Khang Dang *Editors*

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IPL Symposium Program

Date: 29 November 2017

Venue: Room 9, Fontenoy Main Building, UNESCO

Time	Presenter/ Leader	Organization	IPL Project Proposal
Session Chair for AM: Peter Bobrowsky (ICL President from 2018) and Matjaz Mikos (Chair of IPL evaluation committee)			
Part 1. IPL Proposal			
9:00 ～ 9:15	Sabid Zekan	The Geotechnical Society of Bosnia and Herzegovina	BLISM (Bosnian Landslide Investigation and Stabilization Method)
9:15 ～ 9:30	Ping Lu	Tongji University	Landslide Rapid Mapping from Remote Sensing
9:30 ～ 9:45	Zeljiko Arbanas	Croatian Landslide Group from Faculty of Civil Engineering University of Rijeka and Faculty of Mining, Geology and Petroleum University of Zagreb	Rockfall Hazard Identification and Rockfall Protection in The Coastal Zone of Croatia
9:45 ～ 10:00	Martin Krkač	Croatian Landslide Group from Faculty of Civil Engineering University of Rijeka and Faculty of Mining, Geology and Petroleum University of Zagreb	Kostanjek Landslide Monitoring Project (Zagreb, Croatia)
10:00 ～ 10:15	Veronica Tofani	University of Firenze, Earth Sciences Department	PS continuous streaming for landslide monitoring and mapping
10:15 ～ 10:30	Daniele Spizzichino	ISPRA-Italian Institute form Environmental Protection and Research	Landslide risk analysis and mitigation for the ancient rock-cut city of Vardzia (Georgia)
10:30 ～ 10:45	Igwe Ogbonnaya	Department of Geology, University of Nigeria, Nsukka	Landslides in Africa: the Emerging Trends of Slope Catastrophes and the Factors Driving Instability in the Continent

Time	Presenter/ Leader	Organization	IPL Project Proposal
10:45 ～ 11:00	Alexander Strom	JSC "Hydroproject Institute"	Combination of radar and optical remote sensing for hazard assessment of the potentially river-damming landslides: cases of the Vakhsh and the Brakhmaputra River basins
11:00 ～ 11:15	Matjaz Mikos	University of Ljubljana, Faculty of Civil and Geodetic Engineering (ULFGG)	Recognition of potentially hazardous torrential fans using geomorphometric methods and simulating fan formation.
11:15 ～ 11:30	Mateja Jemec Auflič	Geological Survey of Slovenia	Studying landslide movements from source areas to zone of deposition using a deterministic approach
11:30 ～ 11:45	A A Virajh Dias	Central Engineering Consultancy Bureau (CECB)	Development of a Web Based Landslide Information System for the Landslides in Sri Lanka
Part 2. Research Presentation			
11:45 ～ 12:00	Olgert Jaupaj	Albanian Geological Survey	Landslide inventory and susceptibility map in Durresi and Kavaja region
12:00 ～ 13:00	Lunch		
Session Chair for PM : Giuseppe Arduino (Division of Water Science, UNESCO) and Alik Ismail-Zadeh (Secretary General, IUGG)			
13:00 ～ 13:15	Peter Bobrowsky	Geological Survey of Canada	Update on the Ripley Landslide – new technology applications
13:15 ～ 13:30	Wei Shan	Institute of Cold Regions Science and Engineering, Northeast Forestry University	Problems and Countermeasures of Highway Engineering Geology Related to Landslide in the Background of Permafrost Degradation in High Latitude Permafrost Regions
13:30 ～ 13:45	Ping Lu	Tongji University	Establishing a stereo multi-sensor network for giant landslide monitoring

Time	Presenter/Leader	Organization	IPL Project Proposal
13:45 ～ 14:00	Snjezana Mihalic Arbanas	University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering	Landslide prone areas in the Dinarides and Pannonian Basin in Croatia and Bosnia and Herzegovina
14:00 ～ 14:15	Vit Vilimek	Charles University, Faculty of Science	Activities of WCoE in Prague
14:15 ～ 14:30	Jan Klimeš	Institute of Rock Structure and Mechanics Academy of Sciences of the Czech Republic, Department of Engineering Geology,	Giant landslides on oceanic island volcanoes – Atlantic Ocean
14:30 ～ 14:45	Dwikorita Karnawati	University of Gadjah Mada	Development of Slope Mass Stability Assessment in Tropical Altered Slope in Indonesia.
14:45 ～ 15:00	Teuku Faisal Fathani	University of Gadjah Mada	Landslide hazard assessment and mitigation measures in geothermal fields
15:00 ～ 15:15	Nicola Casagli	University of Firenze, Earth Sciences Department	Advanced Technologies for Landslides (ATLas)
15:15 ～ 15:30	Raul Carreno	Grudec Ayar	A Brief Diagnosis on Instability Phenomena Menacing Calorcko (Bolivia), the World'S Largest Palaeoichnites Site
15:30 ～ 15:45	Olga Barykina	Department of Engineering and Ecological Geology, Geological Faculty, Moscow State University	The influence of paleo-landslide activity on the modern slope stability
15:45 ～ 16:00	Timotej Verbovšek	University of Ljubljana, Faculty of Natural Sciences and Engineering (UL NTF)	Report on the ICL-216 project entitled "Diversity and hydrogeology of mass movements in the Vipava valley, SW Slovenia"

Time	Presenter/ Leader	Organization	IPL Project Proposal
16:00 ~ 16:15	A A Virajh Dias	Central Engineering Consultancy Bureau (CECB)	Soil Moduli E50 of Residual Soil Slopes, Sri Lanka
16:15 ~ 16:30	Iurii Kaliukh	Institute of Telecommunication and Global Information Space	IPL 191: experimental and theoretical assessment of structural health of retaining walls under low frequency dynamic loading in the seismic zone of the Carpathians foothill (Vrancea zone)
16:30 ~ 16:45	Binod Tiwari	California State University, Fullerton & Tribhuvan University, Institute of Engineering	Use of Spectral Acceleration to Evaluate Seismically Induced Landslide at Lokanthali, Kathmandu due to 2015 Gorkha Nepal Earthquake
Session Chair: Kyoji Sassa (WLF5 Forum Chair) and Kaoru Takara (Chair of the local organizing committee of WLF5)			
16:45 ~ 17:45	Preliminary discussion and consultation for Kyoto 2020 Commitment, ICL associates, national/regional unit of ICL including possible coordinating sessions by ICL. During the IPL symposium, preparatory working group under 7 major themes may be held in Room 8 to prepare WLF5 organizing committee meeting on 30 November when necessary.		

Contents

Landslide risk analysis and mitigation for the ancient rock-cut city of Vardzia (Georgia)

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Abstract The rock-cut city of Vardzia is a cave monastery site in south-western Georgia, excavated inside the volcanic and pyroclastic rock layers of the Erusheti mountain on the left bank of the Mtkvari river. The main period of construction dates back to the second half of the twelfth century. The site has been affected by frequent instability phenomena along the entire volcanic cliff. These pose serious constrains to future conservation, as well as to the safety of tourists. In order to improve knowledge about slope stability issues in the Vardzia site and to develop a proper site specific approach, the National Agency for Cultural Heritage Preservation of Georgia (NACHPG) promoted, with the support of Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Geological survey of Italy, a landslide hazard assessment for the entire area. The main goal of the ongoing project is to study the complex structure of Vardzia, to assess reliable mechanical parameters of outcropping rocks and to monitor slope and monument deformation in order to identify critical areas prone to collapse. All these information are allowing the elaboration of a sustainable approach for retrofitting and conservation of rock cut monuments. In the mean time, real time monitoring is also providing a valuable support not only to detect the development of hazardous processes but also to protect visitors and local personnel from sudden rock mass collapses.

Keywords Landslide, Vardzia, Cultural Heritage, sustainable mitigation.

Introduction

The rock-cut city of Vardzia is a cave monastery site in south western Georgia, excavated from the slopes of the Erusheti mountain on the left bank of the Mtkhvari river. The main period of construc-tion was the second half of the twelfth century.

The caves stretch along the cliff for some 800 m and up to 50 m within the rocky wall (Fig. 1).

The monastery consists of more than 600 hid-den rooms spread over 13 floors. The main site was carved from the cliff layer of volcanic and pyroclastic rocks, Gillespie & Styles (1999) at an elevation of 1300 m above sea level. The cave city included a church, a royal hall, and a complex irrigation system.
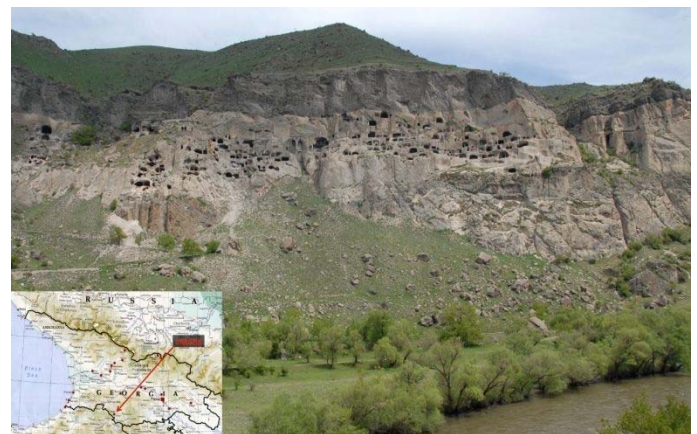
Figure 1 The rock-cut city of Vardzia (Georgia).

The earthquake that struck Samstkhe in 1283 AD destroyed about two thirds of the city cave and the irrigation system, exposing the majority of the rooms to view outside. The site was largely abandoned after the Ottoman takeover in the sixteenth century.

The Vardzia-Khertvisi cultural landscape is one of Georgia's most important cultural sites, in the tentative list of UNESCO World Heritage Sites. Considering its poor condition and an urgent need to conserve the Vardzia Cave complex, in recent years the National Agency for Cultural Heritage Preservation of Georgia has taken significant steps to carry out multidisciplinary research and preserve the site.

The activities are carried out by both national and international experts, mainly from Geological Survey of Italy (ISPRA) and Cultural Heritage and Environment Research Centre of Ilia State University, Georgia (Margottini et al. 2015).

Vardzia represents a unique cultural heritage monument – an ancient city completely carved in rock, which unites architectural monument and Natural-

Geological complex. Such monuments are particularly vulnerable and their restoration and conservation requires complex approach.

This heritage, as many similar monuments worldwide, is subjected to slow but permanent process of destruction, expressed in many factors: surface weathering of rock, active tectonics (seismic displacement along the active faults and earthquakes), interaction between lithologically different rock layers, existence of major cracks and associated complex block structure, surface rainwater runoff and infiltrated ground water, temperature variations and of course human influence (e.g. visitors and heavy vehicles arriving at site).

To achieve sustainable preservation of cultural heritage rock-cut monuments of this particular type various threats should be addressed. They include rock fall and slides, frequent seismic load combined with relatively rear catastrophic earthquake damage and slow but permanent erosion/weathering of rock.

Geological and Geomorphological Settings of Vardzia Rock Cut City

From the geological point of view, the area is characterised by volcanic and pyroclastic rocks of the Upper Miocene — Lower Pliocene (Goderzi Formation).

The entire rock wall has a length of about 800 m and a height of 130 m with a general EW orientation.

Theboundaries between the different volcaniclastic levels are not always apparent, but they are all sub-parallel according to the style of deposition. A schematic litho-stratigraphic cross section of the slope is shown in Fig. 2.
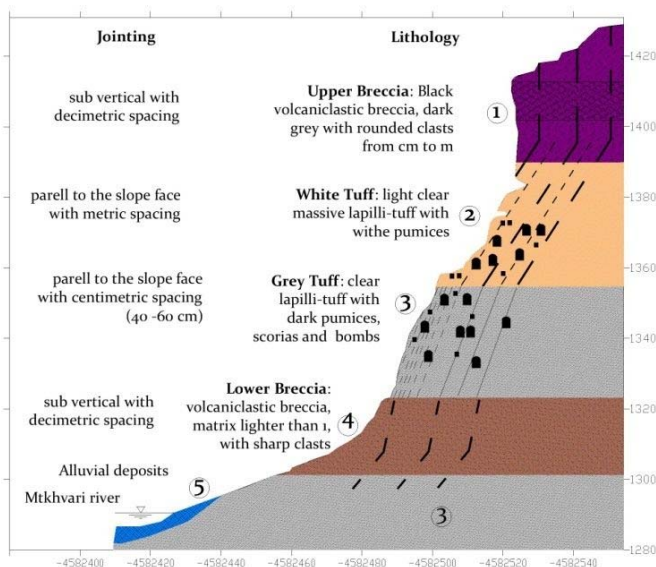

Figure 2 Litho-stratigraphic cross section of the Vardzia rocky cliff.

Starting from the top of the cliff, it is possible to discern the following layers: (1) Upper Breccia; (2) White Tuff; (3) Grey Tuff; (4) Lower Breccia and (5) Alluvial Deposits. The slopes, generally, present a rupestrian aspect,

alternatively stratified and massive. Nevertheless, discontinuities of various types are present, possibly originated by cooling phases after volcanic activity (vertical joints), by tectonic phenomena and by geomorphological activity (stress release caused by valley incision).

Geotechnical Characterisation

The geotechnical characterisation of the site was based both on laboratory and in situ tests and was mainly aimed to estimate the strength properties of the rock materials (i.e. the Upper Breccia and the White Tuff) and the strength of the discontinuities for the investigated block.

A summary of the results obtained is provided in Table 1. A number of uniaxial compression tests and Brasilian tests were carried out at the University of Bologna on White Tuff and Grey Tuff specimens both in dry and wet conditions (Boldini,2017).

The White Tuff is characterised by an average porosity of 38.8% and a unit weight γ of 16.0 kN/m3. The uniaxial compressive strength UCS is equal to 9.3 MPa in dry conditions, also confirmed by the results of 5 point load tests that gave an average value of 10.5 MPa as described in Margottini and Spizzichino (2014), and 2.6 MPa in wet conditions, thus indicating a strong influence of water content on the material response. A similar effect was detected for the tensile strength σ_t estimated by the Brasilian tests. The Grey Tuff, subjected to the same tests, is characterised by very similar physical and mechanical properties (Table 1).

The properties of the Upper Breccia material were investigated by a limited number of tests. The unit weight γ was determined at the University of Tbilisi on cylindrical specimens. Point load tests conducted on dry samples at ISPRA (Margottini et al. 2015) gave an average UCS value of 14.8 MPa.

In absence of further determinations, the UCS value for the wet material was assumed as about one-third of that in dry conditions (i.e. equal to 5 MPa), while the tensile strength σ_t was taken equal to one tenth the uniaxial compressive strength UCS (see Table 1). Due to the lack of triaxial compression tests, reasonable values for the friction angle were assumed for the investigated materials, specifically 30° for the White Tuff (Malservisi 2017) and50° for the Upper Breccia.

The corresponding values of the cohesion for dry and wet conditions were then calculated from the corresponding UCS values, as summarised in Table 1.

The properties of the rock joints were investigated during direct surveys carried out in the 2015 and 2016 campaigns (Table 1). At that time, it was not possible to reach the Upper Breccia layer, and the parameters described in the following were obtained on discontinuities located in the Lower Breccia layer instead. (Malservisi 2017). However, no significant differences are expected to occur between the two materials. A Barton

profilometer was used to estimate the joint roughness JRC coefficient (Boldini, 2017).

Table 1 Summary of the geotechnical characterisation (the values in the parentheses refer to wet conditions).

	Upper Breccia	White tuff	Grey Tuff
Rock Material			
γ (kN/m^3)	22.6	16.0	16.3
n (%)		38.8	37.2
UCS (MPa)	14.8 (5.0)	9.3 (2.6)	10.3 (3.6)
φ (°)	50	30	
c (kPa)	2693 (910)	1926 (538)	
σ_t (kPa)	1480 (500)	925 (300)	750 (300)
Joint:			
JRC	14	12	
φ_b (°)	30	27.3	
JCS (MPa)	14.8 (5.0)	9.3 (2.6)	
φ_r (°)	25	22	
i_{max} (°)	35	35	
c_j (kPa)	0	11 (9)	
φ_j (°)	60	43 (36)	
Rock-mass:			
GSI	72	73	63
D	0.7	0.7	0.7
E (GPa)	8.9 (5.1)	7.4 (3.9)	4.4 (2.6)

A Schmidt hammer was employed to measure the rebounds on the natural surface r and on an artificial surface R expressly polished at the site. A value of φb equal to 27.3° was obtained performing tilting tests on small cores of White Tuff (Margottini et al. 2015).

A value of φb = 30° was selected for the Upper Breccia discontinuity in the absence of specific investigations. The use of the Schmidt hammer for estimating the parameter JCS, which indicates the strength of the rock material along the joint wall, is often considered inappropriate for soft rocks.

In fact, taking into account the rebound values measured in situ, unrealistic high values of JCS would be calculated. For this reason, this parameter was set equal to the UCS value, considering separately the two cases of dry or wet material. Equivalent Mohr–Coulomb strength parameters were also evaluated for the rock joints (Table 1) considering a linearisation of the Barton criterion in an appropriate stress level.

The Young's modulus for the different rock masses was obtained applying the expression proposed by Hoek et al. (2002) assuming a disturbance factor equal to 0.7 in consideration of the loose state of the rock slope.

Slope stability and evolution

The site of Vardzia is affected by many examples of slope instabilities such as rock fall, topple and rock slide, with volumes ranging from a few cubic meters to the thousands (WP/WLI 1993).

Many phenomena also occurred in recent years, such as in May 1968 when a huge protective wall was constructed just above the main Church, to support the rock cliff potential instability, till the very recent rock slide of spring 2011. Following the general scheme of the cross section defined in Fig. 2 and with the aim to provide a preliminary assessment according to slope failure type and processes affecting the entire rocky cliff (from the top to bottom), most failures can be classified into various categories (Cruden 1991; Cruden and Varnes 1996), depending on the combination of the main joint sets and the geo-mechanical and geo-structural conditions of the different layers. Only exception is the large roto-translational rock slide, potentially affecting both layers 1, 2 and 3. With reference to the different levels of Fig. 4, the main rock slope failures can be classified as follow and displayed in Fig. 3.

In level 1:

a) Large roto-translational rock slide affecting layers 1, 2 and 3 (Fig. 6A);

b) Rock fall, topple or wedge failure often due to the lack of support of the underlying layer frequently affected by planar sliding (Fig. 6B);

c) Rock fall of clasts, detached from the matrix of volcaniclastic breccia.

In level 2:

d) wedge failure and rock falling (Fig. 6C);

e) high and low angle planar rock sliding along the main discontinuities (Fig. 6D).

In level 3:

f) planar sliding along the main structural settings (Fig. 6E);

g) Rock fall and topples;

Furthermore widespread superficial erosion morphologies features have been recognized and mapped along the slope (Fig.4).

They are mainly due to water runoff and minor stream network able to create slope sediments and small fan delta at the toe of the slop. Depending from the slope angle, alternating erosion, transportation and deposition of such debris material is occurring.

Fig. 3 Slope failure type and processes affecting the rocky cliff of Vardzia. (A) Large roto-translational rock slide involving both layers 1, 2 and 3. (B) Rock fall scarp in the upper part of layer 1. (C) Wedge failure at the contact between layer 1 (on top) and layer 2. (D) High and low angle potential planar rock slide. (E) High and low angle potential planar rock slide.

Figure 4. Unstable blocks and joints and open cracks in the Vardzia cliff

Geo-structural analysis

The mechanical behaviour of rocks is generally controlled by the conditions under which deformation takes place and by the inherent rock properties (Turner et al., 1996). Stress conditions of Vardzia monastery slope- promoted different types of discontinuities in the volcaniclastic igneous rocks (Mitchell et al. 1999). This is due to the stress-strain behaviour (e.g. lateral unloading due to valley erosion coupled with tectonic stress and cooling of the pyroclastics falls) and to the typical petrographical and physical properties of the soft rocks (e.g. chemical and mineralogical composition, grain size, shape, thickness, homogeneity, porosity, permeability, type of cement). The presence of brittle volcanic and pyroclastic rocks in the area, as a general rule, promotes blocky rock masses due to high frequency of discontinuities of various origin (Gamkrelidze, 1986). A geomechanical characterisation of discontinuities has been done along the entire study area in order to describe the structural setting of the area and recognize eventual master joints. Rock weathering, slope degradation and instabilityin the area are the result of different structural combinations of the main joint sets (Spizzichino et al., 2009). Our analyses, although only a preliminary and not exhaustive discontinuity survey was performed over the whole area, allowed to characterize some relevant slope sector in terms of discontinuity orientation. All collected data have been analysed (DIPS® Rocscience software). The rock mass strength has been observed to depend on the density, nature and extent of fracture and rock strength (i.e. lower within the black volcanic breccia, higher within whitish tuff and lapilli tuff). The stereoplots in figure 5 show that the major joint systems are steeply dipping (70°) towards SE (dip direction 140° -165°) and the main results of kinematic feasibility tests are reported in figure 5.
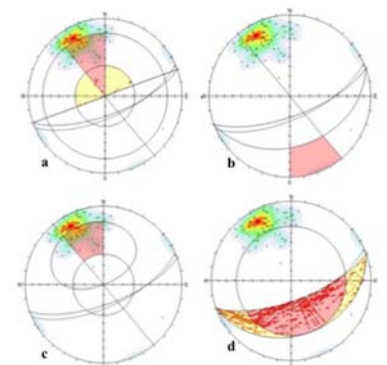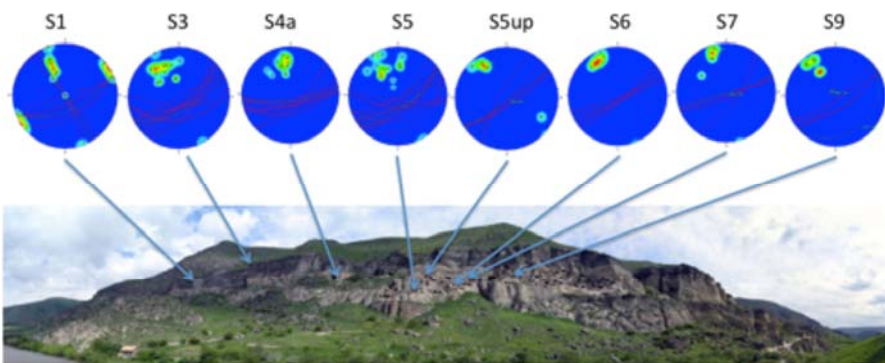

Figure 5. Stereoplots of joint dip measurements from the Vardzia monastery area and kinematic feasibility analyses: a) direct toppling (0,42% of total planes); b) flexural toppling (no critical planes) ; c) planar sliding (32,88%of total planes); d) wedge failure (44,59% of total planes).

Low impact and integrated monitoring of Rock Cut cultural monuments

Landslide monitoring is required for a wide variety of reasons. These may include: the determination of the extent, magnitude and style of landslide movement, risk and even emergency risk management assessments and/or assistance with the design and implementation of site remedial and/or mitigation works.

4

Since each monitoring project has specific requirements, the measuring device used for deformation monitoring depends on the application, the chosen method and the required regularity and accuracy.

Therefore, monitoring of slopes or landslide areas can only be defined, designed and realized in an interdisciplinary approach (Wunderlich, 2006).

A close cooperation with experts from engineering geology, geophysics and hydrology together with experts from any measurement discipline such as geodesy and remote sensing and other academic fields is an indispensable requirement.

As a matter of fact, a monitoring system is designed for the specific site, following an interdisciplinary approach and, finally, when dealing with a heritage site has to fulfil the requirement of a low environmental impact, in order not to deteriorate the site.

These concepts were applied to Vardzia monitoring network. Considering the threats to face, a complex monitoring network was designed and implemented in Vardzia. This includes: monitoring displacement and deformation of Vardzia cliff by means of Ground Based Radar Interferometry, monitoring micro tremors and ambient seismic noise (local strong motion network), monitoring local meteorological conditions (meteorological station), monitoring microclimate in caves (temperature and humidity in the air and rock), regular continuous high resolution photo fixation of the whole cliff. Realization of network has been started since 2012 with installation of Ground Based Interferometric Radar. Installation of all major components has been accomplished in 2014 and ended in 2015. Special local wireless communication network was created inter-connecting all sensors with the local servers in Vardzia and then transmitting information to data center in Tbilisi that also avoided cabling of cultural monument, promoting low visual impact approach and sustainable monitoring systems for cultural heritage environment.

Ground Based Radar Interferometry

Considering the morphological settings and slope instability processes (different typologies in size, magnitude and probability of occurrence), a new advanced simple and flexible monitoring system has been implemented in order to obtain: measurements, processing and remote control in real time, and to transform eventually the monitoring system into a warning system. The system adopted for the monitoring of the entire cliff is based on a ground based interferometric radar (IBIS system from IDS Fig. 6). This equipment allows the monitoring of displacement in the line of sight with a resolution of mm.

The radar system is a Stepped-Frequency Continuous Wave (SF-CW) coherent radar with SAR and interfeometric capabilities. The acquisition station has been realized with the valuable support of the NACHPG and the pre-acquisition and start up activities have been finalised since 2013. The differential interferometry

technique enables the measure of the displacement of the objects resolved through coupling SF-CW analysis. The system has been installed during the May 2012 field mission. During the period May – October 2012 the system has been initialized and tested. The radar configuration adopted is reported in the following table, the "selection mask" contains about 50.000 points.
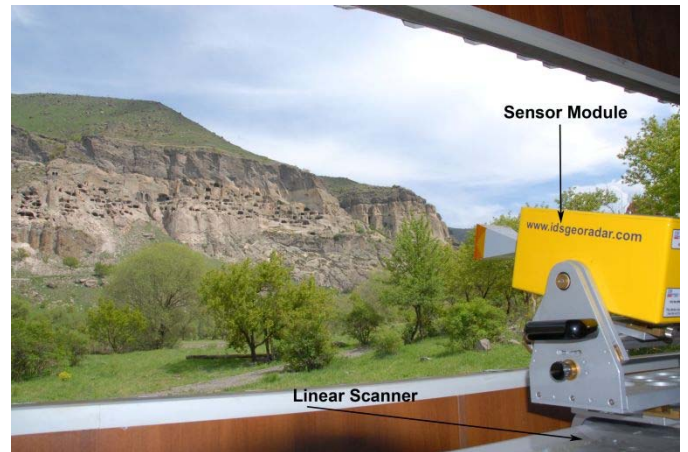

Fig. 6 IBIS-L radar monitoring system HW description and application in Vardzia

Table 2 Main parameters of radar configuration

Main Parameter	Unit of measure	Range of value
Distance from the slope	(m)	350 - 500
Antenna beam width	(deg)	> 70
Number of points	-	50.000
Range resolution	(m)	0.5
Cross range resolution	(mrad)	4.3
Scanning time	(min)	5

A TLS derived DTM has been used as 3D model for the visualization of the main monitored quantities (displacement and velocity) as collected and stored in real time by the monitoring system.

After data processing, displacement maps were built. The displacement is presented in millimetres per analyzed time period; Measured values are always in the direction of radar signal imaginary line. Data collection covers period from 2013 to 2016 years.

First stage of retrospective data analysis was performed in 2015 and covers period of 2013-2015 years, with the aim to derive a general picture on surface deformation and define the critical areas with permanent deformational processes (Fig. 7). Totally up to 10 areas, where identified, showing different patterns of ongoing displacement during the whole observation period. The outcomes from radar monitoring data were compared with the results of field survey in order to define general master plan of mitigation measures.
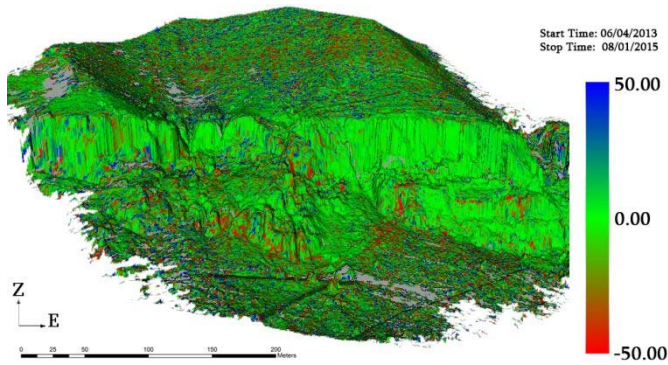
Fig. 7 Cumulative displacement map of Vardzia Cliff, implemented with ground-based radar interferometry technology for the time period of 2013-2015 years.

InfraRed Thermographic Surveys

With the aim of detecting moisture sectors and analyse the drainage pattern along the monastery slope, IRT multi-temporal surveys were carried out in different seasonal conditions, on July 16th-17th 2016, and October 20th 2016, by means of a FLIR SC620 thermal camera (FLIR, 2009).

Field inspections were also carried out during the monitoring campaign in order to validate the outcomes of the remotely sensed data. Various acquiring positions were tested during different times of the day in order to survey the slope scenario daily illumination conditions (Fig. 8).
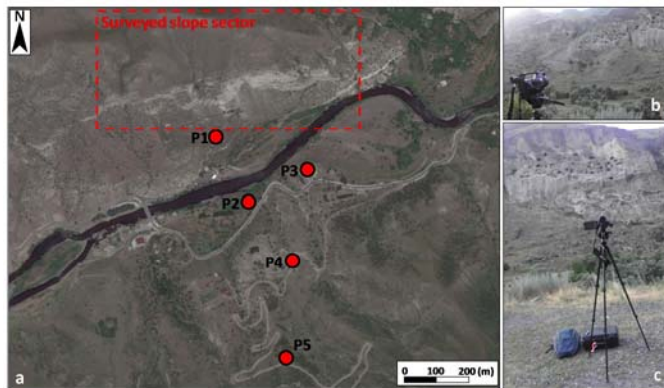

Fig. 8 Vardzia IRT surveys acquisition points (P1=monastery road; P2=GB-InSAR position; P3=river bank; P4= mountain road 1; P5= mountain road 2) (picture form Frodella 2016 field survey).

The obtained surface temperature maps are represented by means of a colour scale, in which the higher temperatures are displayed by the lighter colours, whereas the lower temperatures by the darker ones (Frodella 2014b). The mosaicked surface temperature maps acquired from positions P1, P2, P3, P4 and P5 confirmed the pattern of the cold thermal anomalies in correspondence of the slope topmost vegetated sector, the sub-vertical open decametric fractures within the rockwall, and the debris taluses underlying the slope

Furthermore by comparing the surface temperature maps acquired from position P4, both on July and October 2016, and by integrating the thermal data with

the available terrestrial laser scanning (TLS) 3D model, a refinement of the slope drainage pattern and a 3D mosaicked surface temperature maps of the Vardzia slope was obtained (Fig.9).
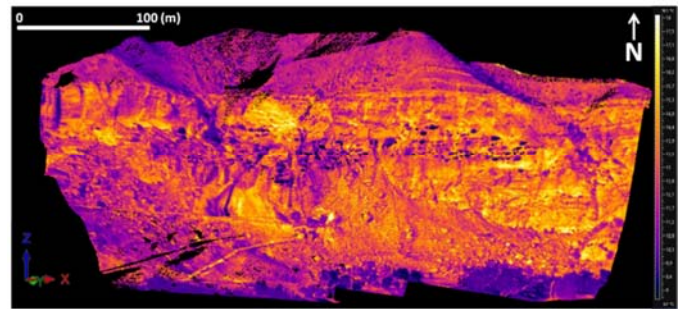

Fig. 9 Mosaicked 3D surface temperature maps of the vardzia monastery, obtained by merging the single thermograms (acquired from P4 position on October 20th 2016 at 15:30 a.m.) with TLS point cloud (picture form Frodella 2016 field survey).

This allowed to map the moisture drainage pattern of the overall analysed slope area, for a better understanding of rain infiltration and runoff in correspondence of the slope more critical sectors, as well as the detection of the overall drainage network and the main ephemeral creeks. The monastery slope eastern sector is less affected by the presence of ephemeral creeks, due to the slope conformation and the presence of a runnels-retaining wall system (Fig. 10).
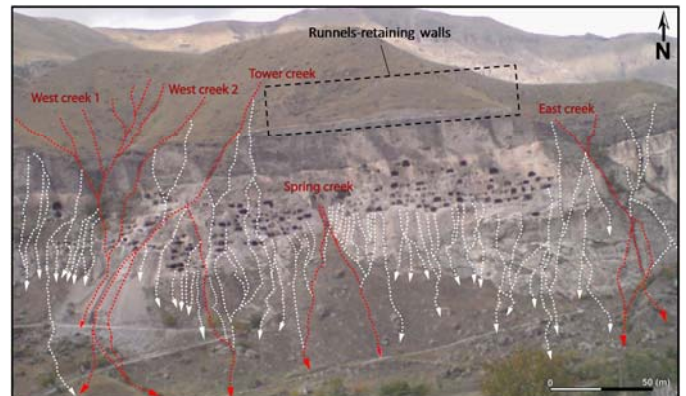

Fig. 10 Inferred pattern of the vardzia slope ephemeral drainage network, including the main detected ephemeral creeks (picture form Frodella 2016 field survey).

This was built for the purpose of preventing the monastery slope from erosion and runoff, as well as mitigating the risk of rock falls, due to the presence of potentially unstable scattered rock boulders on the slope topmost sector. On the contrary, the monastery slope western sector is intensively cut by ephemeral creeks. A new low-cost/impact system of runnels-retaining wall, as well as weirs within the creek bed rock cuts, should therefore be designed and implemented also in this slope sector, by using the scattered boulders for its construction.

Stability analysis

The stability analysis on some potential unstable blocks was carried out (both numerical and analytical methods), using the limit equilibrium method. For each individual block detected in the period 2013-2017 a detail local stability analysis was performed (Fig. 11).
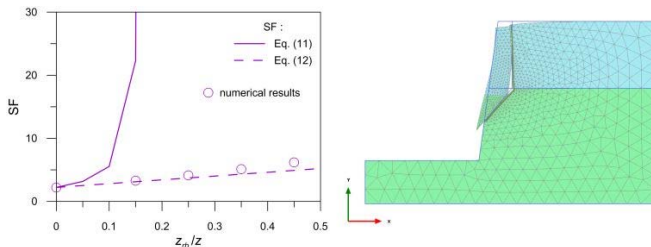

Figure 11. Variation of the safety factor against sliding considering different percentages of rock bridges along the breccia joint for the simplified model with two discontinuities: comparison between limit equilibrium and numerical results (Lrb/L = 0.45) (on the left) and deformed mesh at failure (zrb/z = 0.15) (on the right) (Boldini et al., 2017).

All the simulation shows that only the presence of rock bridges along the base and the sub-vertical joints has guaranteed the current stable conditions. In conclusion, stability analysis in Vardzia site and related design of mitigation measurements, cannot disregard a proper investigation and estimation of rock bridges contribution.

Risk mitigation policies and sustainability

Cliff instability mitigation measures usually require the use of either structural or non-structural measures, or a combination of both. Structural measures imply intensive earthwork and the construction of concrete structures (Van Dine 1996) and may be visually intrusive.

Design of stabilization and protection works of the Vardzia cliff have the challenge of reconciling safety and conservation of the site with sustainability and visual integration. Surface reinforcement techniques can be used to prevent small size rock wedges and blocks to produce rockfalls.

They aim at providing surface reinforcement and restrict loosening of the rock mass. High strength messes that are low visually intrusive can be considered usually combined with nails or rock bolts to fix them to the rock surface (Corominas 2013). Stabilization elements have to be carefully selected. Volcanic rocks in which the caves have been excavated are highly weatherable materials that experience fast surface deterioration, raveling and spalling.

Results from the mathematical models (slope stability and rock fall scenarios), combined with GBR monitoring system and historical rockfall database analysis, allow us to reach a complete description of future possible failure scenarios and to propose susceptibility and hazard zoning, up to a risk assessment for exposed people and structures.

This analysis will also support the choice and design of risk mitigation countermeasures to be installed for a safe exploitation of the historical site (Fig.12).
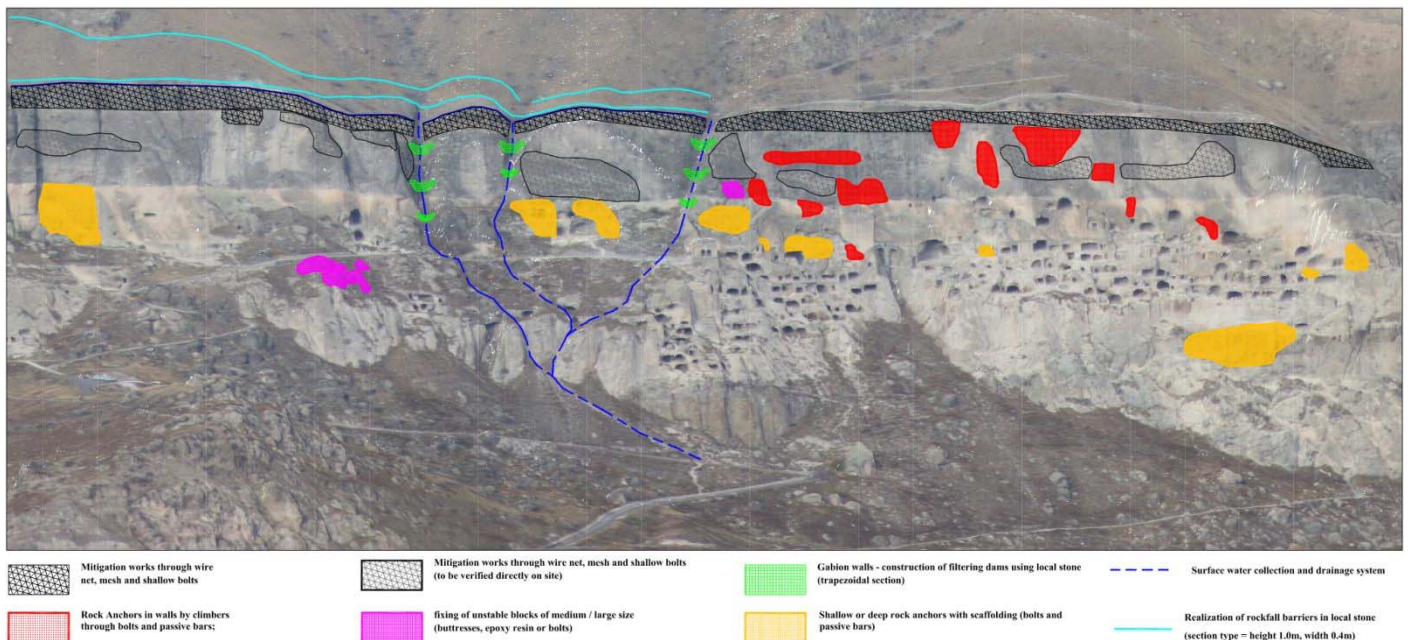

Fig. 12 General Master Plan for the proposed mitigation measures for the whole Vardzia Monastery

Conclusion

The Vardzia Monastery is one of the most important Georgian Cultural Heritage. The site has always been affected by slope instability processes along the entire slope, threatening security of the site and future tourist exploitation. National Agency for Cultural Heritage Preservation of Georgia has supported and promoted

interdisciplinary landslide risk analysis, assessment and management during last five years. An integrated monitoring systems for the whole rock cliff has been developed and implemented and it is still operative.

The main geomorphological, geo-structural and geomechanical evidences obtained after field missions suggest the following observations and recommendations:

• the potential instability processes and mechanisms observed for the entire rock cliff can be referred to different failure modes (or their combination): rock fall; planar rock slide; roto-translational rock slide; wedge and toppling failure;

• actual and/or potential instability processes at the Vardzia monastery are the result of a combination of different predisposing factors such as: lithology, presence, frequency and orientation of discontinuities vs. slope orientation, physical and mechanical characteristics of materials, morphological and hydrological boundary conditions as well as human activities;

• relevant factor in Vardzia slope stability is the reduction of UCS and tensile strength, from laboratory tests, when saturated; such drop can reach up to 70% of original values, then suggesting an important role in rainy period;

• the coupling of different survey techniques (e.g. 3D laser scanner, engineering geological and geomechanical field surveys) is the best strategy to be adopted in the interdisciplinary field of Cultural Heritage protection and conservation policies;

• The future development for the Vardzia monastery provide mitigation measures both structural and non-structural for the next years in order to reduce risk and increase safety of the site and visitors.

Finally, a mitigation project addressed to evaluate and mitigate risk associated to slope failure was implemented, for both short and long term actions. This emphasized the low environmental impact of adopted solutions, as fundamental management tool of the general master plan for the safe and sustainable future tourist exploitation of the historical site.

Acknowledgments

References

Boldini, D., Guido, G.L., Margottini, C. et al. Rock Mech Rock Eng (2017). https://doi.org/10.1007/s00603-017-1299-7.

Cruden DM (1991) A Simple Definition of a Landslide. Bulletin of the International Association of Engineering Geology 43, 27-29

Cruden DM, Varnes DJ (1996) Landslide types and processes. In: A.K. Turner, R.L. Schuster (eds.) Landslides investigation and mitigation (Special report 247, pp. 36-75). Transportation Research Board, Washington, D.C.

Corominas J (2013) Avoidance and Protection Measures. In: John F. Shroder (ed.) Treatise on Geomorphology, Volume 7, pp. 259-272. San Diego: Academic Press.

FLIR (2009) FLIR ThermaCAM SC620 technical specifications. www.flir.com/cs/emea/en/view/?id=41965.

Frodella W., Morelli S., Gigli G., Casagli N. (2014b) Contribution of infrared thermography to the slope instability characterization. Proceedings of World Landslide Forum 3, Vol. 4, pp. 144-147, 2-6 June 2014, Beijing, China

Gillespie, M., & Styles, M. 1999. BGS rock classification scheme, Volume 1. Classification of igneous rocks. Keyworth, UK: British Geological Survey.

Malservisi A (2017) Caratterizzazione meccanica e modellazione agli Elementi Finiti della parete rocciosa di Vardzia. Master thesis in Environmental Engineering. University of Bologna.

Margottini C, Spizzichino D (2014) How Geology Shapes Human Settlements. In Bandarin F. & van Oers R. (eds.), Reconnecting the City. The Historic Urban Landscape Approach and the Future of Urban Heritage. Chichester: Wiley Blackwell.

Margottini C, Antidze N, Corominas J, Crosta GB, Frattini P, Gigli G, Giordan D, Iwasaky I, Lollino G, Manconi A, Marinos P, Scavia C, Sonnessa A, Spizzichino D, Vacheishvili N (2015) Landslide hazard, monitoring and conservation strategy for the safeguard of Vardzia Byzantine monastery complex, Georgia. Landslides 12:193-204. doi: 10.1007/s10346-014-0548-z

Margottini C, Spizzichino D, Crosta GB, Frattini P, Mazzanti P, Scarascia Mugnozza G, Beninati L (2016) Rock fall instabilities and safety of visitors in the historic rock cut monastery of Vardzia (Georgia). Volcanic Rocks and Soils – Rotonda et al. (eds) Taylor & Francis Group, London ISBN 978-1-138-02886-9. pp. 372-378.

VanDine DF (1996) Debris flow control structures for forest engineering: British Columbia Ministry of Forests Research Program, Victoria, B.C., Working Paper 08/1996. www.for.gov.bc.ca/hfd/pubs/Docs/Wp/Wp22.htm. Accessed 12 Nov 2009

Wunderlich (2006): Geodätisches Monitoring - Ein fruchtbares Feld für interdisziplinäre Zusammen-arbeit. Vermessung & Geoinformation 2006.

Landslides in Africa: the Emerging Trends of Slope Catastrophes and the Factors Driving Instability in the Continent

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Abstract While landslides and associated hazards in Africa are not new, the current trend of slope failure events leading to enormous loss of lives and property certainly is novel. Not only have the dimensions and frequency of landslides increased, uncommon types of debris flow, debris-rock avalanche and a complex mix of others have emerged. From Sierra Leone to DR Congo, to Uganda, to Nigeria the signature of disaster bears close resemblance. Evidences available to the author suggest an increasing trend of landslide catastrophes that may extend to terrains where landslides are rare, and other zones across the west, south and central Africa where the markers of instability are present but unknown. Increase in rainfall intensity (probably due to global warming) as well as destabilization of slopes by activities related to urbanization may be regarded as the primary drivers of instability patterns in the continent. However, the present research discovered that secondary effects of landslides such as blocked drainages and channels (by sediments derived from slope movements and from domestic and industrial wastes), diversion of river courses, and inertness of environmental laws are also significant factors driving landscape evolution, slope movements and increasing the probability of people dying by other forms of natural disasters in Africa. This paper proposes that landslide management strategies taking into consideration the impact of blocked drainages may offer better outcomes.

Keywords Africa, landslides, emerging trend, catastrophe, rainfall, sediments, wastes

Introduction

Landslides occur in diverse forms and in different types of environments, and are generally triggered either solely or in combination by rainfall, earthquakes, volcanic activities, changes in groundwater dynamics, and the activities of man. One or more predisposing factors such as the presence and intensity of discontinuities, weathering, slope angle, slope morphology and the nature of slope material can significantly increase the vulnerability of a slope to failure when triggering factors exceed a certain threshold. Rainfall is the commonest trigger in Africa where increasing rain intensity can readily equate to bigger, faster and greater number of landslides, and higher number of casualties. Poverty and the pressure of urbanization has driven many Africans to live close to the foot of steep mountains whose stability cannot be guaranteed. As was the case in Nigeria in October 2010 where a rapid avalanche that travelled over 2 km destroyed everything in its path, the Sierra Leone and DR Congo landslides in August 2017 killed many people who lived or worked near the failed steep hills. It is instuctive that the catastrophic landslides all occurred on steep slopes and when rainfall intensity and duration are usually high. Correlations of over 200 landslides (Figs. x, y) in the sedimentary, igneous and metamorphic terrains show that most of the landslides in the sedimentary terrain occurred between 30 and 55°; which represents over 75% of the total landslides recorded in the study area. The highest frequency of landslides occurred between 45 and 50°; which represents approximately 25% of the total landslides documented in the sedimentary terrain. Figure x shows the correlation between the frequency of landslides in the metamorphic terrain where it can be seen that over 98% of the total landslides recognized occurred between 35 and 55°. The highest frequency of landslides occurred between 45 and 50°; which represents approximately 42% of the total landslides recorded in the study area.
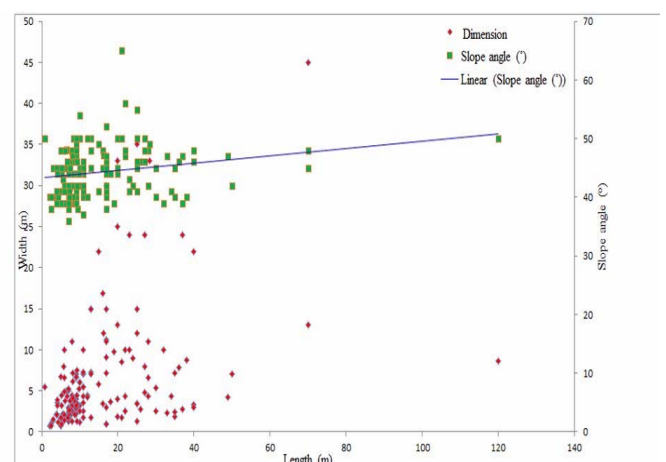

Figure 1 The trend of landslides in sedimentary terrian in recent years

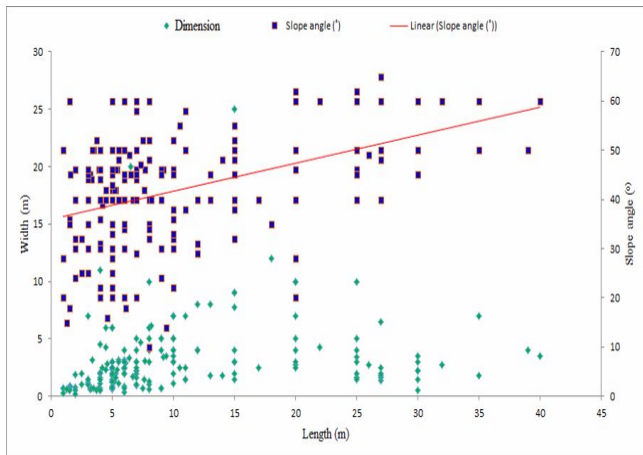This paper presnts new data on landslide in Africa and summarizes the main factors driving instability.

Figure 2 The trend of landslides in metamorphic terrian in recent years

The Sierra Leone Landslide

The Sierra Leone mudslide of August 14, 2017, took place in the Regent area of Freetown on the steep slopes of Mount Sugar Loaf. Sugar Loaf forms a part of extensive and forested highlands south of the city. The city of Freetown and its suburbs have grown in recent times to almost encircle this roughly elliptical highland region.

The Geological units of Sierra Leone can be divided into 3 units: the eastern part of the country is made up of the Archean granite gneisses, greenstones, granitoids and supercrustals of of the Kenema-Man Domain. These rocks are the westernmost part of the West African Craton. To the west of this domain is the NNW-SSE Rockslide orogenic belt consisting of Archean, Neoproterozoic and Early Paleozoic rocks thrust faulted upon each other during the Pan African orogeny 550Ma. Along the coast lies Neogene to recent sediments of the Bullom Group(Schlüter, 2006). Intruding these rocks are isolated basic intrusives of Triassic to Early Jurassic age. The most prominent of this is the Freetown Layered complex which forms the extensive higlands which Freetown surrounds and which Mount Sugar Loaf is a part of. The Freetown layered complex consists of troctolitic gabbro and anothositic rocks dated 193 Ma(C. I. Chalokwu, 2001; Christopher I. Chalokwu, Armitage, Seney, Wurie, &Bersch, 1995; Umeji, 1983). This intrusion formed part of the basic volcanism associated with the initial rifting stage of the opening of the Atlantic Ocean.
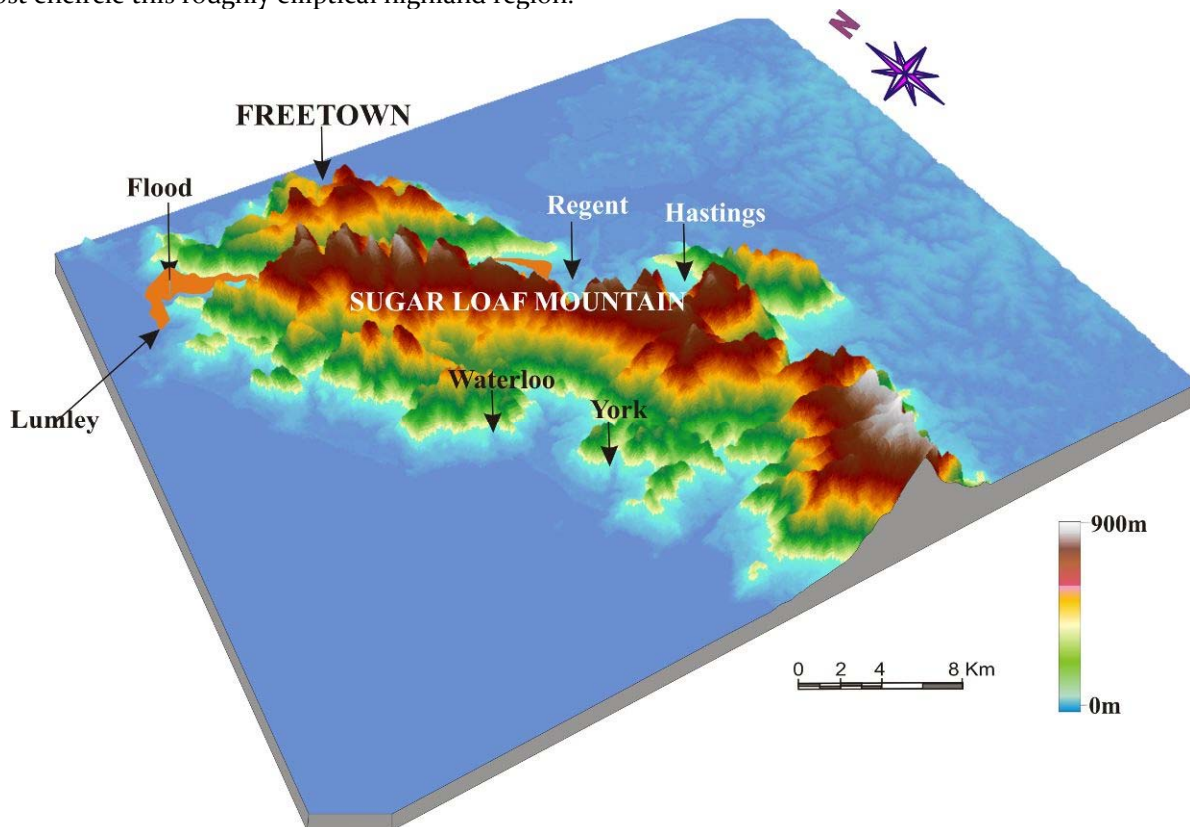
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Figure 3 3D ASTER DEM of the Sierra Leone Landslide area revealing geomorphology and the slide path

The hills of the Freetown Layered Complex show major NE-SW and minor NW-SE trending lineaments. These lineaments are most likes fracture zones within the rocks of the Freetown complex. The lineaments clearly control the drainage and the erosion of the hills in the region. One of these structurally controlled NE-SW streams cuts through the Regent area where the mudslide occurred. The landslide latched on the flood which travelled through a river path and caused havoc in the city. Over 500 people died and properties worth several millions of dollars were destroyed.

The slope had been predisposed to failure by intense weathering. The soil that slipped when the pore pressure exceeded a threshold was weak and semi-consolidated. The soil was a direct result of the weathering processes on the mountain. After the slip, and with the rain unabated, the numerous fractures on the mountain provided easy pathway to enhance the speed of movement. Simulation result shows that it took only 5 seconds after the slip for the slide to mobilize and transform into a debris flow; a situation consistent with Igwe et al 2013.

Figure 4 The Sierra Leone landslide showing residence pattern near the foot of the mountain

The residence pattern in Africa is a source of anxiety from the viewpoint of safety. Poverty and pressures associated with urbanization have compelled people to choose unsafe areas as dwelling places. In a continent where funding landslide prevention works is rare, huge slope disaster is a matter of time. In Kogi State Nigeria, as in many other parts of the country, people live at the foot of vulnerable mountains unaware of the danger within (Fig. 5).

Figure 5 Thousands of people live at the foot of a vulnerable mountain in Kogi Nigeria

In such areas the main controlling topographic factors for landslides is slope angle and anthropogenic activities. The weakening of slopes by rivers/streams and excavations for construction are important preparatory factors. Rainfall-triggered landslides are the most common. Landslide occurrences in Africa are influenced largely by climatic conditions, anthropogenic activities, lithology, structural discontinuities, and erosion. It is noted that wide human interference in different areas for mining, road constructions, change in land use, buildings, bush burning, deforestation and global warming have contributed to slope instability and subsequent landslides in Africa. The rise in the number of long travel landslides in Africa is mainly due to this factors. Avalanche was not know in nigeria, and was rarely known in Africa until the 2010 debris-rock complex avalanche at the mountain range bounding Nigeria and Cameroon (Fig. 6).
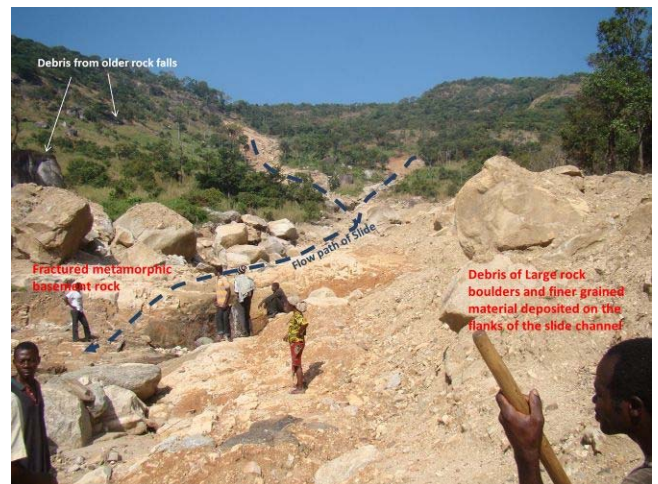

Fig. 6 The 2010 complex avalanche at the Nigeria-Cameroon border

Two landslides occurring simultaneously converged at a point (about 400 m from their scarps) and produced a rock-debris avalanche unprecedented in the history of landslides in the study area. Landslides are quite usual in the Nigeria-Cameroon border, but they occur as one single landslide event. On this particular occasion however, few days after rain had ceased, two landslides joined as one to produce destruction. Two people (farmers at work) died while farmlands, forests and other natural resources were wiped. Human casualty was small because landslide occurred in a mountainous range far from residential zones. Previous rainfall event and the existence of a spring originating just above the head scarp and flowing on the slip surface in the same direction as the debris suggested the soils overlying the bedrock had been under increased stress prior to the slip and eventual movement. Increased pore pressure resulting from elevated groundwater table within the slide mass is a significant factor in the slip initiating the slide. Sliding surface apparently developed at the boundary between the weathered basement rock and the residual soil overlying it. The thickness of the residual soil is about 1 m at some places and up to 20 m at others. Just above the sliding surface is a thin layer (35 cm) of soil that is sufficiently porous, mica-rich, very soft and a bit sticky when wet, and friable when dry. In dry state, the soil could carry the weight of legs but quickly swallows them as soon as water is added.

Following the slip, the moving masses quickly transformed into a debris avalanche carrying materials less than 2 mm as well as blocks of rocks up to 20 m in diameter. Near the source of the slide, the sliding surface is almost entirely bereft of debris and the sliding surface seems planar. As the masses rolled downslope, more soils, rocks, and fluid were encountered leading to more breaking, grinding, crushing and rearrangement of solid materials with heighted possibilities of numerous localized shear zones or surfaces. Liquefaction of some of the materials involved along these sliding surfaces transformed the slide into flow creating scenes comparable to earthquake and volcanic activity. This research observed that there was a definite gradation in the size of displaced materials from the toe of the landslide to the head scarp. The size of particles at the toe where it blocked a river and formed a small temporary lake averaged 2 mm in diameter. A few meters upslope, the size of particles increased. The "coarsening" up sequence continued upslope until rocks of several sizes are encountered.

As was the case in Sierra Leone and DR Congo water-infiltration engendered an increase in pore-water pressure in the loose residual soils, correspondingly decreased the shear strength of the slope mass, and facilitated the formation a slip surface. The mass of soil involved in the slip began to slide and later accelerated as high pore-water pressure is generated. The disturbance and possible soil-structure destruction accompanying the surging mass encouraged further growth of pore pressure and mass liquefaction process (Sassa 1998; Igwe et al 2013a). As the liquefied mass travelled down a more gentle part of the slope, deposition of boulders at the debris flow lobe signaled the cessation of flow movement. Because of the presence of more water (in the case of Sierra Leone), movement could even became more violent and carried everything on its path. In other cases movement was more gradual at this stage but could not cease completely as a mass of smaller particle sizes began a relatively rapid descent down the gentle part of the slopes. At the flat ground, movement continued further down the valley but no longer under the influence of gravity as flow changed to hydraulic debris flow or lateral spread (as opposed to the gravity flow).

These new forms of landslides represent a serious problem almost in Africa, because they cause economic or social losses on private and public properties. They constitute a serious environmental concern not only because they becoming more catastrophic, destroying lives, and damaging property but also because the variations in their mode of occurrence, frequency, and spatial distribution are wide and becoming unpredictable. Annually, precipitation during rainy season induces long-travel landslides in the continent. Cities closer to the coast such as Sierra Leone and Conakry receive higher amount of rainfall that may trigger bigger landslides in the furure. The concentration of the popultion along the mountains in Kogi, Freetown and Conakry are sources of

concern. The pointers to vulnerability of these monutains are clear, and lessons learnt based on recent catastrophes should aid effective preventive measures in the cities across Africa. To preserve the environment and also minimize loses, landslide prevention strategy and adequate measures for landslide hazard mitigation are a necessity.

Figure 7 3D Satellite image of Reagent area of Freetown

Figure 8 Satellite image of Conakry Guinea

Figure 9 3D Terrain image of Reagent area of Freetown showing the vulnerable portions

The terrain image of Reagent area of Freetown has a lot of similarities with that of Conakry (Figs. 9 and 10) Landslides are likely to occur on any of the several NNE-SSW trending, roughly symmetrical ridges (Figs 9 and 10). These ridges may be residual features of erosion that took advantage of fracture-controlled lineaments. The ridges are high and convex making them good environments for landslides. The residual soils on the slope studied are

moderately permeable because of the percentage of fines, which made them susceptible to rapid changes in properties when subject to varying hydrologic conditions.

Figure 10 3D Terrain image of Conakry Guinea showing the vulnerable portions

Disaster timeline

On August 14, 2017 a part of the Suger Laof mountain in Sierra Leone failed. Its failure concided with high intensity and prolonged rainfall which caused the debris to move rapidly along paths that futher excerbated the threat to safety. In the end, over 500 people died with property worth milloins of dollars lost A few days later, as Africa mourned, another landslide caused heavy loss of life in DR Congo. In DR Congo, Uvira and Tora have experienced catastrophic landslides; and they all occurred during heavy rainfall period. The case of Sierra Leone was paticularly unique and represents one of the examples of emerging threats in the continents. Firstly. Weathering, discountinuties arising from past tectonic activities and sundry constuction works had combined to reduce the factor of safety of the slope. Secondly, the failure coincided with the proloned rainfall in the area. Thirdly. the debris from the landslide was quickly carried by the flood arising from the rain and excerbated by some blocked drainages and channels along the path of a river(Fig. x). As the rain poured unabated and as entrainment of materials slid path gained momentum only few peole on the path of debris movemnt were able to evacuate.

To predict landslide events, it is important to understand the mechanisms of rock-slope failures by analyzing the features that could also serve as early warning signals. Therefore, rigorous field work, laboratory experiments and stability analyses are recommended to determine the specific factors inducing slope failures in the area.
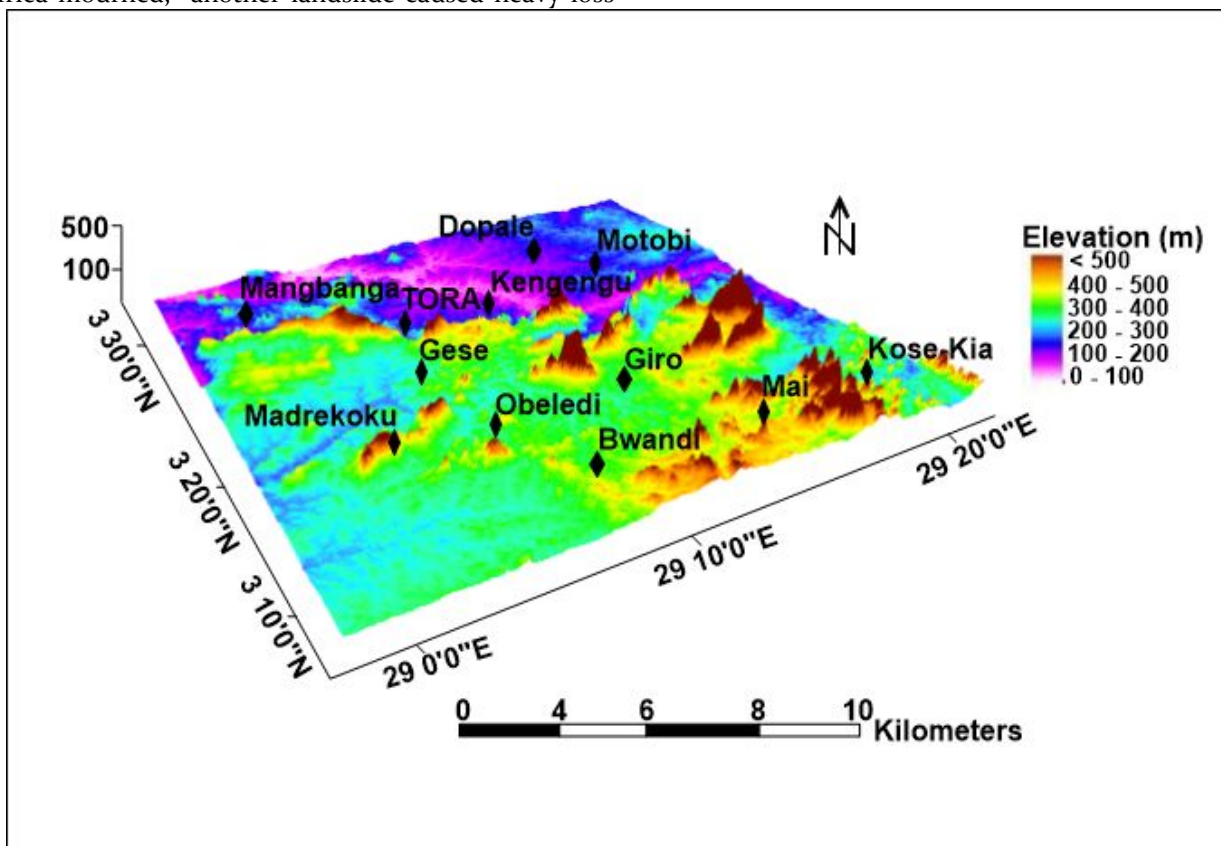

Figure 11 3D ASTER DEM of the Tora landslide DR Congo revealing the geomorphology of the area

Based on the results of analyses, rapid landslides in the areas studied occur because of high excess pore pressure and the large difference between shear stress and shear resistance.

13

New factors driving disaster in the continent

Blocked drainages are increasingly becoming the single most important factor in landslides in Africa. And it is becoming clear that one of their effects is to increase the propbability of an African being killed by a natural disaster other than landslides. Sediments from previous slides fill the drains and channels preventing effective flow of water; a situation that puts more pressure on existing slopes leading to not only the evolution of varying patterns of failure but also to more devastating movements. In Fig. 12 the blocked drainage apparently produced higher pressures that increased the erosive and liquefying capacities of the available water. Preventive and mitigating measures taking into account this factor may offer more reliable outcomes in future.

Figure 12 Effect of a blocked drainage on mass failure

Lessons from Nanka landslide Nigeria

The mechanisms and failure processes leading to the evolution of Nanka landslide, widely regarded as the biggest landslide in West Africa, were investigated by a collaborative initiative involving researchers from Kyoto University, Japan and University of Nigeria, Nsukka. By means of laboratory tests and a GIS technology integrating satellite data, aerial photography and field measurements, the major causes of instability were identified. The resultant DEM clearly showed that streams flowing on impermeable shale units penetrated the thick sand bodies and initiated gulling and landsliding (slumping). Aided by the hydraulic conductivity of the sands, the streams contributed to the erosion or liquefaction of the basal units, and the spontaneous collapse of the overlying units leading to the deepening and widening of the gully. The basal units were eroded mainly in periods of heavy rainfall when the velocity of the streams increased, but failed by liquefaction when the basal moisture content encouraged the generation of destabilizing excess pore-water pressure. Laboratory results revealed that representative specimens were characterized by strain-softening behavior, progressive development of positive pore pressure and high brittleness index. Notably, at higher normal stresses the friction angles at peak and critical stress states coincided. This coincidence was caused by the tendency for static liquefaction at higher pressures, indicating the high vulnerability of the basal units confined at great depth. While the two mechanisms involved in the propagation of instability can proceed together, variations in intensity and periods of rainfall

may ensure that one dominates the other at different times.

Figure 13 Nanka landslide

Nanka landslide is in Anambra State, south-east Nigeria (Fig. 1). The landslide is probably the biggest landslide in West Africa and has been a source of serious concern to national governments and international organizations because of the size of land wastage, amount of property damage and risk posed to lives (Fig. 2). The area is located between latitude 6° 00'N – 6° 05'N and longitude 7° 00'E – 7°10'E; and has been designated a disaster zone by the Nigerian environmental agency. Local and state authorities had severally attempted to no avail mitigating measures aimed at containing the increasing threat of the mass movements. What began as a small landslide the size of a footpath many years ago has progressively advanced to the size of four football fields put together (Fig. 3). Available records show that considerable financial resources have been invested without success in remedial and remodeling techniques aimed at arresting or diminishing the rate of erosion and gully development in the area. Erosive agents steepen the slopes and encourage landslides which widen and deepen the gully. Construction of drainages has yet to yield the desired results on the growth of the sinkhole-like gully measuring 2.5 km and 1.2 km in length and width respectively. Past mitigating efforts, such as planting of trees, compaction, and drainage construction have failed to stem the tide of structural and economic damage arising from the instability.

The successive failure of containment measures may be related to the unavailability of studies clarifying the mechanisms and failure processes in area. At present, there is no documented detailed study of the combined effect of geotechnical, geomophological and hydrological properties of the soils on the progressive mass wasting phenomenon in the area. New technologies utilizing digital elevation models DEM, shuttle radar topographic mission SRTM and ring shear analysis have not been applied to study instability in the area. Residents' account indicates that failure of the loose sediments occurs most periods of the year but with greater intensity during the rainy season; making control methods based solely on one mitigating concept ineffective. Although it is widely known that rainfall can result in decreased shear strength on a potential failure surface (Reid et al. 1988; Simon et al. 2002; Huang 2008) leading to failure when the slope equilibrium can no longer be sustained (Tsai et al. 2008;

Igwe 2014), the relationship among stratigraphic sequence, drainage pattern, shear strength reduction and eventual failure of the unconsolidated sediments is poorly understood. The apparatus which simulates pore pressure generation and shear strength reduction along a well-defined shear zone is suitable to study the properties of the unstable sands. The understanding of the mechanism of transient seepage in unsaturated soils and its impact on the stability of slopes founded on weak, shallow marine sediments of the south-east Nigeria will permit adequate correlation of the soil properties with geologic and geomorphologic settings.
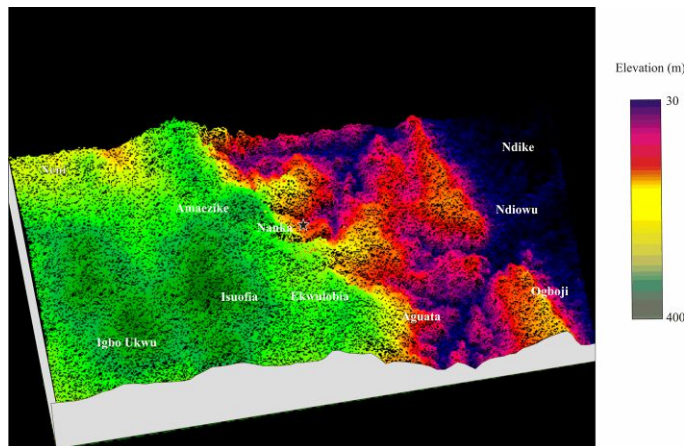
Figure 14 3D DEM of Nanka landslide

The geologic and geomorphologic information obtained from the field survey, geotechnical assessment and literature review led to the production of the first digital elevation model of the area (Fig. 14), and a geologic map showing the major rock types. The DEM captured the actual drainage pattern and showed that the area is relatively low with the Nanka landslide located on elevation < 400 m. Areas shown in green are higher and are underlain by sandstone, while areas in red are underlain by shale units. The bluish zones are the drainage system in the area. The geologic map shows that there are two dominant lithologic units - Nanka sand (Eocene) and Imo shale (Paleocene). A cross-section of the area (Fig. 15) shows that the shale is overlain by the sandstone. It also shows that the landslide occurred in the sandstone and progressively developed into a huge gully. Sequential study of the thick sandstone beds indicated the materials at the base were more compacted than the overlying layers. Analysis showed that the sediments were products of shallow marine environments consisting of friable, cross-bedded fine to coarse sandstones that were pebbly in some places, and plastic shale units with varying degrees of activity.

The 3D DEM shows clearly the topographic, stratigraphic and drainage controls on the progressive instability at Nanka (Fig. 9). The streams flow on the Paleocene Imo shale and are seen in Figure 9 terminating on the Eocene Nanka sands. The streams' action begins at the shale-sandstone contact where depending on the period of the

year erosion or liquefaction is initiated. The basal sandstone units are under elevated overburden pressure, and experimental results have shown that at such conditions the sands are considerably predisposed to static liquefaction which conforms to liquefaction assessments in Casagrande (1936),Castro and Poulos (1977), Poulos et al. (1985), Lade (1992), Igwe and Fukuoka (2014) and Igwe (2014).
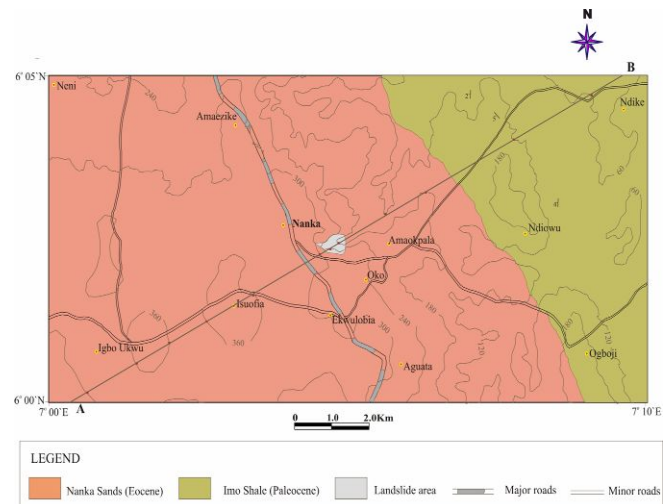

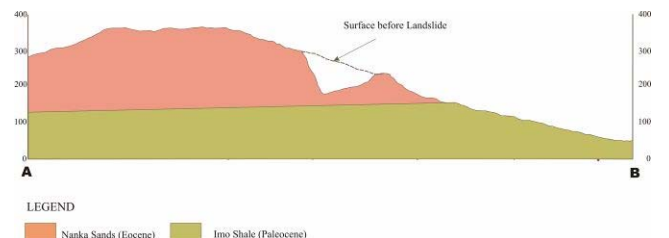Figure 15 Geologic map of the Nanka area

Figure 16 Cross-section of the Nanka landslide

The new technique used in the present analysis which integrates satellite data, aerial photography and field measurements using GIS technology produced the first DEM of the Nanka area. The model revealed the micro-topographic details of the study site and showed that streams flowing on impervious shale units entered the permeable sands at the base, eroding or aiding liquefaction failure. It was shown that the basal failure of the sediments resulted in the collapse of the overburden units; a process driving the deepening and widening of the gully and predisposing the slope to diverse forms of mass movements. The adopted technique also resulted in a detailed geologic map which cross-section depicts the stratigraphic sequence and the morphology of the gully.

The basal units were evidently more compacted than the overlying units and demonstrated the higher confining stress existing at the base. Experimental results showed that at similar normal stresses, the friction angle at peak and critical stress states were equal, and indicated high vulnerability to static liquefaction because the frictional properties of the sediments at peak (small strain) may correspond to those at critical state (large strain).

Conclusion

Landslides in Africa are becoming more freocious and catastrophic; and many more cities are likely going to be affected in future. As the effect of global warming spreads in the continent, and as the pressures of urbanization mounts on the people and their governments, it will become easier for rainfall to trigger dangerous landslides on several vulnerable slopes whose stability has been intensely breached by weathering, varying discontinuities, deforestation, mounting pressure at the foot of the hills due to drainage clogging and changing landuse practices. While African cities that receive more than 2000 mm of rain annually are at risk, those receiving > 2500 mm appear to be at greater risk. Recent events should be a source of concern to Nigeria, Cameroon, , Mali, Sierra Leone, and Conakry. Several catastrophic landslides in DR Congo and Uganda should also be a warning that the Cental regions of Africa are also in danger.

The loss of lives and property to landslides can be curtailed through thorough application of advances in landslide research. In this light, a landslide susceptibility map for Africa is long over due. African governments should unite against landslides and the future dangers they portend. Resources should be made available for an integrated action on landslides prevention works, and on early warning systems in the region. Universities across the region should partner with international associations such as the International consotium on Landslides ICL to device effective ways of landslide prevention and mitigation.

Detailed landslide investigation in different parts of Africa was carried out, and over 400 landslides were recognized and fully documented. The characteristics and spatial distributions of these landslides were recorded and grouped into several categories based on locations, lithology, geomorphology and mode of occurrence. Some are mainly shallow translational slides while other are rotational slids. Landslides in Nanka and Iva valley underlain by unconsolidated, friable, weak sands inter-bedded with claystone/shale. shallow translational debris slides and slumps dominates these areas and are primarily caused by the devastating effects of gully erosions that have destabilized slopes and created high slope angles that normally fail during or after short intense rainfalls. A new landslide mechanism associated with destabilization of slope due to the alternating swelling and contraction of interbedded smectite-rich shales was recognized at some locations. Catastrophic debris flows and avalanches were also recognized.

The present research is the first to apply the concept of critical pore pressure in interpreting material behavior at landslide sites in Africa. Using the stress-displacement behavior as evidence, it is possible to observe the pre- and post-failure progressive and steady positive pore-water pressure buildup and the resultant decline in shear resistance. The result is in agreement with the proposed mechanisms of basal failure, and overburden collapse as the streams enter the permeable material at the shale-sand contact, or as infiltration occurs during or after rainfall. More importantly, where perched water table was not formed above the main water table, the factor of safety will be influenced more by initial groundwater table and intensity of rainfall; and less by permeability ratio, which correlates the proposed failure mechanisms. In the cases where a perched water table formed, the failure mechanism drastically changes.

Acknowledgments

References

Igwe O (2013) ICL/IPL activities in West Africa: landslide risk assessment and hazard mapping approach. Landslides, 10: 515–521

Igwe O, Fukuoka H, Sassa K (2012) The effect of relative density and confining stress on shear properties of sands with varying grading. Geotech Geol Eng. Springer 30: 1207-1229.

Igwe O (2014)The role of weathering in the initiation and mobility of a rare complex avalanche at the Nigeria–Cameroon border, West Africa. Landslides 11: 319-326

Igwe O, Onwuka S, Oha I, Nnebedum O (2016) WCoE/IPL projects in West Africa: application of Landsat ETM+ and ASTER GDEM data in evaluating factors associated with long runout landslides in Benue hills, North-central Nigeria. Landslides DOI 10.1007/s10346-016-0703-9

Igwe O (2015) The study of the factors controlling rainfall-induced landslides at a failure-prone catchment area in Enugu, Southeastern Nigeria using remote sensing data. Landslides DOI 10.1007/s10346-015-0627-9

Igwe O (2015) Predisposing factors and the mechanisms of rainfall-induced slope movements in Ugwueme South-East Nigeria. Bulletin of Engineering Geology and the Environment DOI 10.1007/s10064-015-0767-0

Igwe O, Mode W, Nnebedum O, Okonkwo I, Oha I (2015) The mechanism and characteristics of a complex rock-debris avalanche at the Nigeria-Cameroon border, West Africa. Geomorphology 234: 1-10

Igwe O, Fawu W, Sassa K, Fukuoka H (2013) The laboratory evidence of phase transformation from landslide to debris flow. Geosciences Journal DOI 10.1007/s12303-013-0049-4

Problems and Countermeasures of Highway construction Related to Landslide in North-eastern China

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Abstract With the highway construction in the northeastern cold area, many engineering geological problems encountered in cold area are gradually exposed. Bei'an to Heihe highway project is expansion project, the special geological structure and permafrost degradation together formed the unique geological disasters along the highway. Mainly is that, in digging section: icing in winter and slope slump in spring, in filling section: the seasonal landslide on one side, which is threatening the roadbed. This paper is focus on those problems, analysis one by one, and put forward engineering measures.

Keywords highway construction, north-eastern China, permafrost, countermeasure

1.Background

Heilongjiang Province is located in northeastern China, the latitude is high and belongs to cold areas. From 2012 to 2015, the development of highway construction in Heilongjiang Province is very rapid, total 2000km within 3years.With the highway construction in the northeastern cold area, many engineering geological problems encountered in cold area are gradually exposed. Bei'an to Heihe Expressway is widening expansion project and is one of the construction planning. Due to the complex geological conditions in the area, engineering geological problems are particularly prominent. This paper is focus on those engineering geological problems encountered in road construction, analysis one by one, and put forward engineering measures.

1.1 Geological and climatic background in Northeastern China

1.1.1 Topography and landforms in northeastern China

The landform in northeastern China can be simply summarized as "three mountains and two plains". "Three Mountains" is the northwestern Greater Khingan Mountain, the northern Lesser Khingan Mountain and the eastern Zhang Guangcai Mountain, Laoye Mountain, Wanda Mountain. Between the three mountains, there are northeastern Sanjiang Plain, western Songnen Plain. The Songnen Plain follows the Songhua River Valley connected to Sanjiang Plain. The altitude of most mountains is 300-1000 meters, and the plains is 50-200 meters above sea level. The topography of Northeastern China is higher in northwestern, northern and southeastern, lower in northeastern, southwestern.

1.1.2 Geological Structure and Evolution in Northeastern China

The modern terrain of northeastern China is gradually formed in the evolution of long geological history. It mainly is divided into two stages: the first period is the rising period, from the marine environment in Proterozoic (Pt) to sea water exiting and mostly part rising to land in end of Palaeozoic(Pz), Greater Khingan Mountain and eastern mountain landscape has been basically formed. The second period is the period of someplace depression, fracture and volcanic activity, from Mesozoic(Mz) Jurassic(J) to Holocene(Q4/Qh), after several crustal movements, fold fracture and other internal forces, coupled with thawing, weathering, wind and rain erosion and other external operations, finally form a complex terrain in northeastern region.

1.1.3 Climate in Northeastern China

Northeastern China region belongs to the temperate continental monsoon climate, long winter short summer, also short spring and autumn, low air temperature, cold and wet, four seasons change is very obvious. Wind and easy drought in spring, mild and rainy in summer caused by the southeast monsoon control, and more east and southerly wind; often early frost damage in autumn; controlled by Siberia-Mongolia high pressure, more northwest and northerly wind in winter , long cold and dry.

1.1.4 Permafrost Distribution and Characteristics in Northeastern China

In the northeastern China, with the increase of latitude, from south to north, it is seasonal frozen soil area, discontinuous permafrost region and continuous permafrost region. In the past 50 years, permafrost in the northeastern region is degradation, and its southern boundary is moving north(Fig.1). That is spatial distribution of the permafrost is broken, the local PF island disappears, the temperature of PF increases, the thickness of PF decreases, and the thermal stability of PF decreases.
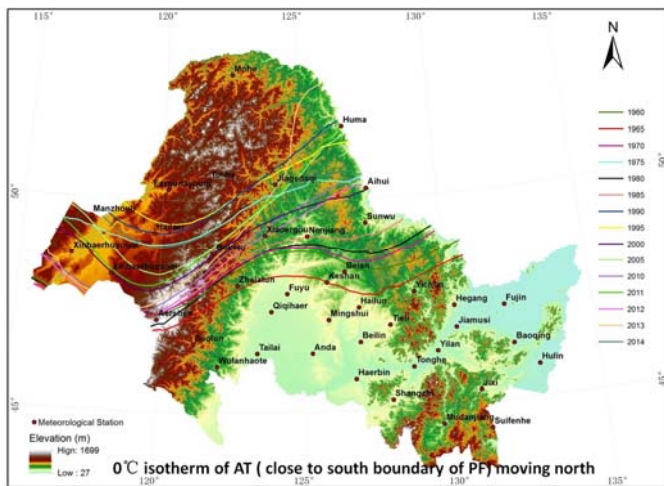
Figure 1 Change of PF southern boundary in NE China

The first reason for PF degradation is the climat. According to the National Weather Service, the annual average air temperature increased more than 2.5℃ in northeastern China over the past 50 years. Secondly, the destruction of vegetation (forest fires, deforestation) and the construction of artificial structures (highways, pipelines, buildings etc.) have accelerated the process of permafrost degradation.

The order of PF degradation is closely related to its previous occurrence. The PF in northeastern China is known as the "khingan Baikal type" permafrost, suggesting that its two major formation elements, both the stretched valley terrain and the Mongolian-Siberian high pressure from Baikal Lake. In winter, inversion layer caused by Mongolia - Siberian high temperature controlled most of the PF regions of northeastern China. With shrubs, moss and other planting cover the surface, which reduce solar radiation, hinder the temperature rise, so the lower place such as riverside terraces, valleys, marshes and shallow slope become good place for PF development. When the PF began to degenerate, its degradation order is also from sunny slope to shallow slope, from top slope to bottom slope, from naked land to green land, eventually form a unique distribution of PF.

1.2. Geological situation of the road area

The geological conditions of Bei'an-Heihe Expressway is very complex, the PF in the road area is degraded rapidly, then triggering a series of engineering geological problems.

1.2.1 Geological environment of the road area

Road area is part of the Sun Wu fault depression,that is Xigangzi fault depression (1036m2, buried depth of 200-1600m, deposition period is Quaternary Cretaceous (KRQ)). The new tectonic movement in the area is mainly the block movement, and the new fault traps are first descending and then rising, which is mainly composed of coarse sand or sand rock. At the top of the mountain or hills, is covered by Sandstone thin layer like cap cover. Mudstone, sandy mudstone clip, shaly sandstone and fine sandstone is exposed in low hilly or the lower part of mountain, the rock is weak cementation.

The surface is mostly weathered, weathering layer is thick. The irregular stratification of the formation of the fault will form a special permeable interlayer. Irregular layer structure caused by fault and deposition will form special permeable interlayer.

1.2.2 Climate environment of the road area

According to t Meteorological data of Sunwu County, this is the nearest city around the road. By applying linear regression, we found that, from 1954 to 2013, the annual average temperature in the study area increased by 3.2 ◦ C; and the average annual minimum temperature increased by 5.2 ◦ C(Fig.2).
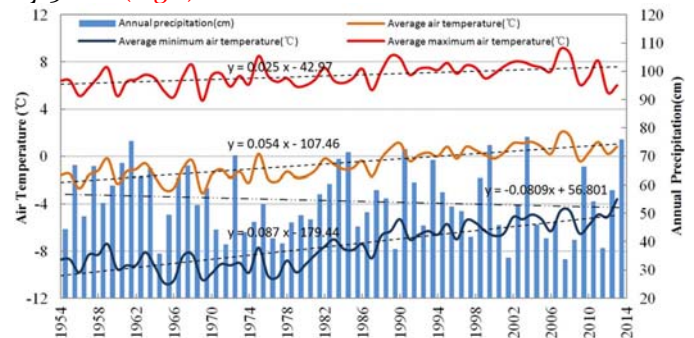
Figure2 Average annual air temperature changing near road area（1954-2014）

1.2.3PF Degradation of the road area

Fig.3A is a PF distribution map of the road area ,which is based on the Landsat 7 ETM + image data in 2012. It has obvious distribution characteristics of "Xing'an Baikal type" permafrost. Fig.3B is deformation distribution map of the road area ,which used the D-Insar method and same data （2007-2011） with above. It could be found that there are less deformation where has more PF; there has some deformation where close to the place of more PF area, which means PF is thawing, and there has more deformation where has little PF, which means PF has been thawed completed and the deformation is the biggest. We also drill the sample at the corresponding location and prove this（Wei Shan,ChunJiao Wang et al.2012；Wang Chunjiao et al.2015；Shan W.Hu Z.Guo Y.and Wang. C. 2015）.

Figure3 A: PF distribution using Landsat 7 ETM+ Imagine data,2012; B: PF distribution and the surface deformation

2. Problems and Countermeasures of Highway Engineering Geology Related to Landslide

2.1 Highway Engineering Geology Problems Related to Landslide

To build roads in the cold area, frozen up and melting settlement is the common engineering geological problems. During Beian-Heihe Highway construction, in

addition to frozen up and melting settlement, there are some other engineering geological problems because of special geological structure and PF degradation. This article will focus on the latter. These special problems often occur in the hills area, there are often two cases.

2.1.1 In digging section: icing in winter and slope slump in spring

In the autumn of 2009, the excavation construction was carried out. In February 2010, a large amount of water outflow from the cutting slope, and was frozen, form icing. Icing directly covers the road. In May 2010, after icing melting, cutting slope slumped（Fig.4）. The next winter, the icing in this section occur again, but the scale has been reduced（Shan W. Hu Z. Guo Y. 2015）.

Figure 4: In digging section: icing in winter and slope slump in spring

2.1.2 In Filling section: the seasonal landslide on one side, threatening the roadbed

Along this section, there are four different degrees, different shapes of landslides in the 20 km range. For example K178+530 landslide, it is the seasonal creep landslides, beginning in spring, reach the largest in summer and stop in winter(Fig.5). it is not related with the annual precipitation. but the sliding scale decreased year by year. The back edge of the landslide directly attack the roadbed and have great harm(Shan W. Hu Z. Guo Y. et al.2015).

Landslide scene photos:
a) Panoramic view of landslide (in November 2014);
b) The back edge of landslide (in June 2010);
c) The front edge of landslide (in October 2013)

Figure 5: In Filling section: the seasonal landslide on one side, threatening the roadbed

2.2 The mechanism and Countermeasures of two kinds of geological disasters

For these two kinds of geological disasters, we used variety survey methods and monitoring methods, after more than five years of investigation and monitoring, ultimately found their mechanism, and put forward the corresponding engineering control measures.

2.2.1 The mechanism of icing and engineering control measures

On the cutting slope where the icing occurred, we obtained the soil layer structure inside the cutting slope by drilling. We buried temperature and pore water pressure sensors in different locations on the slope and conduct monitoring collection for 5 years. We find that this section belongs to the typical fault depression and sedimentary zone, and the soil layer is obvious, and there is a large area parallel distribution of the permeable layer and barrier layer, which can provides favorable conditions to water collection and outflow. This area is also in the PF degradation area, the cutting project directly changed the original water and heat balance, and promotes the melting of PF nearby, melting water collected through the geological layer. When the winter comes, with the temperature drop, the frozen fronts gradually move down, the water just above the geological barrier layer began to have pressure, when the pressure is large enough, it will break out from somewhere weak frozen surface and flow, which is icing. When the icing covers the road, it seriously affects the safety of the traffic. After icing melting in the spring, the cutting slope was erosion and landslides(Shan W. Hu Z. Guo Y. 2015).

From the above analysis we can see that the construction of cutting slopes made the original water and heat balance in the slope be destroyed, increases the melting of the PF, as well as made the permeable layer be exposed to the cutting slope, that is the two main reason for icing. So we conduct a certain depth of the gravel blind ditch along the cutting slope, which can cut off the slope outflow path and prevent icing. Practice in the field has proved that control measures is effective(Fig.6).
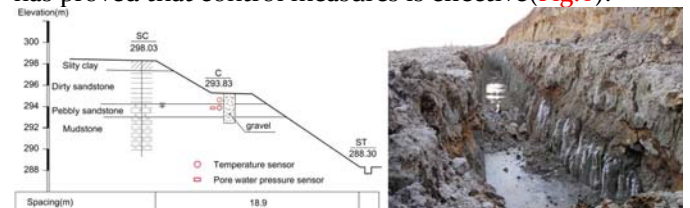
Figure 6: Gravel blind ditch along the cutting slope

2.2.2 The mechanism of creep landslide and engineering control measures

We mainly use three kinds of detection methods: The first is drilling detection, it includes sampling from drilling hole, drawing geological map and burring sensors in drilling hole. The second is geophysical prospecting, that is use high-density resistivity (HDR) and ground-penetrating radar(GPR) to find the location of the creep landslide and landslide sliding surface, as well as the surrounding geological conditions(Wei Shan, Zhaoguang et al. 2013;Hu Z. and Shan W. 2015). Finally it is data collection and analysis of 5 years, the data come from soil sensors such as temperature and pore water pressure. Next, we will take the case of K178 + 530 creep landslide as an example to explain and analysis.

Through the results of drilling and geophysical prospecting, we can see that this section also belongs to the faulted deposition area, the permeable layer and barrier layer are distributed in parallel, and the groundwater can be collected along the permeable layer. At the same time, there are some remnant PF blocks and the PF begin to melt because of road construction. By analyzing the monitoring data of soil temperature and pore water pressure , we found that the sliding rate of landslide is independent of precipitation, but is related to the melting of nearby PF block. In spring and summer, PF block began to melt, melting water along the permeable layer gather in the lower place and form sliding surface, then triggered creep landslides. In winter, PF melting stop, creep landslides stopped also. Then same happened in the second year. When nearby PF block all melt, seasonal creep landslides disappeared.

In view of the above mechanism, we adopted different prevention measures according to different scene situation. First thing is know the geological structure and residual PF situation. If the residual permafrost is small in size and degraded rapidly, we will accelerate its melting consolidation. If the PF is larger and will take years to degrade and stabilize. We will use anti-slide piles to reinforce and build bridge to take place the road, they will get through the PF layer and reach a solid foundation for support(Fig.7). Beian-Heihe Highway is the expansion project, there is no choice in the road line selection. If it is the new road project, we believe that when have a new project in the PF degraded area, we should try to avoid the place rich PF , that is riverside terraces, valleys, marshes and shallow slope.

Figure 7: anti-slide piles and building bridge to reach a solid foundation for support

3. Conclusion

Through the construction of highway engineering in northeastern China in recent years, as well as the surrounding survey of PF. We got the following conclusion:

1. The topography of NE China is gradually formed in the evolution of long geological history. After its overall uplift, it undergoing several crustal movements, fold fracture and other internal forces, coupled with thawing, weathering, wind and rain erosion and other external operations, finally form a complex terrain in northeastern region.

2. The PF in northeastern China is known as the "khingan Baikal type" permafrost, in winter, inversion layer caused by Mongolia - Siberian high temperature controlled most of the PF regions of northeastern China. With shrubs, moss and other planting cover the surface, which reduce solar radiation, hinder the temperature rise, so the lower place such as riverside terraces, valleys, marshes and shallow slope become good place for PF development.

3. In the past 50 years, permafrost in the northeastern region is degradation, and its southern boundary is moving north. The first reason for PF degradation is the climatic. Secondly, the destruction of vegetation and the construction of artificial structures have accelerated the process of permafrost degradation. When the PF began to degenerate, its degradation order is also from sunny slope to shallow slope, from top slope to bottom slope, from naked land to green land, eventually form a unique distribution of PF.

4. Road area is part of the Sun Wu fault depression, that is Xigangzi fault depression. At the same time, climate warming made permafrost degradation accelerated. special geological structure and PF degradation function together form unique geological hazards in this area. Mainly is that, in digging section: icing in winter and slope slump in spring. in filling section: the seasonal landslide on one side, threatening the roadbed.

5. The formation of the landslide in the cutting section is the construction of cutting slopes made the original water and heat balance in the slope be destroyed, increases the melting of the PF, as well as made the permeable layer be exposed to the cutting slope. So we conduct a certain depth of the gravel blind ditch along the cutting slope, which can cut off the slope outflow path and prevent icing. Practice in the field has proved that control measures is effective.

6. The formation of the landslide in the filling section is caused by the melting of PF block nearby. In spring and summer, PF block began to melt, melting water along the permeable layer gather in the lower place and form sliding surface, then triggered creep landslides. In winter, PF melting stop, creep landslides stopped also. Then same happened in the second year. When nearby PF block all melt, seasonal creep landslides disappeared. So we think when have a new project in the PF degraded area, it should try to avoid the place rich PF , that is riverside terraces, valleys, marshes and shallow slope. And then to know the geological structure and residual PF situation. If the residual permafrost is small in size and degraded rapidly, it should accelerate its melting consolidation. If the PF is larger and will take years to degrade and stabilize. it should use anti-slide piles to reinforce and build bridge to take place the road, in order to get through the PF layer and reach a solid foundation for support.

References

Hu Z, and Shan W, (2015) Landslide investigations in the northwest section of the lesser Khingan range in China using combined HDR and GPR methods. Bulletin of Engineering Geology and the Environment. Open access at Springerlink.com. DOI: 10.1007/s10064-015-0805-y.

Shan W, Hu Z, Guo Y, Zhang C, Wang C, Jiang H, Liu Y, Xiao J, (2015) The impact of climate change on landslides in southeastern of

high-latitude permafrost regions of China. Frontiers in Earth Science. 3:7. DOI: 10.3389/feart.2015.00007.

Shan W, Hu Z, Guo Y, (2015) The monitoring of soil pore water pressure and soil temperature in cutting slope before and after aufeis. The proceeding of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference, 20-23 September 2015. Québec.

Shan W, Hu Z, Guo Y, and Wang. C, (2015) Environmental and Engineering Geology of the Bei'an to Heihe Expressway in China with a Focus on Climate Change, Engineering Geology for Society and Territory.1. DOI: 10.1007/978-3-319-09300-0_51.

Wang Chunjiao, Shan Monan et al, (2015) Multi-spectral remote sensing based land surface temperature retrieval and isolated permafrost zone segmentation. Infrared and Laser Engineering. Vol.44 No.4 1390-1396.Apr .2015.

Wei Shan,ChunJiao Wang et al, (2012) Expressway and Road Area Deformation Monitoring Research Based on InSAR Technology in Isolated Permafrost Area. International Conference on Remote Sensing, Environment and Transportation Engineering. IEEE. 1-5. DOI:10.1109/RSETE.2012.6260574.

Wei Shan, Zhaoguang et al, (2013) Mechanism of Permafrost Landslide Based on GPS and Resistivity Surveying. Progress of Geo-Disaster Mitigation Technology in Asia,Environmental Science and Engineering. Springer-Verlag Berlin Heidelberg. 349-361. DOI: 10.1007/978-3-642-29107-4_18.

Landslide prone areas in the Dinarides and Pannonian Basin in Croatia and Bosnia and Herzegovina

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Abstract Two neighboring countries in the southeastern region of Europe, Croatia and Bosnia and Herzegovina (BIH), belong to the same geotectonic units of the Dinarides and to the Pannonian Basin, which influence relief types, lithology, and types of slope movements, i.e., landslides. The paper describes the general geological and geomorphological conditions in Croatia and BIH that are preparatory causal factors for landslides. Landslide types, dimensions and activities in the described areas are related to natural conditions primarily influenced by tectonic evolution and by recent anthropogenic processes, e.g., urbanization. Recent rainfall triggering conditions of landslides in Croatia (2013) and BIH (2014) are also specified to emphasize the landslide risk and necessity of landslide risk management. The conclusions of the paper also note historical and potential damage due to landslide reactivations together with the spatial distribution of landslide-prone areas, which requires landslide mapping in the form of landslide inventory, susceptibility, hazard and risk maps.

Keywords Dinarides, Pannonian Basin, landslide prone areas, Global Landform Classification

Introduction

The Dinarides (Fig. 1) are a mountain chain that spans from Slovenia in the northwest through Croatia, Bosnia and Herzegovina (BIH), and Montenegro to Albania in the southeast. These mountains extend in the northwest-southeast direction for 645 kilometers along the Adriatic coast. The Dinarides were uplifted during the Paleogene and Neogene (similar to the Southern Alps, Albanides and Hellenides), and they are the largest European karstic area (Bognar et al. 2012, Bonacci 1987), which is primarily built of Mesozoic and Cenozoic deposits of marine and lacustrine origin.

The Pannonian Basin (Fig. 1) lies at the boundary between Central and Southeastern Europe, and it is situated within the Alpine, Carpathian and Dinaric mountain belts. The Danube and Tisza Rivers are located approximately in the middle of the basin. The Pannonian Basin extends between Vienna (Austria) in the northwest, Zagreb (Croatia) in the southwest, Belgrade (Serbia) in the southeast and Satu Mare (Romania) in the northeast. The geomorphological term Pannonian Plain is more widely used for the lowlands and plains of nearly the same region, which remained after drying out of the Pannonian Sea in the Pliocene. The Pannonian Basin is a geomorphological subsystem of the Alps-Himalaya system that is covered by very thick Mio-Pliocene deposits.

Fig. 1 shows the area of Croatia and BIH, two countries located in the Dinarides and the Pannonian Basin. A total of 51% of the area of Croatia belongs to the Dinarides, and 49% of the area belongs to the Pannonian Basin. In BIH, approx. 88% of the area belongs to the Dinarides, and 12% of the area belongs to the Pannonian Basin. The complex temporal and spatial evolution of the area resulted in the tectonic units of the External and Internal Dinarides (Schmid et al. 2008, Tomljenović et al. 2008), which are shown in Fig. 1. In the Dinarides, Dalmatian Zone, High Karst Unit, Pre-Karst and Bosnian Flysch Unit, units of thrust sheets and Western Vardar Ophiolitic Unit can be recognized with the various types of relief prone to mass movements (landslides and erosion processes). Table 1 lists the relief types in the Dinarides of Croatia and BIH according to Global Landform Classification, GLC (Panagos et al. 2012). Low- and mid-altitude mountains prevail, constituting approx. 62% of the area together with hills (approx. 28%) and lowlands (approx. 8%). In the Pannonian Basin, the Sava Zone and Tisza Mega Unit are the largest tectonic units with the dominant area of plains (approx. 56%). However, approx. 44% of the area of the Pannonian Basin is comprised of relief types prone to landslides, as it is indicated in Table 2: low-altitude mountains (approx. 2% of the area), hills (approx. 18%), and lowlands (approx. 24%).
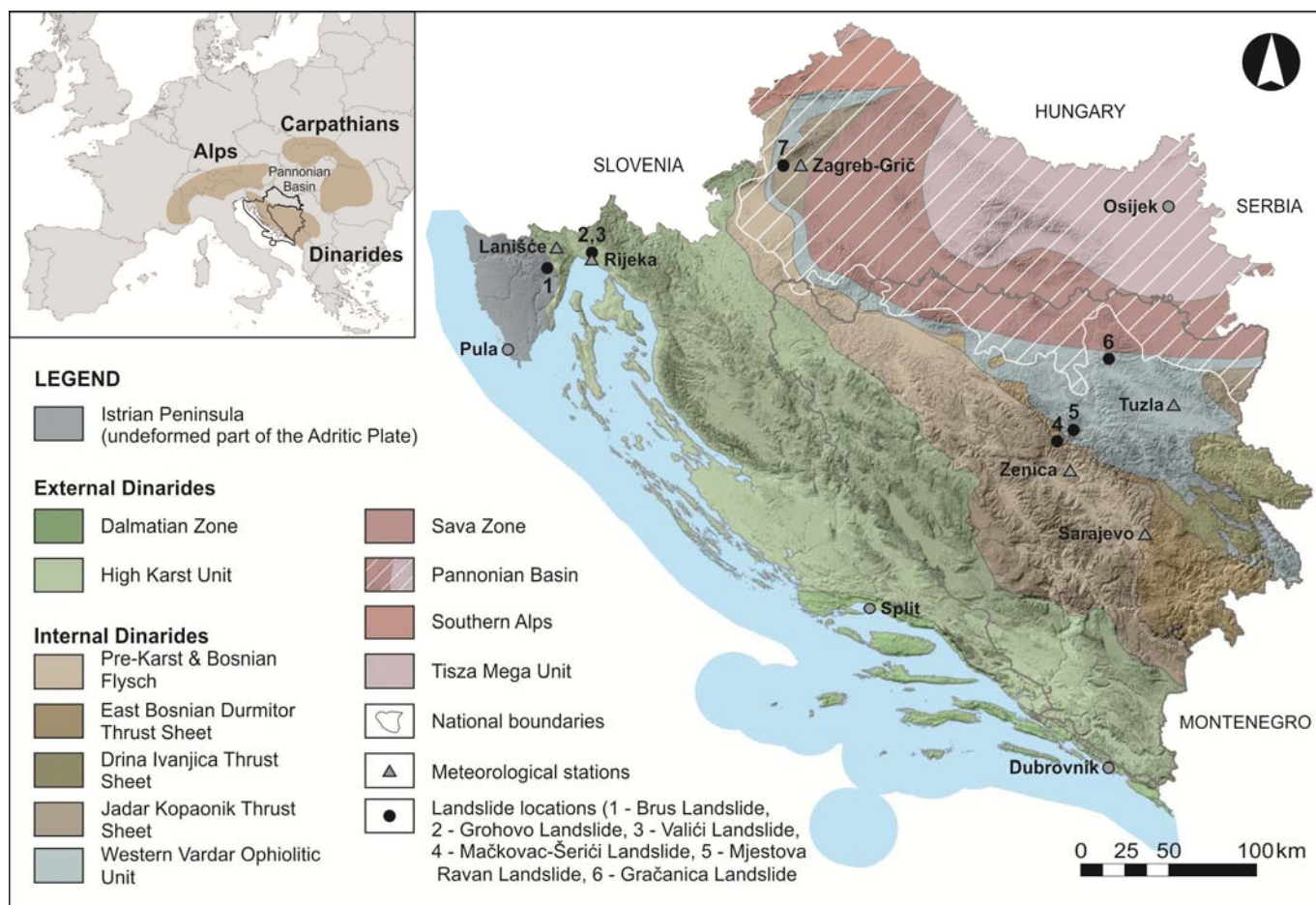
Fig. 1 Tectonic units of the Dinarides and the Pannonian Basin in the area of Croatia and BIH according to Schmid et al. (2008)

Table 1 Relief types in the Dinarides of Croatia and BIH according to GLC (Panagos et al. 2012)

Relief type	Area (km2)	Area (%)	Maximal altitude	Maximal relative relief
High-altitude mountains	11 km^2	0.02%	2,386 m a.s.l.	434 m
Mid-altitude mountains	13,409 km^2	21.46%	2,181 m a.s.l.	1,571 m
Low-altitude mountains	25,035 km^2	40.08%	1,457 m a.s.l.	1,243 m
Hills	17,737 km^2	28.39%	797 m a.s.l.	792 m
Lowlands	4,733 km^2	7.58%	418 m a.s.l.	429 m
Plains	1,544 km^2	2.47%	215 m a.s.l.	215 m

Table 2 Relief types in the Pannonian Basin of Croatia and BIH according to GLC (Panagos et al. 2012)

Relief type	Area (km2)	Area (%)	Maximal altitude	Maximal relative relief
Low-altitude mountains	568 km^2	1.84%	1.053 m a.s.l.	716 m
Hills	5,692 km^2	18.49%	676 m a.s.l.	543 m
Lowlands	7,344 km^2	23.85%	348 m a.s.l.	268 m
Plains	17,185 km^2	55.81%	240 m a.s.l.	240 m

A review of the geotectonic units of the Dinarides and geographic position of the Pannonian Basin in Croatia and BIH, as well as the spatial distribution of the relief types according to GLC (Panagos et al. 2012), enabled synthesis of spatial distribution of landslide-prone areas within the analyzed area (total size of 107,800 km^2). The areas inside the main geotectonic units with higher frequency of landslides are identified based on the prevailing relief types and material types of the bedrock. The type, depth and volume of the dominant landslides and the most vulnerable elements at risk are also specified for all listed areas in Croatia. Used classification according to landslide depth is as follows: <1 m – surficial; 1–5 m – shallow; 5–20 m - moderate-shallow; 20-50 m - deep- moderate; 50–100 m – deep; 100–500 m - very deep; >500 m - extremely deep. Used classification of landslide volume is the following: <10^3 m^3 very small; 10^3-10^4 m^3 – small; 10^4-10^5 m^3 - moderate-small; 10^5-10^6 m^3 - large-moderate; 10^6-10^7 m^3 – large; 10^7-10^8 m^3 - very large; >10^8 m3 - extremely large.

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Spatial distribution of landslide prone areas

Landslide prone areas in Croatia

Table 3 shows bedrock lithology and releif types of the main geotectonic units in Croatia in addition to typical landslide types. Most of the landslide-prone areas in Croatia belong to hills and lowlands composed of:

(i) Neogene clastic rocks (marlstones), carbonate rocks and soils in the Pannonian Basin (approx. 6,000 km²), and in the tectonic unit of the High Karst (approx. 160 km²), the Pre-Karst and Bosnian Flysch Unit (approx. 130 km²), the Western Vardar Ophiolitic Unit (approx. 100 km²) and the Sava Zone (approx. 35 km²);

(ii) Plio-Quaternary soils in the Pannonian Basin (approx. 2,300 km²);

(iii) Paleogene association of clastic rocks (flysch-type rocks) in tectonic units of undeformed part of the Adriatic Plate (approx. 450 km²), the High Karst Unit (approx. 400 km²), the Dalmatian Zone (approx. 330 km²), the Western Vardar Ophiolitic Unit (approx. 80 km²) and the Sava Zone (approx. 80 km²); and

(iv) Paleozoic and Precambrian igneous and metamorphic rocks in the Pannonian Basin (approx. 380 km²);

(v) Paleozoic rhythmic alteration of clastic rocks in the Pre-Karst and Bosnian Flysch Unit (approx. approx. 300 km²); and

(vi) Paleozoic alteration of clastic and metamorphic rocks in the Pannonian Basin (approx. 250 km²).

Low-altitude mountains with landslide-prone areas in Croatia are only present in:

(i) Paleozoic rhythmic alteration of clastic rocks in tectonic unit of High Karst (approx. 270 km²);

(ii) Paleozoic alteration of clastic and metamorphic rocks in the Pannonian Basin (approx. 220 km²);

(iii) Paleozoic and Precambrian igneous and metamorphic rocks in the Pannonian Basin (approx. 190 km²); and

(iv) Paleogene flysch-type rocks in tectonic unit of Dalmatian Zone (approx. 20 km²) and the Western Vardar Ophiolitic Unit (approx. 10 km²).

Non-landslide prone areas in Croatia

There is a large portion of the territory composed of carbonate and clastic rocks (marine deposits) in Croatia, which is not susceptible to landslides, regardless of whether the relief is flat and smooth (e.g., plateaus, lowlands and planes) or rough with steep slopes (e.g., low- and mid-altitude mountains and hills). These areas are present in:

(i) the undeformed part of the Adriatic Plate (approx. 1,800 km²), the area of the External Dinarides (High Karst Unit and Dalmatian Zone approx. 22,200 km²), and

(ii) the area of the Internal Dinarides (approx. 450 km²).

The most dangerous slope movement processes are small rock falls and rock topples which are most frequent along road and railway cuts, are generally triggered by man-made processes or heavy rainfall, and tend to be located inside infrastructure corridors.

Landslide prone areas in BIH

Table 4 shows bedrock lithology and relief types of the main geotectonic units prone to landslides in BIH. Most of the landslide-prone areas in BIH belong to low- and mid-altitude mountains (approx. 10,800 km²) and hills and lowlands (approx. 3,600 km²) in the Pre-Karst and Bosnian Flysch Unit. Spatial distribution of landslide prone areas in BIH is composed of rock formations belonging to: passive continental margin in the Bosnian Flysch Zone ("Flysch Bosniaque"); Triassic and Paleozoic allochthonous complexes of sedimentary and metamorphic rocks; and Neogene and Quaternary post-orogenic sediments and sedimentary rocks. Size of landslide-prone areas in the Western Vardar Ophiolitic Unit and Unit of Thrust Sheets is very similar, approx. 7,600 km². Hills and lowlands (approx. 4,480 km²) and low- and mid-altitude mountains (3,030 km²) in the Western Vardar Ophiolitic Unit are composed of: mélange ("Wild Flysch") and ophiolites in the Dinaridic Ophiolite Zone; Neogene post-orogenic formations of sedimentary rocks; active continental margin formations of sedimentary rocks; and formations of igneous rocks from post-orogenic magmatism. Low- and mid-altitude mountains (approx. 6,300 km²) and hills and lowlands (approx. 1,300 km²) in the Unit of Thrust Sheets are composed of: Triassic and Paleozoic allochthonous complexes of sedimentary and metamorphic rocks; and formation of igneous and pyroclastic rocks from post-orogenic magmatism. Hills and lowlands in the High Karst Unit differ significantly from the abovementioned according to origin of sedimentary rocks that belongs to Dinaric Carbonate Platform. Consequently, there is relatively small area in the High Karst Unit (approx. 3,600 km²) prone to landslides that belong to Neogene post-orogenic formations. In the Pannonian Basin, lowlands and hills (approx. 3,200 km²) are dominantly composed of postorogenic Neogene formations of sediments (soils) and sedimentary rocks with isolated hills built of sedimentary, metamorphic and igneous rock formations of active continental margin and synkinematic magmatism (Motajica and Prosara hills). Area of hills and lowlands (approx. 720 km²) and low-altitude mountains (approx. 60 km²) in the Sava Zone in BIH is relatively small, because it is covered by thick Pannonian Basin sediments (soils) and sedimentary rocks. Most formations of the Sava Zone belong to sedimentary rocks of active continental margin.

Non-landslide prone areas in BIH

There is a large portion of the territory composed of carbonate and clastic rocks (marine deposits) in BIH,

Table 3 Bedrock lithology and relief types of the main geotectonic units in Croatia in addition to typical landslides

Geotectonic unit according to Schmid et al. (2008)	Total area (km^2)	Lithology	Areas with higher frequency of landslides				
			GLC relief type	Landslide type	Landslide depth (m)*	Landslide volume (m^3)**	Elements at risk
Undeformed part of the Adriatic Plate (area of approximately 2,500 km^2)	approximately 450 km^2	association of clastic rocks - flysch-type rocks	hills and lowlands	slide	shallow	small	transportation routes, settlements sporadically
High Karst Unit (area of approximately 22,100 km^2)	approximately 400 km^2	association of clastic rocks - flysch-type rocks	lowlands and hills	slide, rock falls	shallow to deep	small to very large	transportation routes, surficial waters, settlements sporadically
	approximately 270 km^2	rhythmic alteration of clastic rocks	low-altitude mountain	slide	moderate-shallow	moderate-small	transportation routes
	approximately 160 km^2	clastic rocks (marlstones) and carbonate rocks; soils	lowlands, plateaus and hills	slide	shallow	small	transportation routes
Dalmatian Zone (area of approximately 2,900 km^2)	approximately 350 km^2	association of clastic rocks - flysch-type rocks	lowlands, hills and low-altitude mountains	slide	shallow	small	settlements, transportation routes
Pre-Karst and Bosnian Flysch Unit (area of approximately 980 km^2)	approximately 300 km^2	rhythmic alteration of clastic rocks	hills, plateaus, lowlands	slide	moderate-shallow	moderate-small	settlements, transportation routes
	approximately 130 km^2	clastic rocks - marlstones and carbonate rocks; soils	lowlands, plateaus, hills	slide	shallow	small	settlements, transportation routes
Western Vardar Ophiolitic Unit (area of approximately 260 km^2)	approximately 100 km^2	clastic rocks - marlstones and carbonate rocks; soils	lowlands, hills, plateaus	slide	shallow	small	transportation routes
	approximately 90 km^2	association of clastic rocks - flysch-type rocks	hills, plateaus, low-altitude mountains	slide	shallow	small	transportation routes
Sava Zone (area of approximately 130 km^2)	approximately 80 km^2	association of clastic rocks - flysch-type rocks	hills, plateaus, lowlands	slide	shallow	small	transportation routes
	approximately 35 km^2	clastic rocks - marlstones and carbonate rocks; soils	plateaus, lowlands, hills	slide	shallow	small	transportation routes
Pannonian Basin (area of approximately 27,130 km^2)	approximately 2,300 km^2	soils	lowlands, plateaus	slide	shallow	small	settlements, transportation routes
	approximately 6,000 km^2	clastic rocks - marlstones and carbonate rocks; soils	lowlands, plateaus, hills	slide	shallow	small	settlement, transportation routes
	approximately 570 km^2	igneous and metamorphic rocks	hills, plateaus, low-altitude mountains, lowlands	slide	moderate-shallow	moderate-small	transportation routes, settlements sporadically
	approximately 470 km^2	alteration of clastic and metamorphic rocks	low-altitude mountains, hills, plateaus, lowlands	slide	moderate-shallow	moderate-small	transportation routes, settlements sporadically

Table 4 Bedrock lithology and relief types of the main geotectonic units prone to landslides in BIH

Geotectonic unit according to Schmid et al. (2008)	Areas with higher frequency of landslides		
	Total area (km2)	GLC relief type	Lithology
High Karst Unit (area of approximately 14,500 km^2)	approximately 3,570 km^2	hills and lowlands	rhythmic alteration of clastic rocks
Pre-Karst and Bosnian Flysch Unit (area of approximately 14,600 km^2)	approximately 10,800 km^2	low- and mid-altitude mountains	association of clastic rocks - flysch-like rocks, flysch-type rocks, molasse; rhythmic alteration of clastic rocks (mudrocks) and carbonate rocks; metamorphic rocks; soils; rhythmic alteration of evaporite and clastic rocks; igneous rocks
	approximately 3,600 km^2	hills and lowlands	
Western Vardar Ophiolitic Unit (area of approximately 7,660 km^2)	approximately 4,480 km^2	hills and lowlands	association of clastic rocks - melange ("Wild Flysch"), flysch-like rocks; ophiolites; clastic rocks - mudrocks and carbonate rocks with evaporates; igneous rocks
	approximately 3,030 km^2	low- and mid-altitude mountains	
Thrust Sheets (area of approximately 7,600 km^2)	approximately 6,300 km^2	low- and mid-altitude mountains	rhythmic alteration of carbonate, clastic and pyroclastic rocks; rhythmic alteration of clastic and carbonate rocks; rhythmic alteration of evaporite and clastic rocks; association of clastic rocks - flysch-type rock; metamorphic rocks; igneous rocks
	approximately 1,300 km^2	hills and lowlands	
Sava Zone (area of approximately 820 km^2)	approximately 720 km^2	hills and lowlands	association of clastic rocks – flysch-like rocks, flysch-type rocks; metamorphic rocks; igneous rocks; pyroclastic rocks
	approximately 60 km^2	low-altitude mountains	
Pannonian Basin (area of approximately 6,100 km^2)	approximately 3,200 km^2	lowlands and hills	soils and clastic rocks; carbonate and clastic rocks; metamorphic and clastic rocks; igneous rocks

which are not susceptible to landslides, regardless of whether the relief is flat and smooth (e.g., plateaus, lowlands and planes) or rough with steep slopes (e.g., low- and mid-altitude mountains and hills). These areas are present in the area of the External Dinarides (High Karst Unit), and the area of the Internal Dinarides (Pre-Karst and Bosnian Flysch). The most dangerous slope movement processes are small rock falls and rock topples which are most frequent along road cuts, are generally triggered by man-made processes or heavy rainfall, and tend to be located inside road corridors.

Landslide types

Landslide types in Croatia

In Croatia, a total of 8,930 km² of hills and lowlands is in Pannonian Basin composed of: Neogene clastic rocks - marlstones and carbonate rocks and soils (approx. 6,000 km²); Plio-Quaternary soils (approx. 2,300 km²); and Pre-Neogene igneous and metamorphic rocks and alteration of clastic and metamorphic rocks (approx. 630 km²). The most frequent are small shallow slides formed in soils (transported or residual soils) and weathered rocks along contact with fresh rocks or Neogene and Plio-Quaternary soils (Fig. 2). The main causal factors are ground conditions originating from weathering of soft clastic rocks, in addition to weak material of transported soils, enhanced by the man-made processes related to slope undercutting or concentrated flow of superficial water. Consequently, the most endangered elements at risk are transportation routes

(roads and railways), whereas settlements are only sporadically at risk. The most endangered settlements are in cities and small municipalities in the NW part of the Pannonian Basin. The biggest endangered urban area is in Zagreb (the capitol of Croatia) developed in lowlands and hills (approx. 100 km²) composed of marlstones and soils (Neogene and Plio-Quaternary age) with more than 30 shallow and small landslides per square kilometer (Bernat Gazibara et al. 2017a). The main triggering factor is precipitation (heavy rainfall and snow), which was demonstrated during extreme weather conditions in 2012 and 2013 in NW Croatia (Bernat Gazibara et al. 2017b). A unique landslide in Croatia is large deep-seated Kostanjek

Figure 2 Typical soil slide developed in Plio-Quaternary soils in the City of Zagreb. The cause was concentrated flow of superficial water from road which activated sliding during heavy precipitation in 2013 (Bernat Gazibara et al. 2017b)

Landslide ($32*10^6$ m³) because it is caused by mining activities in 1965 (approx. 60 m high slope cut and uncontrolled blasting) in area of lowlands and hills composed of Neogene marlstones (Krkač et al. 2016). The triggering factor of multiple reactivations of the slow-moving Kostanjek Landslide includes heavy precipitations, which was demonstrated by landslide monitoring data from 2013 to 2014. Hills and lowlands composed of Pre-Neogene rocks are only approximately 630 km² in the Pannonian Basin. Moderate-shallow and moderate-small landslides are developed in jointed or fissured material of heterogeneous rock mass, and triggered by extreme precipitations (snow and rainfall).

A total of 890 km² of hills and lowlands is in the External Dinarides (High Karst and Dalmatian Zone units) composed of: association of clastic rocks - flysch-type rocks (approximately 730 km²); and Neogene clastic rocks (marlstones), carbonate rocks and soils (approximately 160 km²). Similar size of landslide-prone area (approximately 725 km²) in the geotectonic units of the Internal Dinarides is composed of: Pre-Neogene clastic rocks in rhythmic alteration (approximately 300 km²); Neogene clastic rocks (marlstones), carbonate rocks and soils (approximately 265 km²); and association of clastic rocks - flysch-type rocks (approximately 160 km²). Additionally, there is a total of 450 km² of hills and lowlands in the undeformed part of the Adriatic Plate composed of flysch-type rocks.

The spatial distribution of landslide-prone areas composed of flysch-type rocks in Croatia shows that they are present in different geotectonic units. Clastic and flysch-type rocks in the High Karst Unit are located in narrow elongated valleys of tectonic origin, where they are in fault contact with carbonate rocks. Consequently, such valleys have high frequencies of active geomorphological processes enhanced by excessive erosion of flysch-type rocks. Very often are recent small shallow sliding of colluvial soils derived by historical or even fossil sliding. The described Rječina River Valley is an example of a valley with very large deep-seated fossil slides where reactivated recent landslides can reach the sizes of large-moderate or shallow-moderate slides, e.g., the Grohovo Landslide presented in Fig. 3 (Arbanas et al. 2014). Moreover, carbonate cliffs at the top of valley slopes are prone to rock falls and accumulation of large rock blocks and debris covering superficial deposits derived from clastic and flysch-type rocks. The main causal factors in tectonic valleys in the High Karst Unit are ground conditions originating from adversely oriented structural discontinuities (including faults and sedimentary contacts) enhanced by the previously described weathering of soft clastic rock and sporadically fluvial erosion processes. The Rječina River Valley is unique because of earthquakes as a main triggering factor for very large deep fossil slide and one deadly large landslide, which buried the village of Grohovo and the river channel. Recent reactivation of the large deep moderate Valići Lake (Fig. 4) due to heavy rainfall in 2014

draw attention to rainfall as a main trigger of recent landslides in flysch-type rocks and its derivatives in the Rječina River Valley (Mihalić Arbanas et al. 2017a). In the Dalmatian Zone Unit, greater number of small slide activations in flysch-type rocks is related to construction activity. In "Gray Istria" (undeformed part of the Adriatic Plate), the previously described erosion processes (gully erosion and Hortonian overland flow) of clastic and flysch-type rocks, especially removal of vegetation and formation of barren relief, are also important preparatory causal factors for sliding. Slides in flysch-type rocks in Istria are mostly small. The main causal factors are ground conditions originating from weathering of soft flysch-type rocks, in addition to weak material of transported soils, enhanced by the man-made processes related to slope undercutting or concentrated flow of superficial water. The main triggering factor is heavy rainfall (Fig. 5).

Low altitude mountains prone to landslides in Croatia (total areas of 710 km²) are mostly placed in the High Karst Unit (280 km²) and the Pannonian Basin (410 km²) and are composed of: Pre-Neogene igneous and
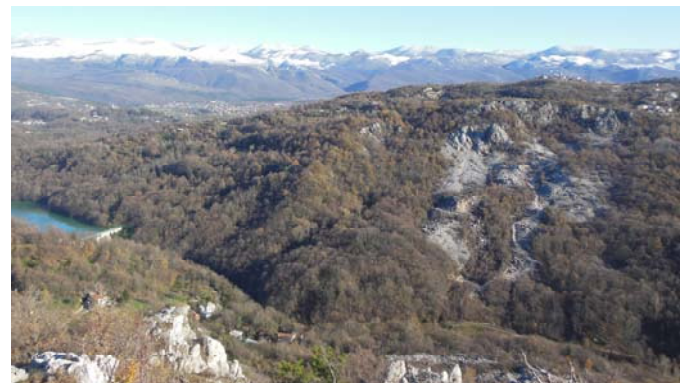
Figure 3 Grohovo Landslide located in narrow elongated valleys of tectonic origin composed of flysch-type rocks which are in fault contact with carbonate rocks. The recent Grohovo Landslide is visible as deforested area and it is developed inside very large deep-seated fossil slides (Arbanas et al. 2014)

Figure 4 Valići Landslide developed in flysch-like rock in the Rječina River Valley. The cause was heavy precipitation in February 2014 (Mihalić Arbanas et al. 2017)

Figure 5 Atypical block slide developed in flysch-like rocks in Istria which belongs to "Gray Istria". The trigger was heavy rainfall in 2004 (Arbanas et al. 2010)

metamorphic rocks and alteration of clastic and metamorphic rocks (680 km²); and flysch-type rocks (20%). Very small area of 10 km2 belongs to the Internal Dinarides (Western Vardar Ophiolitic Unit) and is composed of flysch-type rocks. Landslides endanger mostly transportation routes because the population density in low-altitude mountain areas in Croatia is low. Larger slides in the form of moderate-shallow and moderate-small can be expected in the tectonic unit of the High Karst, which is composed of Pre-Neogene alteration of clastic and metamorphic rocks.

Landslide types in BIH

Landslide-prone areas in the High Karst Unit in BIH belong to lowlands and hills composed of rhythmical alterations of clastic rocks. Approximately 56% of the hilly areas are plateaus and plains, which significantly decrease landslide-prone areas to approx. 1,570 km²: Clastic rocks fill narrow and elongated tectonic valleys and depressions in the Dinaric Carbonate Platform of the High Karst Unit, which implies relatively small localized portions of the terrain being prone to landslides in the High Karst Unit. This unit differs significantly according to landslide susceptibility from all geotectonic units of the Internal Dinarides because of the bedrock lithology (predominantly marine carbonate and clastic rocks) and the dry Mediterranean climate.

The area of geotectonic units of the Internal Dinarides (the Pre-Karst and Bosnian Flysch Unit, Western Vardar Ophiolitic Unit and thrust sheets units), the Sava Zone and the Pannonian Basin area experienced more than 7,000 landslide activations during Cyclone Tamara in spring 2014 (Bernat Gazibara et al. 2017b, Mihalić Arbanas et al. 2017a). The density of recorded landslides was more than 5 landslides per square kilometer, and the most often landslide types were debris flows and slides. Determination of the frequency of landslide depths and landslide materials requires event-based landslide inventory, which is currently lacking. It is assumed that most of the landslides are moderate-shallow and moderate-small (landslide depth <20 m, landslide volume <10^5 m³). Elements at risk are

settlements, watercourses and roads. According to general ground conditions of the geotectonic units of the Internal Dinarides, the Sava Zone and the Pannonian Basin, related to bedrock lithology and relief type, the entire areas of these geotectonic units are considered landslide-prone areas.

In the Pre-Karst and Bosnian Flysch Unit, approximately 74% of the area is comprised of low- and mid-altitude mountains, and approximately 24% is comprised of hills and lowlands. Mountain areas are composed of a rhythmic alteration of clastic, carbonate and evaporite rocks and its associations in the form of flysch-like, flysch-type and molasse deposits with metamorphic and igneous rocks arranged in regional structures of nappes. Bosnian Flysch Nappe (approx. area of 2,400 km²) and Paleozoic Mid-Bosnian Schist Mountains (approx. area of 2,000 km²) are dominant regional units in the mountain area in central BIH. Molasse associations of clastic rocks are present in large basins in mountain areas with approx. total area of 2,000 km2. A hilly area is located in the NW part of the geotectonic unit, and it is composed mainly of flysch-type association of clastic rocks and metamorphic rocks (Sana-Una Nappe).

In the Western Vardar Ophiolitic Unit, 58% of the area is comprised of hills and lowlands, and approximately 40% is comprised of low- and mid-altitude mountains. Hills and mountains are developed in the area of Ophilolite Nappe (association of clastic rocks – mélange or "Wild Flysch" and ophiolite rocks) and Sava-Vardar Zone (flysch-like association of clastic rocks). In the hilly area, there is also a large portion of the terrain composed of Neogene clastic rocks (mudrocks) and carbonate rocks with evaporites (approx. 1,000 km² in the Tuzla Basin). The whole area of the Western Vardar Ophiolitic Unit, including mountains, hills and lowlands, can be considered to be a landslide-prone area because of ground conditions originating from tectonized rocks and deep weathering profiles in igneous, sedimentary and metamorphic rock masses. The Mačkovac-Šerići Landslide (Fig. 6) and Mjestova Ravan Landslide are large-moderate landslides developed in low-altitude mountains with different depths that illustrate the devastating influence of complex landslides, including sliding and flowing component of movement. Both landslides were triggered by heavy rainfall in 2014, one as

Figure 6 Landslide Mačkovac-Šerići, Zenica Municipality, BIH (photo by V. Demir, 2014)

Figure 7 Landslide Lukavica-Prnjavor, Gračanica Municipality, BIH (photo by A. Džindo, 2014)

a deep- moderate slide-flow in a thick weathering zone of ophiolitic mélange (40 m-deep sliding surface) and one as a moderate-shallow slide-flow in superficial deposits (7 m-deep sliding surface). The same landslide type is also frequent in hills composed of flysch-like rocks in the northern part of the geotectonic unit (e.g., moderate-small, shallow Lukavica-Prnjavor Landslide, Fig. 7). Neogene clastic rocks (mudrocks) belonging to lowlands of the Western Vardar Ophiolitic Unit are also prone to moderate-small and moderate–shallow slides.

The area of thrust sheets is mostly located in eastern part of BIH, and it includes low- and mid-altitude mountains (approx. 84%) and hills and lowlands (approx. 16%). The area is composed of rhythmic alterations of carbonate, clastic and pyroclastic rocks, and evaporite and clastic rocks, as well as flysch-type association of clastic rocks, metamorphic and igneous rocks. The hills are mostly composed of pyroclastic and igneous rocks.

The Sava Zone (total area of approx. 820 km^2) is primarily hills and lowlands (approx. 88%), with only approx. 7% of the area comprised of low-altitude mountains. The whole zone is mostly composed of associations of clastic rocks in the form of flysch-like rocks. Hills composed of metamorphic, flysch-like and igneous rocks are placed in the Pannonian Basin. The Pannonian Basin has 52% lowlands and hills composed of Neogene and Quaternary soils and clastic rocks, except hills composed of Pre-Neogene rocks from the Sava-Vardar Zone.

Conclusions

Synthesis of spatial distribution of landslide-prone areas in Dinarides and Pannonian Basin showed that the differences between relative proportion of the same geotectonic units in Croatia and BIH significantly influence extent of landslide-prone area at the national scale. There is approximately 20% of the area in Croatia with landslide prone areas (total area of approx. 12,000 km^2), whereas approx. 70% of the area in BIH belongs to landslide prone areas (total area of approx.

37,000 km^2). The synthesis enabled rough estimation of spatial distribution of landslide types as well as its size and type of elements at risks. Size of landslide-prone areas in different geological and geomorphological environments can be used for preliminary planning of landslide inventory mapping in a range of scale. Used maps with GLC relief type units and generalized stratigraphical units gives sufficient information which can be combined with regional or local administrative units and land-use to delineate priority areas for landslide hazard mapping.

References

Arbanas Ž, Mihalić Arbanas S, Vivoda M, Peranić J, Dugonjić Jovančević S, Jagodnik V (2014) Identification, monitoring and simulation of landslides in the Rječina River Valley, Croatia. In: Sassa K, Khang QD (eds) Proc. of the SATREPS workshop on landslide risk assessment technology. ICL, Kyoto, pp 200–213

Arbanas Ž, Mihalić S, Grošić M, Dugonjić S, Vivoda M (2010) Landslide Brus, translational block sliding in flysch rock mass. In: Zhao J, Labiouse V, Dudt J-P, Mathier J-P (eds) Rock mechanics in civil and environmental engineering. Taylor & Francis Group, London, pp 635–638

Bernat Gazibara S, Krkač M, Sečanj M, Mihalić Arbanas S, (2017a) Identification and mapping of shallow landslides in the City of Zagreb (Croatia) using the LiDAR-based terrain model. In: Mikoš M er al. (eds) Advancing culture of living with landslides, volume 2: advances in landslide science. Springer International Publishing AG, Switzerland, Cham, pp 1093-1100

Bernat Gazibara S, Mihalić Arbanas S, Krkač M, Sečanj M (2017b) Catalog of precipitation events that triggered landslides in northwestern Croatia. In: Abolmasov B et al. U (eds) Proc. of the 2nd Regional Symposium on landslides in the Adriatic-Balkan Region. University of Belgrade, Faculty of Mining and Geology, Belgrade, pp 103–107

Krkač M, Špoljarić D, Bernat S, Mihalić Arbanas S (2016) Method for prediction of landslide movements based on random forests. Landslides 14(3):947–960.

Mihalić Arbanas S, Sečanj M, Bernat Gazibara S, Krkač M, Arbanas Ž (2017a) Identification and mapping of the Valići Lake landslide (Primorsko-Goranska County, Croatia). In: Abolmasov B, Marjanović M, Đurić U (eds) Proc of the 2nd Regional Symposium on landslides in the Adriatic-Balkan Region. University of Belgrade, Faculty of Mining and Geology, Belgrade, pp 197–202

Mihalić Arbanas S, Sečanj M, Bernat Gazibara S, Krkač M, Begić H, Džindo A, Zekan S, Arbanas Ž (2017b) Landslides in the Dinarides and Pannonian Basin—from the largest historical and recent landslides in Croatia to catastrophic landslides caused by Cyclone Tamara (2014) in Bosnia and Herzegovina. Landslides, In press. DOI: 10.1007/s10346-017-0880-1

Panagos P, Van Liedekerke M, Jones A, Montanarella L (2012) European soil data Centre: Response to European policy support and public data requirements. Land Use Policy 29(2):329–338.

Schmid SM, Bernoulli D, Fügenschuh B, Matenco L, Schefer S, Schuster R, Tischler M, Ustaszewski K (2008) The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. Swiss J Geosci 101(1):139–183.

Tomljenović B, Csontos L, Márton E, Márton P (2008) Tectonic evolution of the northwestern internal Dinarides as constrained by structures and rotation of Medvednica Mountains, North Croatia. In: Siegesmund S et al. (eds) Tectonic aspects of the alpine-Dinaride-Carpathian system, special publications, vol 298. Geological Society, London, pp 145–167

A Brief Diagnosis on Instability Phenomena Menacing Calorcko (Bolivia), the World'S Largest Palaeoichnites Site

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Abstract Calorcko (Chuquisaca department, Bolivia) is the World's largest Paleoichnites site with about 12000 dinosaur footprints. The site was discovered thanks to the FANCESA cement quarry exploitation in the 1970's but the studies started only in 1998. In February 2010, a dip slope failure combining planar slide and rock fall mechanisms destroyed a part of the tracks putting in evidence the extreme geodynamic fragility of the paleoichnic cliff, which derived of lithological and structural features (soft interbedded rocks on a very steep slope), Synsedimentary cracks, infiltration and, mainly, of elastic rebound process, started by the sudden download of overlying material. The plants growing, the climbing practice (currently forbidden), the heavy mining machinery vibrations and the thermic diurnal-nocturnal variations are others contributing instability factors. In general, the geodynamic conditions of Calorcko site is very critical and need immediate intervention. After at least two failed attempts, the local authorities with the technical support of Basel University announced recently that the candidature dossier for the UNESCO World Heritage List is ready and will be submitted this year.

Keywords Calorcko (Bolivia), Paleoichnites, Dip slope failure, elastic rebound.

Introduction

Calorcko, the largest dinosaur paleoichnites or megatracksite of the world, is located about three km at ENE of the Sucre city downtown, capital of the Department of Chuquisaca, South-Central Bolivia (Fig. 1).

Figure 1 Location map of Calorcko.

Those footprints were already known in the 1970's by the workers of the quarry of the actually State-owned cement factory FANCESA. In 1985, the Bolivian geologist Hugo Heymann photographed them, without making any major observations. It was only in October 1994 that the Bolivian amateur palaeontologist Klaus Pedro Schütt detected its paleoichnites nature, confirmed by Freddy Paredes, director of the Paleontological Museum of Tarija. Schutt (2009, 2015) communicated his discovery to different specialists, museums, the National Geographic Society, the Smithsonian Institute and, even, the filmmaker Steven Spielberg, but he did not receive any response until 1998, when Professor Christian Meyer, director of the Museum of Natural History of Basel University, Switzerland, receiving the Schutt's video, became interested in the discovery and began important studies shortly thereafter. In 2006 FANCESA and the Municipality of Sucre created the "Cretaceous Park", including a museum, which is now the main touristic attraction of the region.

The preservation of this cliff was an almost miraculous fact: the limestone exploitation for the cement factory was stopped just arriving to the paleoichnites level due to its high magnesium content, not suitable to manufacture cement (Fig. 2).

Figure 2 A partial view of Calorcko paleoichnic cliff. In the middle, the so called "advanced deterioration triangle" collapsed in February 2010.

In February 2010 a landslide destroyed around 200 footprints, putting in evidence the high instability of the site. "In 2009, Bolivia attempted to have Cal Orcko designated as a UNESCO World Heritage Site (which would have provided USD$8-million in funding to

preserve the dinosaur tracks) but after FANCESA had opposed the proposition, the effort was abandoned" (Goran 2016), In 2015 the process has been restarted and in August 2017, Professor Meyer and local authorities announced that the dossier was ready to be submitting to UNESCO (Correo del Sur 2017). It's absolutely necessary that ICL support this initiative.

Geological setting

The Calorcko tracksite belong to El Molino Formation, Super Group Puca, of the Early Cretaceous-Late Tertiary; there are different datings for this formation: Campanian?-Maastrichtian, or Campanian-Paleocene (Gayet et al. 1991), Maastrichtian-Danian (Sempere et al. 1997) or Maastrichtian-Paleocene (Fink 2002). The sediments were deposited in the regressive phase of the Atlantic transgression forming the so-called Pacha Sea, in a seasonal endorheic lake system, as demonstrated by Talbot's (1990) geochemical studies.

The quarry show a dip interbedded feature of Shales and laminated carbonated mudstones (which are usually designated as limestone), typical of fresh water lacustrine environments, within a large folding of NE-SW direction.

The paleontological strata are silicified limestone deposited about 68 million years ago (Meyer et al. 2006). The cliff has 80-120 meters high and about 1200-meters long; paleoichnological wall concerns approximately 25000 m^2.

Although tourist information talks about more than 5000 footprints of 25-30 different species, Professor Meyer's Swiss team estimated in 1998 they were 3000, in 2007 about 5000, in 2015 10000-12000. To date, seven paleoichnological levels have been identified, but it's sure that many thousands of other tracks are still covered under the outcropping strata or in the surrounding areas.

Figure 3 An example of Theropods footprint (Photo: Sucre Cretaceous Park)

According to Meyer, the footprints belong to six types of dinosaurs, mostly Theropods (Fig. 3) and Ornithopods, including Tyrannosaurus Rex, Titanosaurs, Carnotaurus as well as the rare Ankylosaurian, dinosaur which, it thought, had not existed in South America. As indicated, in Calorcko the world longest dinosaur track

has been registered: 581 meters (up to then, a track located in Mongolia was the known largest, with 200 meters), corresponding to a baby Tyrannosaurus Rex, nicknamed "Johnny Walker". Unfortunately, the 2010 planar slide swept those footprints.

Antecedents

On February 2010 a dip slope failure (combining dip-slope rock block slide /rock fall phenomena) destroyed some 200 paleoichnites, including 80 meters of a 65 million years track belonging to a pair of Titanosaurs. The 2003 geotechnical study had already warned about the instability of this section which, a few years after, was qualified as an "advanced deterioration triangle" (Fig. 4) by what its collapse was qualified as inevitable. The drainage works, applied in the crown area, were unable to avoid the failure. According to local newspapers, the Chilean subsidiary of the Swiss Company Geotest, in charge of geotechnical evaluations, "had not guaranteed the stabilization of the current collapsed sector" due to the advanced deterioration state of the wall.

Figure 4 The paleoichnic cliff before and immediately after the February 2010 dip slope failure (Pictures: Willy Jordán)

A permanent but short-scale disintegration process of the shales and mudstones of Calorcko is also evident as result of their strong tendency to the craquelamiento; several small colluvial fans formed continuously at the foot of the cliff confirm this process, which is also an indicator of the slow and permanent deformation

affecting different portions of the wall, as result of the elastic rebound.

There was another case of landslide induced loss of dinosaur footprints in Bolivia: at Parotani, Department of Cochabamba, paleoichnites discovered at the beginning of the 1980's bt Leonardi (1981) and lost after a landslide (Apesteguìa & Gallina 2011).

Causes

Calorcko has been the subject not only of paleontological studies but also of a geotechnical assessment in the past. There is a monitoring program using extensometers along the cliff crown and the museum zone. During the 2012 monitoring campaign, the company Geosinergia measured movements of nearly 1 millimeter/month, that would tend to increasing in the future, thanks to the humidity and to the roots development. Drainage and waterproofing works, as well as eradication of plants have been made periodically, all in the Crown of the cliff. Meyer et al (2006) also recomended "Sealing of the wall head above the parallel Titanosaur trackways" and the "Impregnation of test-surfaces with a water solute chemical water repellant in order to slow down chemical erosion".

The geodynamic assessment and remedial works carried out until now have been based apparently on an insufficient instability diagnostic, which can influence its effectiveness. The assumed hypothesis point the infiltrated water from the cliff crown during the rainy season and the vegetation growing there as the main causes of general fragility and landslides occurred in the past. The mining machinery vibrations are also mentioned. In consequence, the company in charge of studies recommended waterproofing the top of the cliff "where the humidity and the plants roots cause the movement of the plates". That could be valid for the head of the cliff but cannot explain the whole deformation/instability process, which is more complex.

Our analysis determined two types of factors governing the geotechnical and Geodynamic behavior of the cliff: intrinsic or syngenetic factors and external agents. The first ones are related to: the structural feature, the Lithological factor (geomechanical nature of the rocks derived from their sedimentation and lithogenic conditions) and the elastic rebound process. External agents include: infiltration, vegetation, mining, the practice of the climbing.

Structural feature

The intrinsic fragility of the cliff is essentially related to its position as a very steep dip slope (73 degrees), derived of Andean orogeny folding processes.

Lithological factor

The paleoichnites are in a thin layers interstratified ensemble (less than 20 cm of thickness) of soft and friable pelitic rocks with a low layer thickness/cliff height ratio, mechanically weak, without a greater resistance to vertical strengths. The weakness of Calorcko rocks it's a result of sedimentation in shallow lacustrine environments, indubitably subject to strong water level fluctuations, as well as the proximity of foothills or pediments feeding regularly fine materials to sedimentary basins. That explain why strata are so thick.

Synsedimentary cracks

The water level fluctuations during the clayey sediments accumulation induced the formation of desiccation cracks during the dry seasons, when the water level downed. These cracks show a parallel distribution pattern and a more or less regular spacing (20 centimetres in average). This cracking was aggravated by tensional strengths developed by the folding process (Fig. 5).

Figure 5 Synsedimentary cracks worsened by the elastic rebound

Elastic rebound

It constitutes the main worsening factor of the paleoichnitic layers extreme fragility, which were compressed by the overlying strata and just outcropped when quarry exploitation arrived to those levels. This sudden release of loads produced a more or less abrupt elastic rebound exacerbated by geomechanical nature of the soft and fissured mudstones.

The elastic rebound induced a greater opening of cracks, the progressive detachment of exposed layers and, on some points, some degree of warpage and flaking of thin calcareous layers containing the footprints, giving even the impression of having suffered small explosions (Fig. 6).

The combination of the elastic rebound with the geomechanical characteristics of the calcareous mudstones and Shales has generated a crust, roughly 1 inch thick that tends to separate into flakes or by disintegration. It is likely that heat stroke also play some role in this, by diurnal-nocturnal dilatation-contraction cycles. A possible action of Frost (not very common in the area) could not be also discarded.

Figure 6 Elastic rebound effect on the paleoichnic crust.

Infiltration

The past evaluations considered the most of infiltration comes from the crown of the cliff; this hypothesis was the base for waterproof and vegetation clean works carried out in this zone, which results have been rather mitigated. This would respond to the fact that these waters constitute only a part of the total water intake, because a considerable amount (even greater than the crown's) penetrates through the aforementioned cracks of the friable crust, which expansion by elastic rebound facilitates the direct water infiltration and circulation between diastems.

This is the problem root because the cliff catchment surface is much larger than the Crown strip. The existence of blanks separation between the aforementioned crust and the lower part of the wall, as well as the height and the strong dip of the cliff, facilitate the development of important hydrostatic columns. Thus, hydrostatic pressure, coupled with the burden of very steep strata, is greater at the bottom of the cliff, and inducing higher strengths, as evidenced by the intense disintegration and more open cracks in the lower part of the wall.

Vegetation and other aggravating factors

In the open cracks on the rock wall grow plants whose root development generates evidently mechanical expansion and chemical reactions in the fissures and diastroms, worsening the disintegration of the footprints "crust".

The periodic plant elimination (recommended by the geotechnical study), is not enough; a similar intervention at the rock wall is also necessary. Given that a continuous monitoring of the vegetation in the cliff doesn't seem possible by logistical constraints, the time intervals between the different cleaning campaigns are sufficient to allowing plants grow and exert a negative both chemical and mechanical effect (Fig 7).

Figure 7 Plants growing into the cracks

For many years, the cliff was irresponsibly used for climbing, which contributed to further weaken certain sectors of the paleoichnological crust.

The limestone mining using heavy machinery continue close to the cliff foot; the permanent vibrations contribute of course to weaken more the thin layers of cracked rock, accelerating the elastic rebound effect.

Another contributing short scale factor is the tourist's curiosity taking rock pieces as souvenir or testing the rock resistance.

Conclusion

Calorcko's paleoichnological cliff is intrinsically unstable because of its lithological, morphological and geomechanical features: a very steep slope, soft rocks in thin strata and an elastic rebound process derived of the sudden discharge of overlying materials.

The mitigation works carried out in the past years (plants eradication, waterproofing, crakcs sealing), in the cliff crown zone, have had a very limited effect. There are proposals of waterproofing and sealing injections, but their application does not seem very viable, because, first of all, the cracked outer layers could not bear high injection pressures.

Calorcko's site situation is really critical because of lithological and structural setting, the surrounding environment (quarry in activity) and the unfavorable geomechanical and Geodynamic nature of paleoichnitic layers. The 2010 dip`slope failure left without lateral support other footprints panels, which could facilitate the separation and collapse of other portions of the wall, triggering a progressive landsliding process.

Before to apply any remedial work (permanent vegetation eradication, anchored retention plates, sealing injections, etc.) many complementary geotechnical assessments are necessary, specially taking in account the elastic rebound process coupled with a permanent and high resolution monitoring program. It is also urgent that UNESCO incorporated this site into the World Natural Heritage List, which would encourage the involvement of other actors allowing to find the most appropriate solutions for Calorcko's preservation.

References

Apesteguía S, Gallina P (2011) Tunasniyoj, a dinosaur tracksite from the Jurassic-Cretaceous boundary of Bolivia. Anais da Academia Brasileira de Ciências. 83(1): 267-277.

Correo del Sur (2017) Carpeta de Cal Orck'o lista para postulación. La presentarán ante la UNESCO en un par de semanas. URL: http://correodelsur.com/cultura/20170822_carpeta-de-cal-orcko -lista-para-postulacion.html [Last accessed: 21 October 2017].

Fink R J (2002) Sedimentology and Stratigraphy of the Upper Cretaceous-Paleocene El Molino Formation, Eastern Cordillera and Altiplano, Central Andes, Bolivia: implications for the tectonic development of the Central Andes. MS thesis, Graduate Faculty and Agricultural and Mechanical College, Department of Geology and Geophysics , Louisiana State Univ., USA.

Gayet M, Marshall L, Sempere T (1991) The Mesozoic and Paleocene vertebrates of Bolivia and their stratigraphic context: a review. Revista técnica de YPFB 12(3-4): 393-433.

Goran D (2016) A massive wall at Cal Orcko in southern Bolivia reveals more than 5,000 dinosaur footsteps. URL: https://www.thevintagenews.com/2016/09/27/massive-wall-cal-orcko-southern-bolivia-reveals-5000-dinosaur-footsteps/ [Last accessed: 20 July 2017].

Leonardi G (1981) As localidades com rastros fósseis de tetrápodes na América Latina. Anais 2◦ Congresso Latin-americano da Paleontologia 2: pp. 929–940.

Lockley M (2002) Titanosaurid trackways from the Upper Cretaceous of Bolivia: evidence for large manus, wide-gauge locomotion and gregarious behaviour. Cretaceous Research. 3(23): 383-400.

Meyer C A, Thüring B, Graf K, Heim G (2006) A Marriage between Geotechnique and Palaeontology. Three dimensional vizualization of a geological monument for scientific exploration and geotechnical conservation (Cal Orcko, Sucre Bolivia). Proceedings of 4th Swiss Geoscience Meeting, Bern, Switzerland.

Sempere T, Butler R F, Richards D R, Marsahll L G, Sharp W, Swisher C C (1997) Stratigraphy and chronology of Upper Cretaceous-lower Paleogene strata in Bolivia and northwest Argentina. Geological Society of America Bulletin. 109(6): 709-727.

Schütt K P (2009) Las huellas de Cal Orcko, una lucha contra la ignorancia. URL: http://www.duiops.net/dinos/ caminohuellasfama.html [Last accessed: 23 October 2017].

Schütt K P (2015). El boliviano que descubrió los paseos de los dinosaurios. URL: http://cnnespanol.cnn.com/2015/04/27/el-boliviano-que-descubrio-los-paseos-de-los-dinosaurios/ [Last accessed: 20 July 2017].

Talbot M R (1990) A review of the palaeohydrological interpretation of carbon and Oxygen isotopic ratios in primary lacustrine carbonates. Chemical Geology: Isotope Geoscience section. 80(4): 261-279.

The influence of paleo-landslide activity on the modern slope stability

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Abstract Landslide processes in Moscow have been studied more than a hundred years. One of the landslide hazard arias is the Vorobevy Gory – nature reserve within Moscow located on the right cut bank of the Moskva River. The slope is a typical landslide landscape. The geological strata are represented by deposits of the Carboniferous, Jurassic, Cretaceous and Quaternary systems. The volume of soils involved in the landslide deformation reaches 2 million m³. The article is devoted to the description of landslide development mechanisms and landslides distribution based on new data and the interconnection of modern slope with the geological history.

Keywords Paleo-landslides, slope stability, slip surface

Introduction

The historical center of Moscow (the capital of Russia) is located in the Middle Moskva River. Banks erosion induces the development of various landslides along the river. Presently more than 220 modern landslides on the city are reported. Sixteen of them are from several hundred to several million cubic meters in volume. One of the largest landslides is located on the high right slope "Vorobievy Gory" of the Moskva River. Slope deformations on the Vorobievy Gory have been documented since the early nineteenth century. Landslide processes in this area caused to the refusal of the construction of the Christ the Savior Cathedral in 1826. In the mid-nineteenth century the presence of landslides in this area reflected on the Moscow region map (Schubert, 1860). For the same reason, in the middle of the twentieth century the main building of Moscow State University was moved from the slope to about a kilometer. Lately there has been a construction of a cable car through the river and reconstruction of a ski jumping. Also there has been organized systematic survey of the landslide slope with well drilling. Laboratory of Engineering Geodynamics and Substantiation of Engineering Protection of Territories (Moscow State University, Geological Faculty) studies the landslide hazard, influence of paleo-landslides on formation modern engineering-geological settings and assesses the slope stability.

Geological and geomorphological setting

The study area is located in the central part of the Vorobevy Gory, covering the area from the viewpoint to the Moscow Metro Bridge (fig. 1).

Figure 1 The study area (Google) with some boreholes.

It is a right cut bank. Height difference from Moskva River water level (absolute mark 120 m) to crest of slope is 60 - 70 meters and distance is 600 – 800 meters. The slope surface has a typical landslide landscape. The steep slope in the upper part and located below few landslide stages. The lower part of the slope adjacent to the river was significantly anthropogenic changed. The slope was fortified by the embankment some landslide terraces were cut off, protective measures against gully erosion were carried out.

The geological strata are represented by deposits of the Carboniferous (absolute mark of superface of stratum is 78-80 m), Jurassic (layer thickness is to 50 m), Cretaceous (layer thickness is to 49 m) and Quaternary (layer thickness is to 10 - 20 m) systems laid horizontally. Carboniferous rocks, according to borehole data, are presented by middle carboniferous light grey, fine-

grained massive limestone often leached. It should be particularly noted, that eluvial horizon, widely developed at the Moscow territory in the upper part of the Carboniferous strata, was not opened during drilling on studied territory. The roof of Carboniferous deposits forms the complex pre-Jurassic paleorelief. It must be emphasized, that the study area is situated within the Main pre-Jurassic paleo-valley, the relative depth of downcutting of valley reaches 40 – 45 m, according to the difference of subface of Jurassic stratum (in comparison with the adjacent territories). According to most researchers the middle carboniferous limestone in the landslide displacement is not involved. The Carboniferous strata is covered by middle Jurassic Callovian deposits, represented in the lower part by sand and clay coastal-marine deposits, passing up the section in marine massive clays, accumulated in late Callovian-Oxford. The total layer thickness of this clays is 25-30 m. The bed of the Moscow River produced in the clay sediments of the Jurassic system. Most researchers, such as V.V. Kuntsel, M. N. Parezcaya, etc., studying landslides of Vorobevy Gori consider Oxford clay deposits as the main deformed horizon. Based on this view can be considered that all overlaying deposits are in a landslide occurrence within the slope. More sandy Tithonian-Kimmeridgian deposits overlay Oxfordian clays. Their thickness is 25 m. Cretaceous stratum represented by sands, silts with thin interlayers of clays, up to 50 m thick coveres the Jurassic soils. The upper part of the geological section is composed of Quaternary sediments, represented by fluvioglacial sands sandy loams and morainic loams. The thickness of Quaternary sediments is from 10 to 20 m.

Cretaceous, Quaternary and partly Jurassic deposits involved in the landslide process, form bodies up to several thousand cubic meters (fig. 2). Deep landslides with a zone of displacement in Oxford clays form bodies with a volume of more than one million cubic meters.

The length of the visually defined landslides is up to several hundred meters, visible width along the axial part of the landslide is more than three hundred meters. The volume of soil involved in the landslide deformation is estimated in 2 million m^3.

Testing methodology

In 2016-2017 the Laboratory of Engineering Geodynamics carried out research within the framework of the project of slope strengthening site "Vorobievy Gori". Investigations have included re-interpretation of geotechnical data considering the geological history of the area field works collection of soil samples and examination their physical properties. More than 200 drill-hole cores were taken и described.

Results and Discussion

The study of section was conducted on several parallel tracks along the axial part of landslide from crest of slope (Kosygina str.) to the Moskva-River. Initially it was thought that boreholes located on the surface of the watershed "plateau" (Kosygina str.) are in undisturbed state and open bedrock. Detailed study of drill-hole cores which are located on watershed "plateau" (Kosygina str.), near the crest of the slope, in the area of natural occurrence of rocks, as previously thought, revealed a different pattern of development of geological processes. Soil discontinuity was identified in the lower part of the Jurassic clay deposits. So, in borehole 7-K in 85 – 89 m intervals (Oxford clay deposits of the Jurassic system) 97.3 – 99 m (the same deposits) steep slickensides were identified (Fig. 3). In borehole 5-K, also located on the edge of the slope (Kosygina str.) in four intervals (81.3 m 82.5 m, 92 m and 100.5 m) the landslide slip surface were found.

Figure 2. Landslide formed in Quaternary deposits in 2006.

Figure 3. Slickenside in Oxfordian clay (borehole 7-K)

The obtained data clearly show the presence in the natural occurrence of soils in the interval of depths of 80-100 m zones of landslide deformations (as the slickensides). This suggests that deep zone of displacements is beyond the previously adopted boundary of landslide processes, which was detected visually by extensive development of cracks, ruptures, etc. on the slopes of the Vorobevy Gory. Based on the above information, the conclusions about the necessity of moving the boundaries of development of deep seated landslides on the study area into watershed "plateau" were done. In this case the previously described landslide bodies should be considered as secondary, developing within the very large landslide massif, rupture zone which is within the modern watershed "plateau". Perhaps, the surface occurrence of these deep deformations retouch by anthropogenic redevelopment of the territory during its development now. The development of such process is probably connected with the location of the study area within the deep pre-Jurassic paleo-valley of the Moskva River. Such regions are characterized by essential, both horizontal and vertical, variability of geological strata active exchange of water between aquifers which leads to the intensification of exogenic processes. Drilling data confirmed the presence of an uneven boundary of the roof of the Carboniferous deposits. Height difference reached 4–5 meters. The Carboniferous deposits are eroded near the roof. These factors create conditions for the development of landslide processes on the Vorobevy Gory.

On the basis of new data, it is possible to clarify the mechanism of landslide processes of the study area which is based on the features of the motion of individual elements of the landslide. In our case, the simultaneous action of several mechanisms of deformation of soils in different parts of the slope may act. The head of the landslide develops according to the mechanism of shearing of large blocks composed of Mesozoic-Cenozoic deposits, which is confirmed by the presence of a series of slickensides in the thickness of Jurassic clays. The thickness of such landslide blocks, based on the data of drilling operations performed, reaches 80-100 m. It should be noted that the identified slip zones are at absolute elevations substantially below the current level of the river, indicating that the basis of landslide displacements was a lower erosion level, indicating the duration (in geological time) of the development of landslide deformations in the area. In the middle part, landslide deformations appear to represent a plastic flow, when the main deformations are confined to the horizon of watered clay of the Oxford Stage. The central part of the landslide slope is characterized by the presence in the strata of the doubling of sand deposits of Cretaceous age. (boreholy 5-T). Thais testifies to the "enclosed", secondary nature of the landslide body, described directly on the slope of the Vorobyovy Gory. In the toe of the landslide, a significant reduction in the thickness of the Jurassic deposits and a sharp decrease in Cretaceous deposits (up to 2-3 m) are noted, but duplication of the deposits does not occur, which unambiguously indicates a displacement with the bar in the toe.

The second type of landslides can be considered relatively shallow landslides in sand-clay deposits (up to 20 m thick), which is confirmed by the drilling data, in particular, the doubling of the Apt sand deposits (boreholy 5-T).

Conclusions

On the basis of the newly obtained factual data, the following conclusions can be drawn: firstly, the territory involved in landslide processes on Vorobyovy Gory is characterized by significantly larger values, both in area and in depth, than previously assumed, as evidenced by the drilling data; secondly, we can talk about a complex mechanism for the development of landslide processes of the slope - in the composition of which, we can distinguish both primary and secondary. In the head part, where the displacement zone is located at depths of 80 - 100 m, the deformations, confined to the lower part of the Jurassic deposits, have a block character. A similar block mechanism has secondary landslide arrays located in the middle part of the slope with a deformation zone in Cretaceous sand-clay sediments. The toe represented by clays that have experienced plastic deformation, is a landslide extrusion.

Acknowledgements

References

Barykina O.S., Zerkal O.V., Samarin E.N., Gvozdeva I.P. (2017) The questions of the development of landslide processes on the Vorobievy Gory (Moscow). Proceedings of Scientific-Practical conference "Engineering-geological problems of modernity and their solution methods", 13-14 April 2017. Moscow, Russia. pp. 111-117 (in Russian)

Gulakyan K.A., Kuntzel V.V. (1970) Classification of landslides by the mechanism of their development, Trudy VSEGINGEO. 29: 58-64 (in Russian)

Mitta V.V., Glinskikh L., Vuks V.J., Tesakova E.M. (2012) Unified regional stratigraphic scheme of the Jurassic of East European Platform. Explanatory note. Mitta V.V., Alekseev A.S., Shik S.M. (eds). Paleontological Institute of RAS (PIN) & All-Russian Geological Oil Institute (VNIGNI), Moscow (ISBN: 978-5-900941-26-4). 64 p.

Paretskaya M.N. (1975) Dependence of the morphology of landslides extrusion of the Moscow suburbs on the strength of Jurassic clays. Trudy VSEGINGEO. 81: 94-97 (in Russian)

Soil Moduli E_{50} of Residual Soil Slopes, Sri Lanka

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Abstract The soil structure, in-situ moisture and ground stresses strongly influence the stability of residual soil slopes. Tropical landslides show an increasing tendency with rainfall and difficult of model the problem in association with the soil cohesion and angle of internal friction. The, study aimed at improving our understanding and interrelationship between Young's secant soil modulus E_{50} of residual soils with void ratio e_o, dry density and the confining pressures. Extensive series of laboratory testing was conducted for determination of elastic behaviour of residual soil. Results and interpretations were scattered than expected. However, it can be observed that void ratio function can only be applied for a certain category of residual soil by comparing with dry density and the stress state. Two prominent categories of residual soils were recognised including quartz silt (silty sand, SM) and inorganic clayey silts (silty or clayey fine sand with slight plasticity, ML). It is also noted that evaluation of elastic parameters of residual soil slopes is somewhat challengeable task due to large variation of the material properties and in-situ soil structure.

Keywords residual soil, secant modulus, elastic properties,

Introduction

The catastrophic landslide which occurred along the upslope of Aranayake villege in Kegalle district of Sri lanka in May 2016 claimed the lives of 127 people and damaged houses, road and other infrastructure. Excessive rainfall in the area for more than a week has been identified as the triggering mechanism for the failure. Similar patterns of major failures are noted during May 2017. The research IPL 155 is mainly a study on evaluation of inter-related shear strength characteristics of different precipitation regions would yield to understand the sensitivity that can be adopted in each region. The comparison of soil module E_{50} of residual soil slope failures in different rainfall precipitation zones is an experimental study to formulate a relationship between the potential slope failures and stress-strain characteristics of soils which could be easily discussed on scenarios of the first time occurrence failures and repetitive failures in residual soil formation.

Slope stability analysis enables the identification of landslide proven areas and risky areas, but the lack of knowledge in terms of variability against frictional angle, cohesion and elastic deformations of subsurface soil hinder the accurate interpretation of instability in natural slopes (Mallawarachihi, *et.al*,2014). The project team has collected several UDS samples, physical variables and landslide records. Therefore, a comprehensive study was implemented to understand the variable nature of the frictional coefficients and elastic deformity parameters of the residual soils.

Residual Soil Slope Failures in Sri Lanka

The failures at shallower depths are more easily and frequently influenced by rainfall compared to the failures in deeper soil layers. Soil deformation analyses depend on the type of soil and the loading conditions. Hence, the effect of rainfall infiltration on slope could result in changing soil suction and positive pore pressure, raising soil unit weight(in-situ) and reducing shear strength of rock and soil (Fredlund and Rahardjo, 1993; Rahardjo et al. 1995; Griffiths and Lu, 2005). Therefore, elastic parameters of residual soil may be a valid clue to determine long-term stability of soil slopes under different stress increments with saturation.

The recent observations of large soil slope failures such as the Aranayaka Landslide in Kegalle district and the Athwelthota Landslide in Kalutara district (see Fig 1 and Fig 2) are mainly residual form of soils. Visual appearance of residual soil consist of brown to red, or yellowish brown silts and gravels and also contains high plasticity silts due to layers of weathered feldspar. At a slightly greater depth, the residual soils transition to in-situ weathered and highly decomposed rock are typically dark brown, black and dusky red, less plasticity or non-plastic silts. Landslide debries mass contained medium to large in-situ weathered boulders in addition to the parent material.

Fig 1: May 2016 Aranayake landslide in Kegalle District, Sri Lanka, which killed 127 people. The image indicates landslide failure initiated in residual soil and boundary intact with weathered rock face.

Fig 2: May 2017 Athwelthota landslide in Kalutara District Sri Lanka, which killed 09 people. Landslide was initiated from residual soil origin.

Elastic Behaviours of Residual Soil

One of the most important advances in geotechnical engineering in the past decade or so is the general realisation and acceptance of the fact that the stress strain behaviour of almost all soils is non-linear, even for stiff soils in the elastic of the stress-strain response (M. Fahey, 1999). Therefore, evaluation and comparing of non-linear stress-strain response in the soil has been accepted for evaluation of the stability of slope deformities. Such factors are immensely contributed to detailed evaluation work in numerical simulations and slope stability models.

Another important issue is infiltration of rainwater into a residual soil slope may impair slope stability by changing the pore-water pressure in the soil which in turn controls the water content of the soil (Rahardjo, H, *et.al*, 2005). Usually unsaturated residual soils experience high matric suction (i.e., negative pore-water pressure) during dry periods, which contributes to the shear strength of the residual soil. The water content also impacts moduli. At low water contents the water binds the particles, increases the stress and suction between the particles and leads to a high soil moduli. Therefore, elastic moduli of residual soil indicate very high value during dry periods and subjects to losing its capacity during rain.

Determination of E_{50}, C', ϕ' of Residual Soils

Soil Young's modulus (E), commonly referred to as soil elastic modulus, is an elastic soil parameter and a measure of soil stiffness. It is defined as the ratio of the stress along an axis over the strain along that axis in the range of elastic soil behaviour (Ekanayake, *et.al,* 2015). Young's *Secant Modulus* E_{50} determined form the slope of the straight line drawn from the origin and 50% of the maximum stress; a chord modules is the slope of the straight line between any two points on the curve. The Young's Secant Soil Modulus E_{50} may be estimated from empirical correlations, laboratory test results on undisturbed specimens and results of field tests. The study use the triaxial consolidated undrained compression tests to estimate the soil modulus E50 and angle of internal friction. Numerical interpretation of the determination of E_{50} is shown in the Fig.3.
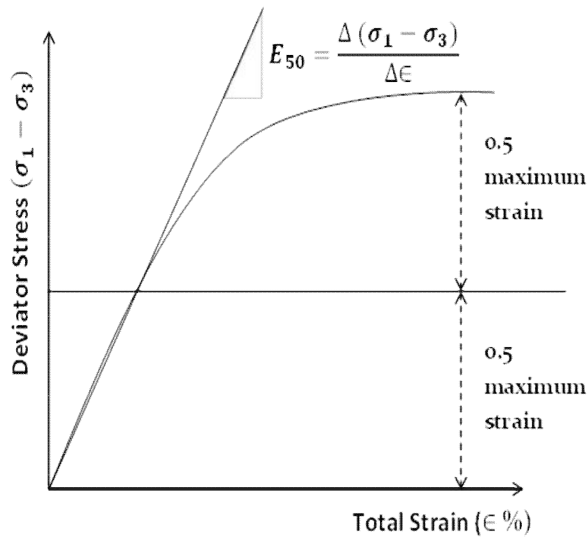
Fig. 3: Determination of E_{50} in a standard stress – strain plot of Consolidated Undrained Triaxial Test

Nineteen locations were selected along with the UDS samples for the determination of initial moisture content, initial void ration, dry density, shear strength parameters and secant modulus of E_{50}. All triaxial samples were 70mm diameter and 140mm height and tested under isotropic consolidated undrained (CIU) triaxial compression state with pore water pressure measurements for the determination of stress strain parameters of soil. All testing were conducted at the Advanced Soil Testing Laboratory at the CECB Laboratory Services, Central Engineering Consultancy Bureau, in Colombo.

The study does not contain a limitation of the number of samples but all were selected according to residual soil formations only. The measurements of E50 (secant moduli) and void ratio (e_o) and S_r (degree of saturation), dry density and in-situ moisture content and frictional parameters (cohesion and friction angle) were determined according to the BS 1377 and corresponding results are presented in Table 1 and Table 2. Significant characteristic variation were noted deviated stress and the axial strain interpretations for different sample quality of residual soils as recorded in the Table 1 and table 2. Some stress-strain behaviour and E_{50} of selected samples are shown in Fig 4 to Fig 12.
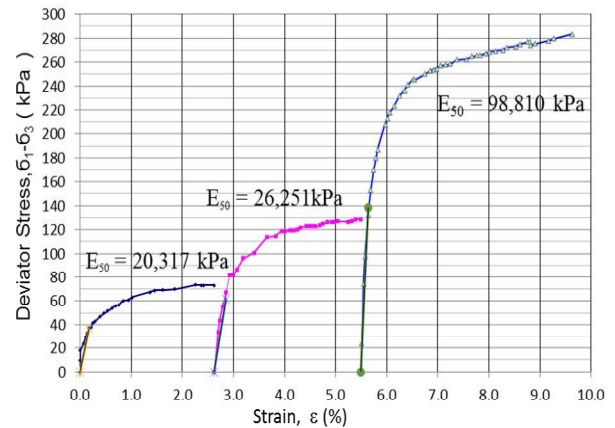
Fig 4: S160724, Brownish medium to coarse gravelly clay
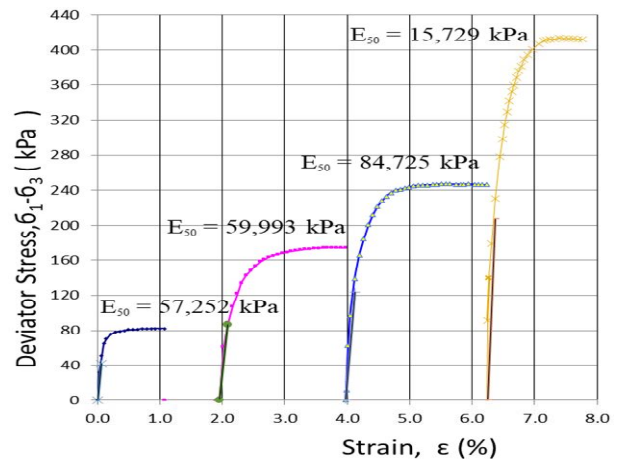
Fig 5: S160694, Brownish fine grained sandy clay
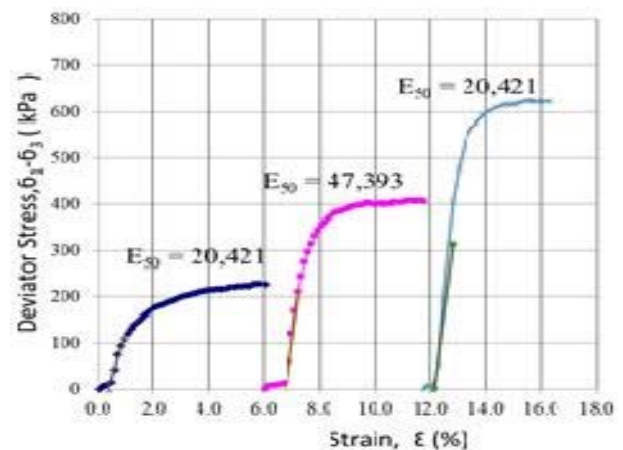
Fig 6: S160705, Brownish fine to coarse grained clayey gravel
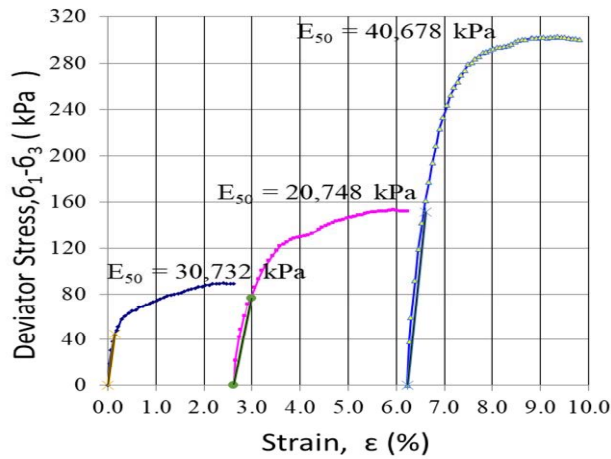
Fig 7: S160713, Brownish clayey gravelly sand
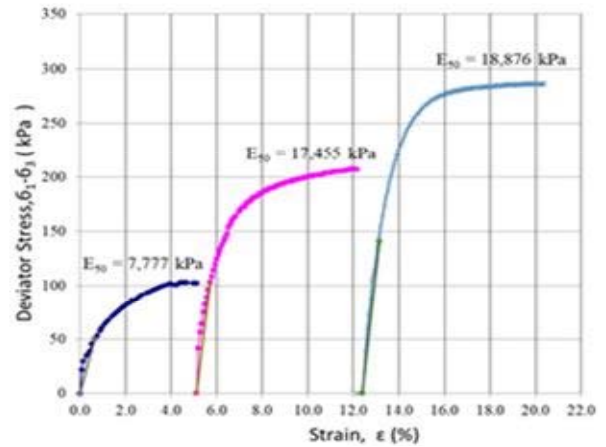
Fig 10: S162811, Yellowish brown sandy clay
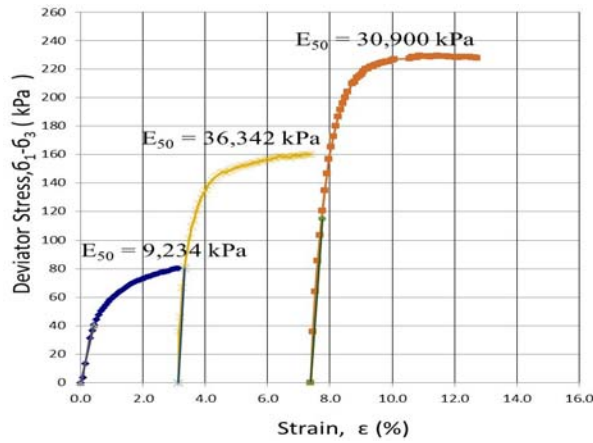
Fig 8: S172677, Yellowish brown clayey sand
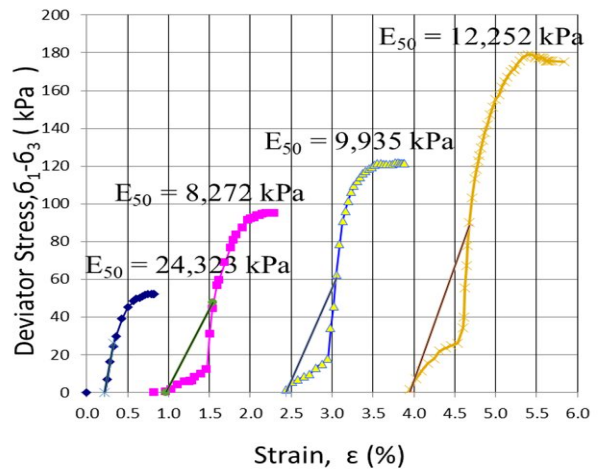
Fig 11: S140077, Reddish brown fine to coarse grained clayey sand
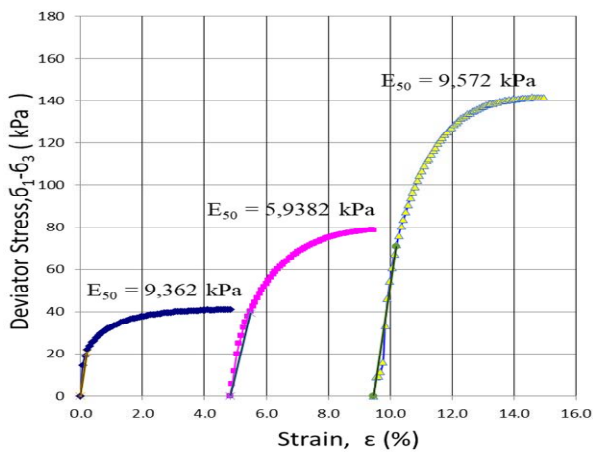
Fig 9: S160717, Brownish clayey sand
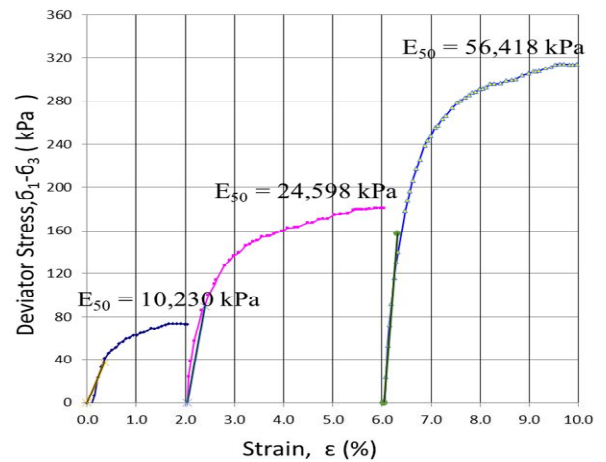
Fig 12: S162781, Whitish yellow clayey silty gravel

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Table 1: Summary of shear strength parameters, densities, and elastic properties, degree of saturation and void ratio of selected residual soil samples tested at the laboratory.

Sample Reference	Landslide / Location Reference	MC (%)	Dry Density Mg/m³	Degree of Saturation	Void Ratio, e_0	CU Triaxial Test C' kPa	CU Triaxial Test φ' deg	Effective Confining Pressure(kPa)	E_{50} kPa
S160705	Brownish fine to coarse grained clayey gravel	9.1	1.90	0.94	0.37	12	33	100	20,421
								200	47,393
								300	47,829
S160694	Brownish fine grained sandy clay	3.53	1.98	0.91	0.33	11	27	100	57,252
								200	59,993
								300	84,725
								400	15,729
S160706	Blackish brown fine to coarse grained sandy clay	20.44	1.64	0.98	0.60	6	23	100	93.254
								200	86,787
								300	66,313
S160711	White, brown, ash clayey sand with weathered secondary formation as rounded particles	5.77	1.70	0.90	0.55	4	25	200	42,803
								300	70,345
S160713	Brownish Slightly clayey gravelly sand	4.97	1.74	0.97	0.51	6	28	100	30,732
								200	20,748
								300	40,678
S160717	Brownish clayey sand	5.77	1.22	0.98	1.36	5	25	60	9,362
								120	5,938
								180	9,572
S160724	Brownish medium to coarse gravelly clay	14.80	1.96	0.93	0.37	4	28	100	20,317
								200	26,251
								300	98,810
S162781	Whitish, yellow fine to coarse gravel, trace silt, well graded, angular, dry	14.62	1.79	0.96	0.42	4	27	100	10,230
								200	24,598
								300	56,418
S162811	Yellowish brown clay with some fine to coarse sand, trace mica, trace gravel, trace silt, low plastic, wet,CL	47.45	1.12	0.98	1.37	2	32	100	7,777
								200	17,455
								300	18,876
S172659	Grayish clay with trace silt, trace sand	24.37	1.51	0.96	0.77	3	23	100	15,896
								300	15,594
								360	43,184
S 172677	White, brown, yellow, clayey sand (Completely weathered rock)	32.75	1.21	0.92	1.23	0	28	100	9,234
								200	36,342
								300	30,900
S 172675	Gray, yellow clay with trace silt, trace sand	11.75	1.80	0.90	0.48	0	24	140	14,554
								220	16,095
								290	27,196

Table 2: Summary of shear strength parameters, densities, and elastic properties, degree of saturation and void ratio of selected residual soil samples tested at the laboratory.

Sample Reference	Landslide / Location Reference	MC (%)	Dry Density Mg/m³	Degree of Saturation	Void Ratio, e_0	CU Triaxial Test		Effective Confining Pressure(kPa)	E_{50}
						C' kPa	φ' deg		kPa
S130022	Loose, Reddish brown, fine to medium grains, soil with more sand, no impurities probably clayey silty sand	11.72	1.83	0.96	0.63	2	26	60	8,159
								100	31,767
								150	69,023
								200	62,754
S130026	Brownish silty sand	15.44	1.45	0.1	0.08	0	21	60	15,728
								100	25,297
								150	23,206
								200	43,091
S130121	Brownish slightly fine to medium grains, soil with more silt, no impurities, probably slightly sandy clayey silt	26.05	1.36	0.96	0.92	16	30	40	13,740
								80	55,607
								120	67,146
								160	155,470
								200	177,810
S140076	Dark brown fine to medium grain clayey sand	12.30	1.64	0.93	0.61	4	26	50	29,241
								100	69,317
								150	31,635
								200	23,957
S140077	Reddish brown fine to coarse clayey sand	26.05	1.78	0.94	0.48	0	30	50	24,323
								100	8,273
								150	9,936
								200	12,252

Discussion & Interpretation of Results

The study on evaluation of E50 (secant modules) is an experiment setup to understand the behaviour of residual soils under changing stress conditions at site.

Residual soils may be formed in place from rock or formed in weathered rock and minerals that have been transported from where the original rock occurred. Residual soil develops in place from the underlying rock. During our experimental study number of prominent issues was noticed other than the results as outline Table 1 and Table 2.

1.   Focussing on the two major factors namely mineralogical composition and texture of soil provides a basis for dividing residual soils into groups that can be expected to have fairly similar engineering properties.

2.   Various attempts have been made to group or classify the samples of residual soils, but visual characteristics of samples differ significantly from each other but most of them are classified as a Silty Sand(SM) or Inorganic Silts (silty or clayey fine sand with slight plasticity, ML) according to the Unified Soil Classification System.

3.   Soils with a strong mineralogical influence and containing low activity clays and inorganic forms of clays, significantly influence the stress-strain characteristic behaviour. Tropical residual soils may contain non-silicate minerals such as oxide minerals.

4.   More deviations are noticed due to complete weathering of feldspar, slickensides, originates of parent rock formations and other remains which mainly form silica.

5. The experimental studying was difficult to rectify stress history and the deformity history. Stress history is created mainly due to rainfall precipitations, soil deposition, movement of soils, unloading effects and re-loading effect caused by erosion etc. The stresses in the past due to various deformities, loading and unloading, will impact the modulus.

6. Water content also impacts moduli. At low water contents the water binds the particles, increases the stress and suction between the particles and leads to a high soil moduli. The effective confining pressure increases E_{50} also significantly as in the Fig 13.
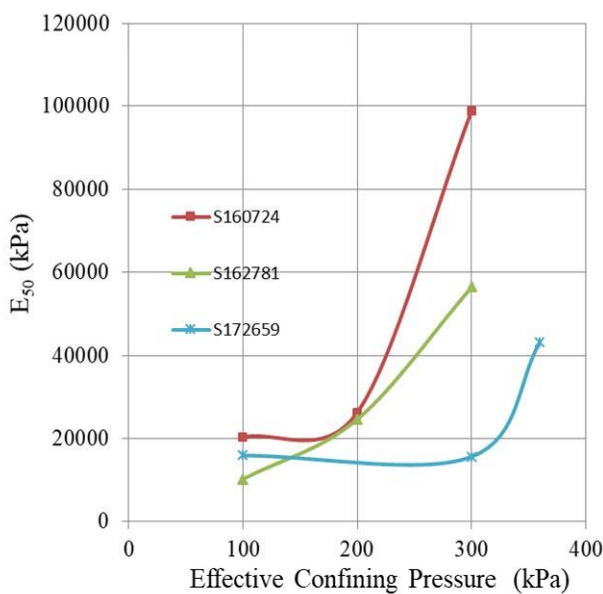
Fig 13: Effective confining pressure Vs E_{50} for samples of S160724, S162781 and S172659

7. Void ratio, which is directly related to packing characteristics of geo-materials, has a strong impact on soil Young's moduli, E_{50}. It is also suggested that the influence of void ratio can be taken into account by using an empirical void ratio function considering the values of E_{50}. The study made an attempt to define a comparison between the void ratio and the elastic parameters as shown in the Fig 14.

8. But coarse grain soils, if water content rises too much, the particles are pushed apart and the modulus is reduced. However, angle of internal friction will increase significantly. This is especially apparent when considering the stiffness of dried clay.
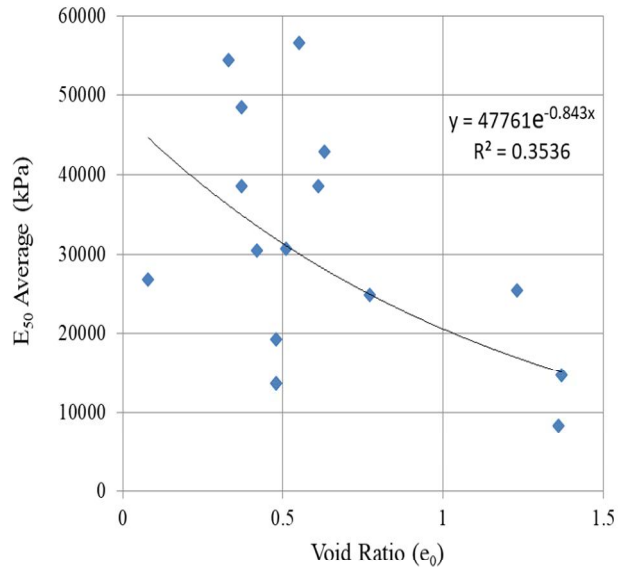
Fig 14: Exponential relationship of Initial void ratio (e_o) Vs Average E_{50}
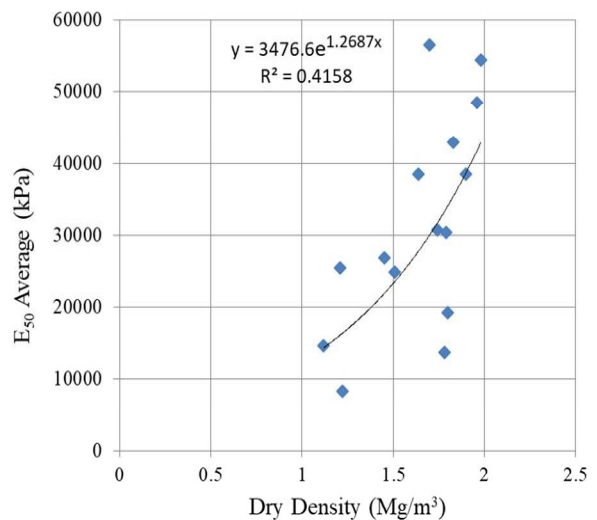
Fig 15: Interpretation of Dry density Vs Average E_{50}

Recent findings indicates two soil samples can have the same dry density but different structures, like loose or dense, and thus have different moduli (Briaud, J L, 2001). If the soil has been subjected to stress in the past, it will impact the modulus. An over-consolidated soil will generally have a higher modulus than the same normally-consolidated soil (Briaud, J L, 2001). No observations were made on residual soils of over consolidated characteristics similar to cohesive soils.

Conclusions & Recommendations

The results presented in this study reflected the relative impacts of void ratio, e_o, degree of saturation, S_r and confining pressure, p on soil Secant Modulus, E_{50}. The evaluation of E_{50} is an experiment setup to understand the behaviour of residual soils under changing stress due to various intrinsic and extrinsic variables such as prolong period of rainfall precipitations, movement of soils, unloading effects and re-loading effect caused by deposition.

In this study, two major categories of residual soils were recognised including quartz silt (silty sand, SM) and inorganic clayey silts (silty or clayey fine sand with slight plasticity, ML).

The characteristics of saturation, pore-water pressure changes, water flow and shear strength of soils are the main parameters associated with rainfall-induced slope failures. These parameters are directly affected by the infiltration and evapotranspiration in actual ground scenario. The natural slopes are generally covered with vegetation and therefore, highly moist environment can be expected.

From the results presented, it can be observed that each void ratio function can only be applied for a certain type of residual soil (minimum to be satisfied with soil structure, moisture content, dry density gradation and LL, and PI). The results do not conclude a strong interdependence of e_o and E50 with the shear strength characteristics due to the small sample size represented in this study. It seems that no universal void ratio function, which can be applied for all soils with their wide range of void ratios, exists.

Considering the findings of the research and observation it is noted that evaluation of elastic parameters of residual soil of slopes is somewhat challengeable task due to large variation of the material properties. The extension of study requires comprehensive and selective additional tests including clay mineralogical composition, particle size analysis, in-situ density, PI and UU triaxial test parameters etc. It is also recommended to conduct a series of plate bearing tests for understanding and interpretation of in-situ stress strain behaviour characteristics and in-situ variability of E_{50} for residual soil formations.

Acknowledgments

References

Bhandari, RK & Dias, AAV (1996) Rain Triggered Slope Movement as Indicators of Landslide Dynamics. Proc. 7th International Symposium on Landslides; 17-21 June 1996, Trondheim, Norway: Balkema. pp. 1515 – 1520.

Bandara, R M S (2012); Seventy landslide-prone areas identified; Sunday Observer; 18th November 2012. Reported by S Mohammed NAALIR .

Briaud,J.l.,2001; Introduction to Soil Moduli, Geotechnical News, June 2001, BiTech Publisehers Ltd, Richmond, B.C.Canada, (geotwchnicalnews @bitech.ca).

Chowdhury, R.N. and Flentje, P. (2002). "Uncertainties in rainfall-induced landslide hazard", Quarterly Journal of Engineering Geology and Hydrogeology,35, 61–70

Ekanayake, E M T M , Herath, H M J M K & Dias, A A Virajh (2015), Empirical Relationships of Elastic Modules and Uniaxial Strength of Intact Metamorphic Rocks of Sri Lanka; International Conference of Geotechnical Engineering(ICGE); PP 515 -518;

Fahey, M. (1999). Determining the parameters of a non-linear elastic model for prediction of ground deformation. Australian Geomechanics, Vol.34, No. 1, March, 39-59

Gasmo, J M, Rahardjo, H & Leong, E C (2000) Infiltration effects on stability of a residual soil slope, Computers & Geotechnics, Volume 26, P 145-165.

Mallawarachchi, M A S N, Ekanayake, E M T M, Kodagoda, S S I and Dias, A A Virajh (2014), Comparison of soil modulus E_{50} of residual soil slope failures in two different rainfall zones; World Landslide Forum3 (WLF3), Volume 1, PP 135- 141..

Rahardjo, H., Lim, T.T., Chang, M.F., and Fredlund, D.G. 1995. Shear-strength characteristics of a residual soil. Canadian Geotechnical Journal, 32(1): 60–77.

Rahardjo, H., Lee, T.T., Leong, E.C. & Rezaur, R.B. 2005. Response of a residual soil slope to rainfall. Canadian Geotechnical Journal 42: 340–351.

Rezaur, R.B., Rahardjo, H., and Leong, E.C. 2002. Spatial and temporal variability of pore-water pressures in residual soil slopes in a tropical climate. Earth Surface Processes and Landforms, 27(3): 317–338.

IPL 191: Experimental and Theoretical Assessment of Structural Health of Retaining Walls Under Low Frequency Dynamic Loading in The Seismic Zone of the Carpathians Foothill (Vrancea Zone)

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Abstract Registered vibrate-acceleration maximum amplitude of the retaining wall under the influence of micro-seismic vibrations and moving trains does not exceed 0.0025m/c^2 along the X axis and 0.008 m/c^2 along the Z axis. The strength of concrete conforms to the class B25. The results of calculations show the corresponding natural frequency oscillations - 9.46 Hz. The difference with the experimentally registered frequency is 1.46 Hz, what corresponds to the deviation of ~ 18%.

Keywords IPL 191, retaining wall, acceleration, frequency, intensity, defects.

Introduction

The speed of movement on the railways was increased to 500-600 km/h. This requires a high level of reliability of all elements of the chain "locomotive - train - railways - protecting reinforced concrete structures (retaining walls, in particular)". Retaining walls are under constant dynamic impact of anthropogenic and natural factors (seismic loads) Trofymchuk (2017). For the proper management of the railway structures it is important to detect deformations of the structures at an early stage. Once deformations are observed, continuous observations and retrofitting works are also important. The aim of the paper is to develop a nondestructive inspection method for the condition rating of the existing retaining walls under low frequency dynamic loading in the seismic zone of the Carpathians foothill (Vrancea zone) (IPL 191).

Unfortunately, visual inspections are mainly qualitative in nature and are directly dependent on the skill of an expert who performs his visual inspection Nakajima (2013). Taking this into account the development of methodology and applied methods of RRW inspection does not depend on subjective factors and allows to perform the analysis of RRW technical state (TS) at the next higher level. This is not only actual, but also necessary taking into account the large number of RRW in Ukraine and high performance of RRW TS diagnosis technology based on nondestructive inspection methods Farenyuk (2017).

Experimental study of dynamic vibrations and strength characteristics of the retaining wall of the landslide protection structure

There was an experimental study of dynamic vibrations and strength characteristics of the retaining wall of the landslide protection structure (Fig. 2) at the railroad haul of Zavalie-Nepolokivtsy of Chernovtsy distance of Lvov railway in the seismic zone of the Carpathians foothill (Vrancea zone).

The retaining wall of the landslide protection structure at the railroad haul of Zavalie-Nepolokivtsy of Chernovtsy distance of Lvov railway was designed to support the dirt fill of the railway foundation. The retaining wall supports the dirt fill of the railway foundation due to the cross-section which is similar in shape to the rectangular trapezoid with the upper base length of 4.5 m and bottom base length of 1.5 m and height of 5 m. On the dirt fill there is a foundation for one-track railway line.

Structurally retaining wall is assembled of separate similar elements "buried wall" with the width of 1,30 m mounted on the foundation with the pile ground beam (see fig. 1).

Figure 1 Location of vibration pickups during the inspection of the retaining wall.

At the top the retaining wall has a monolithic reinforced concrete belt with the sectional area of 600x600 mm. The wall has damages in a form of indents and cracks. Comparing the state of elements surface on the defective areas of the wall with undamaged parts of the wall it can be concluded that part of the elements was installed not after factory fabrication, but after their previous use. During the operation the reinforced concrete belt of the retaining wall got some insignificant damages. The inspection of the railway bed foundation did not show significant differential settlements.

Removing of water from the railway line foundation is performed on both sides of the railway bed. The profile of ground slope at the foot of the retaining wall provides the necessary water removing from RRW. The territory near the landslide protection structure is kept in good conditions.

To determine the dynamic and physical-mechanical characteristics of the retaining wall its complex inspection was performed. External factors of dynamic effects on the retaining wall are the following: alternating microseismic effects of natural character caused by the location of the inspected object in the seismic zone of the Carpathians foothill (Vrancea zone); alternating dynamic effects caused by movement of trains on the inspected area of the railway.

Microseismic ground vibrations occur constantly (Vrancea zone) and have variable character both by direction and intensity. Effects of moving trains on the dirt foundation of the railway track and landslide protection structures are irregular. The visual observations showed that the speed of passenger trains movement on the area near the landslide protection structures does not exceed 50 - 60 km/h.

Within the framework of the developed methodology Trofymchuk (2017) the following schemes of vibration pickups placement were realized. appearance.

Scheme 1. Placement of pickups at the top of RRW at points 1, 2 and 3 to measure the horizontal vibration accelerations in the direction of X axis.

Scheme 2. Placement of pickups at the top of RRW at points 1, 2 and 3 to measure the vertical vibration accelerations in the direction of Z axis.

In fig. 1 the position of X and Z axes shows the directions of vibration accelerations measurement.

To perform the total volume of planned vibrodynamic inspections the records of vibrations were performed for 3 minutes repeating twice in accordance with the schemes of vibration pickups placement. Results of vibrodynamic inspections of retaining wall structure in the horizontal direction along the X axis and in the vertical direction along the Z axis by schemes 1 and 2 include graphics of vibration accelerations and their amplitude spectra. Some experimental results are presented in fig. 2.

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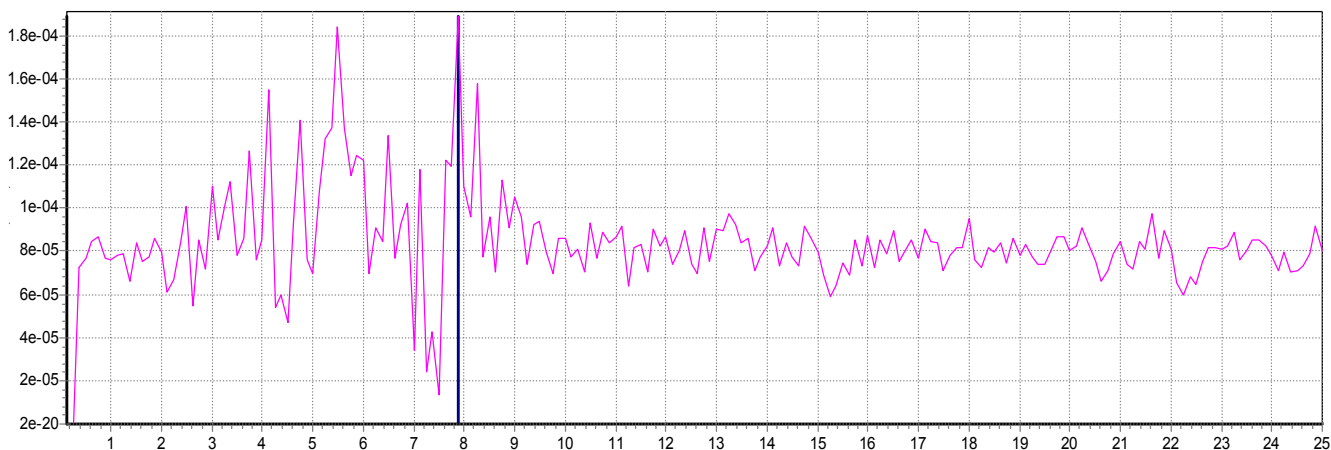
Figure 2 The spectrum of horizontal vibration accelerations along the X axis of the retaining wall.
Vertical axe is signal amplitude (**m/c²**); horizontal axe is frequency (**Hz**).

The concrete compressive strength of the retaining wall structural elements was determined. Eight areas of RRW, which were at equal distance along its length, were inspected. Six measurements of the ultrasonic transmission time in reinforced concrete wall were performed on each area (table).

Concrete mean strength, MPa	Variation coefficient	Appropriate concrete class by compressive strength (Ukraine)
34,2	0,06	B25

Graphic model

The graphic model was developed for RRW in LIRA 9.6 software and calculation complex. RRW has a quite long length and consists of separate similar reinforced concrete elements, which are connected by the monolithic reinforced concrete belt at the top. 7 sections of RRW with the width of 1.3 m were considered in the calculation. Lack of enough source information on the structure of the retaining wall, pile foundation, ground

composition and its physical and mechanical characteristics, accelerograms of dynamic effects on RRW structure caused by passing trains gave grounds to determine the following RRW parameters: vehicle weight was taken as 60 000 kg; semi-hard loams with normative characteristics were taken as ground (Table B.2 and Table B.3, Ukraine Building Code(2009)). Calculated ground characteristics were determined by provisions of the annex Tsytovich (1963); calculated angle ϕ_1 for variant with seismic loads of 7 points was equal to 23.3°; piles space was equal to 1.0 m; inclination angle was equal to 10°; reinforced concrete structures deformation modulus was equal to 306 kg/m/c²; horizontal overhangs of RRW foundation were equal to 0.8 m and 1.5 m with a thickness of 0.2 m: binding of the vertical pile was equal to 1.2 m; binding placed upwards on the inclined pile was equal to 0.8 m. Stresses transmitted to the wall at the level of its top and bottom were calculated by the formulas of limit equilibrium given in Tsytovich (1963).

In calculations of dynamic loads the ground base stiffness under the ground beam base was considered. Stiffness characteristics of ground base for ground beam and piles were determined in accordance with the provisions of

Kaliukh (2015). Ground stiffness on the lateral surface of the vertical wall was calculated by the formula (9.20) Tsytovich (1963) and formulas (5) and (7) USSR Building Code (1988).

8 variants of loads were taken: dead weight of reinforced concrete structures; dead weight of ground on the left edge of the horizontal area of the retaining wall was equal to 31.05 кН/м²; dead weight of ground on the left edge of the ground beam was equal to 12.42 кН/м²; dead weight of ground and load caused by the vehicle on the right edge of the horizontal area of the retaining wall was equal to 191.8 кН/м²; active ground load on the wall (to the right) taking into account the vehicle weight was equal to $\sigma_2' = 26.5$ кН/м², $\sigma_2 = 59.4$ кН/м²; ground load on the wall (to the left) was equal to $\sigma_2' = 0$ кН/м², $\sigma_2 = 12$ кН/м²; snow load for Chernovtsy region was equal to $P = 1.534$ кН/м²; seismic effect of 7 points was equal to $\alpha = 0.1$, $K_1 = 0.25$, $K_2 = 0.5$, $K_3 = 1$, $K_{gr} = 1$.

Results of dynamic calculation of "ground base – pile foundation – RRW structure" system for vibration and seismic effects are given in fig. 3.

| -0.886 | -0.737 | -0.59 | -0.442 | -0.295 | -0.147 | -0.00159 | 0.00159 | 0.147 | 0.159 |

10^{-2}m
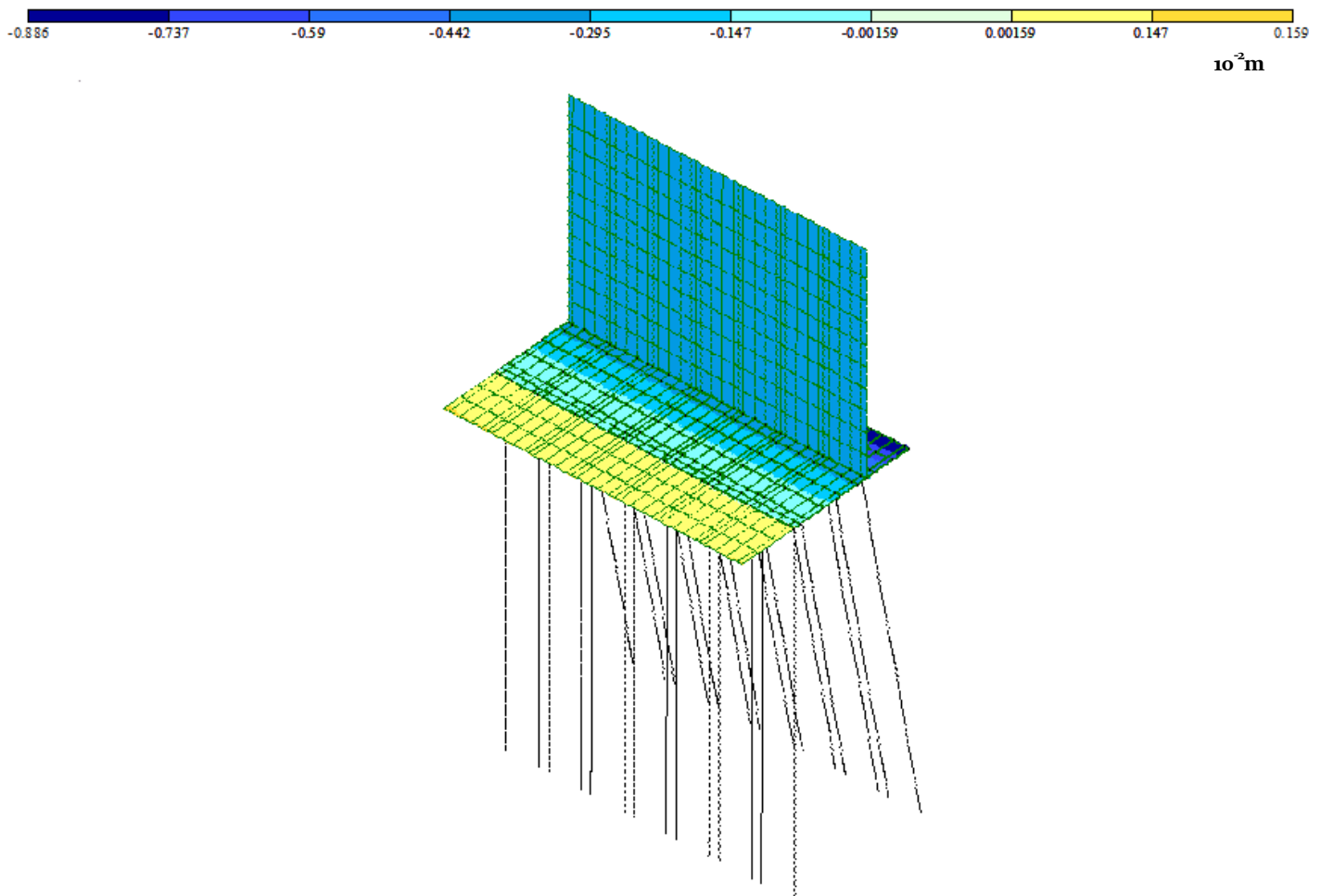
Figure 3 Izofields of vertical movements of the retaining wall along the Z axis at seismic loads acting at a right angle to the railroad bed.

Results of measurements show that period of natural vibrations by the first form is equal to 0,157 c; relevant

natural vibrations frequency is equal to 9,46 Hz.

Conclusions

Based on experimental dyagnosis and mathematical modeling of railway retaining wall at haul of Zavalie-Nepolokivtsy of Chernovtsy distance of Lvov railway the following conclusions were made:

1. Maximal amplitudes of vibration accelerations of the retaining wall at microseismic vibrations and train passage do not exceed 0,0025 m/c² on the X axis and 0,008 m/c² on the Z axis. Compared with the microseismic vibrations the level of vibration accelerations at the movement of trains near the retaining wall is increased by 4 times.

2. Registered vibration accelerations at the level of top area of the retaining wall are lower than it is allowed. At vibrations the structure of the retaining wall has a range of predominant frequencies of 5,0 - 8,0 Hz in the direction of X axis and 9,0 - 12,0 Hz in the direction of Z axis. The maximal wall base vibration accelerations of 0,008 m/c², which are lower than it is allowed (0,15 m/c²), are registered. At this level of vibration accelerations of wall base and absence of conditions for its watering the retaining wall settlements should not be observed during the further operation. Concrete strength of the retaining wall corresponds to concrete class of B25.

3. Experimentally registered maximal amplitude of transverse vibrations along the X axis is observed at the frequency of 8 Hz. Difference with calculated vibrations frequency is 1,46 Hz, what corresponds to inclination of ~ 18%. It is known that decrease of natural structure vibrations frequency indicates the presence of damages in the structure and its increase indicates its strengthening and result of the repair works. It should be noted that calculation model is accurate and cracks in RRW are found during the inspections. The performed inspections show that experimental methods of nondestructive inspection Farenyuk (2017) and mathematical modeling can be used to determine the current technical state of RRW. At the same time it should be noted that experimental methods of vibration diagnosis can indicate the little changes in RRW stress-strain state.

4. In accordance with the results of mathematical modeling and experimental studies the following relevant recommendations are given: to decrease the horizontal displacement of RRW top caused by seismic effects it is advisable to increase the height of ground fill on the left side of the retaining wall; it is necessary to continue to monitor the RRW state, and if the tendency to decrease its natural vibrations frequency is observed, it is necessary to perform repair works followed by vibration diagnosis of their qualities.

Acknowledgments

References (in the alphabetical order)

Farenyuk G., Kaliukh I., Farenyuk E., Kaliukh T., Berchun Y., Berchun V. (2018) Experimental and Theoretical Diagnostics of Defects in Ferroconcrete Piles Based on Reflection of Longitudinal and Transverse Waves. In: Hordijk D.A., Luković M. (eds) High Tech Concrete: Where Technology and Engineering Meet. Springer, Cham: 1307-1317.

Nakajima, S., Shinoda, V., Abe K. (2013) "Inspection of structural health of existing railway retaining walls", Proceedings, 18th International Conference on Soil mechanics and Geotechnical Engineering "Challenges and innovations in geotechnics", Paris, France: 2059-2062.

Trofymchuk, O., Kaliukh, I., Berchun V. (2017) Landslide stabilization in building practice: methodology and case study from autonomic Republic of Crimea. Workshop on World Landslide Forum. Springer, Cham: 587-595.

Tsytovich N. (1963) Soil mechanics, SSEUM, Moscow, USSR.

Ukraine Building Code. (2009) "Bases and foundations of facilities. Main provisions of design (B.2.1-10: 2009)". Kiev, Ukraine.

USSR Building Code. (1988) "Construction norms and rules. Foundations of machines with dynamic loads (2.02.05:87)". Moscow, USSR.

Use of Spectral Acceleration to Evaluate Seismically Induced Landslide at Lokanthali, Kathmandu due to 2015 Gorkha Nepal Earthquake

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Abstract The 2015 Gorkha Earthquake triggered over 15,000 landslides and caused a massive damage to infrastructures. One among those landslides is located at Lokanthali, Kathmandu, along the Araniko Highway. The authors conducted field investigation to get the geometry of the landslide and collected a few soil samples from the landslide area to evaluate the static and dynamic shear strength of the soil. Numerical analysis of the slope deformation using spectral acceleration parameters using the measured soil properties show that the landslide triggered due to the loss of undrained shear strength of black cotton (kalimati) soil due to earthquake induced ground motion. The estimated depth of sliding surface is 20 m.

Keywords earthquake induced landslides, shear strength degradation, FLAC modelling, spectral acceleration

Background information

The Mw 7.8 2015 Gorkha earthquake killed almost 9,000 people and caused a significant damage to properties (Hashash et al., 2015; Moss et al., 2015. The earthquake triggered over 15,000 co-seismic landslides, mostly along the epicentre of the main shock and strongest aftershock (Tiwari et al., 2017). One among the landslides triggered by the earthquake was at Lokanthali of Kathmandu, which is at 2 km east of Tribhuvan International Airport at along the Araniko Highway (Fig. 1). Araniko highway connects Kathmandu to the Chinese border in the north.

Landslide at Lokanthali, also known as Lokanthali landslide, occurred right after the 2015 Gorkha earthquake. This area has been extensively developed since 2008, after the Araniko Highway was expanded under JICA funding. Due to the widening of the road, many three or four-story houses had been constructed and the house price in the area went extensively high. Many of those modern buildings were constructed at the bank of small creek, which was later drained out in through RCC pipes. The landslide cause partially damage to dozens of houses and foundation of a few dozen houses were tilted towards the creek. More than 200 m

strength of the road was settled by more than a meter (Fig. 2). The road was constructed on an embankment, supported by the mechanically stabilized earth (MSE) retaining wall. The buildings in the area were distressed (Fig. 3) and the landslide moved by a distance of 1-1.2 m (Fig. 4). The landslides had been inaccurately referred, by different media, to fault rupture surface or liquefaction, which was later disregarded by the Geotechnical Extreme Event Reconnaissance (GEER) team and considered as the cyclic clay failure (Hashash at al., 2015; Moss et al. 2015).

Figure 1 Location of Lokanthali Landslide site.

Figure 2 Road settled due to the landslide.

Figure 3 Distressed building due to the landslide.

Figure 4 Main scarp of the landslide.

Field and Laboratory investigation

Field investigation

The GEER team led by the first author team mapped the cracks observed in the landslide area a few weeks after the earthquake (Hashash et al., 2015; Moss et al., 2015). A few months after the earthquake, the first and second authors travelled the site and prepared a topographical map as well as landslide cross-section maps using GPS and total station based surveys. Moreover, sub-surface explorations were done at six different locations as presented in Fig. 5. The depth of sub-soil exploration was up to 6 m. Swedish Cone Sounding (SCS) was performed in all of those locations to obtained the continuous profile of undrained shear strength. In four of these bore holes, Vane Shear Tests (VSTs) were also performed to verify the undrained shear strength. It was observed that the undrained shear strength of 28 kPa was continued up to the depth of 4m and then there was an increase of undrained shear strength by 6.7 kPa per meter depth of the soil. The soil at the site was very soft lacustrine deposit, called black cotton soil or kalimati (locally), as shown in Fig. 6.

Figure 5 Location of sub-soil exploration points and landslide cross section used in the numerical analysis.

Figure 6 Soft clay observed at the site.

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He sub-soil investigation revealed that the unioform soft soil is continuous in the area to a grter depth and water table ranged from 0.5 to 1.5 m. No trace of sliding surface was observed up to the depth of 6 m.

Laboratory soil tests

Soil samples were collected from four different depths from BH-2 and shipped to USA under USDA permission. Static and dynamic properties of the soil samples were measured using routine soil tests, static simple she tests, and dynamic simple tests. Static simple shear test results show that undrained shear strength ranged from 0.28 to 0.4, with an average of 0.25. Bender element tests show that the shear wave velocity of the soil samples was 200 m/s. Presented in Fig. 7 are the cyclic strength curves of the soil samples at different double amplitude shear strains. Likewise, Figs. 7 and 8 show the modulus reduction curve and damping curves, respectively. The stress-strain hysteresis loop that was used to prepare the damping curve is presented in Fig. 9. The backbone curve used for the determination of maximum shear modulus is presented in Fig. 10. Strength degradation due to cyclic loading was obtained to be 25%, in average.
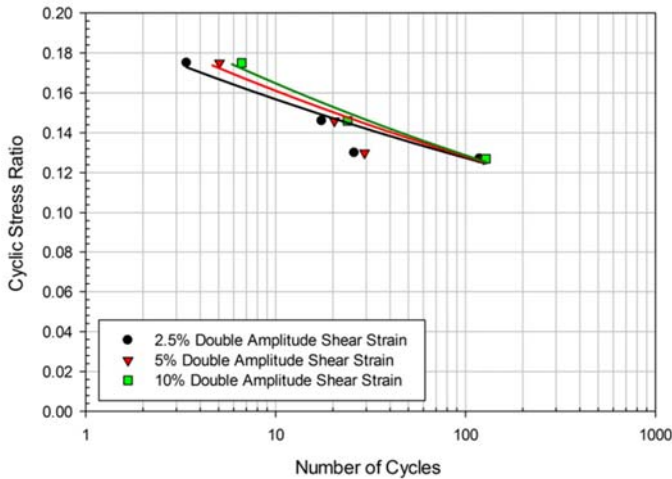
Figure 6 Cyclic strength curves for the Kalimati soil samples.
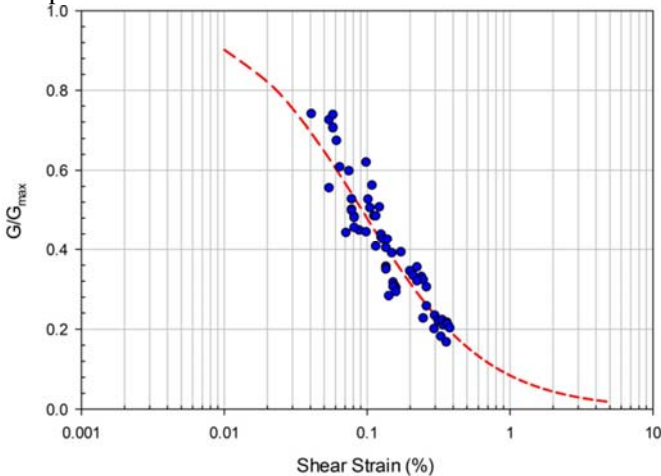
Figure 7 Shear Modulus reduction curve for the Kalimati soil sample.
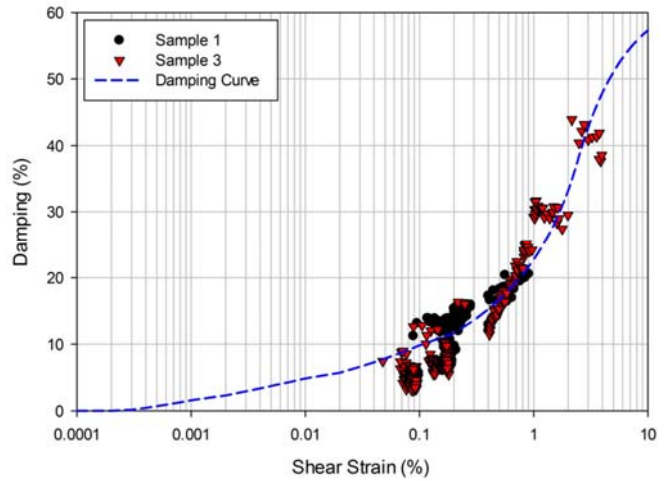
Figure 8 Damping curves for the Kalimati soil samples.
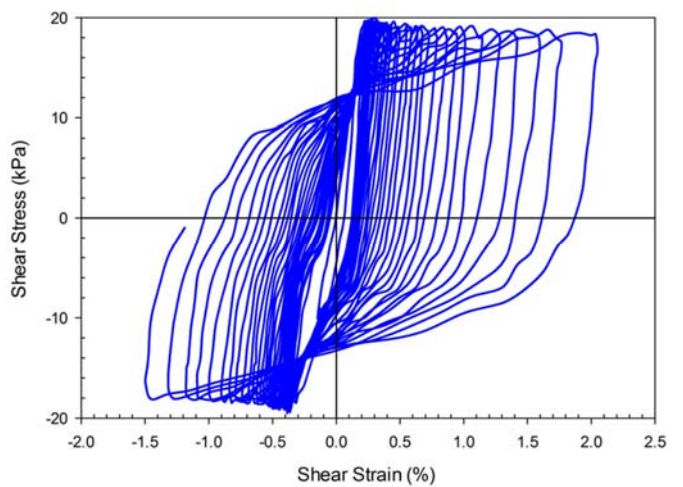
Figure 9 Stress strain hysteresis loop used for the development of damping curve.
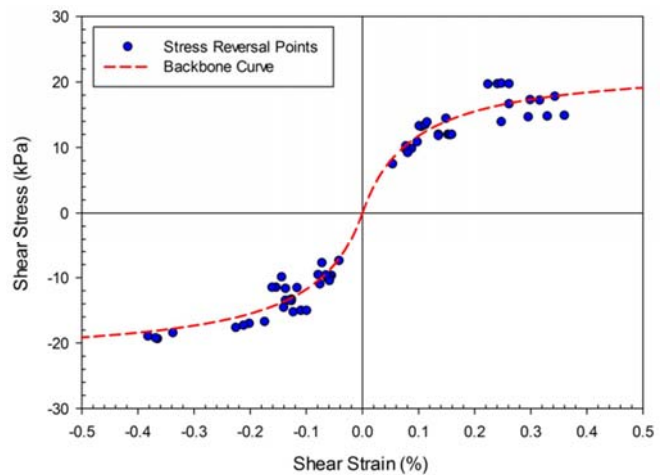
Figure 10 Backbone curve obtained for the Kalimati soil sample.

Data obtained from the laboratory soil testing was used to characterize the normally consolidated lacustrine Kalimati soil where the landslide was triggered. All these information were input into the numerical analysis calculations.

Numerical analysis

Ground motion data used for the analysis

Data from five different ground motion stations were available. However, station THM was closes from the site, i.e. within a distance of less than 2 km, and that was used for this analysis. First, all ground motion data was deconvoluted and spectral response of the ground motion data at 5% damping was developed so that this information can be input into the numerical model using FLAC.
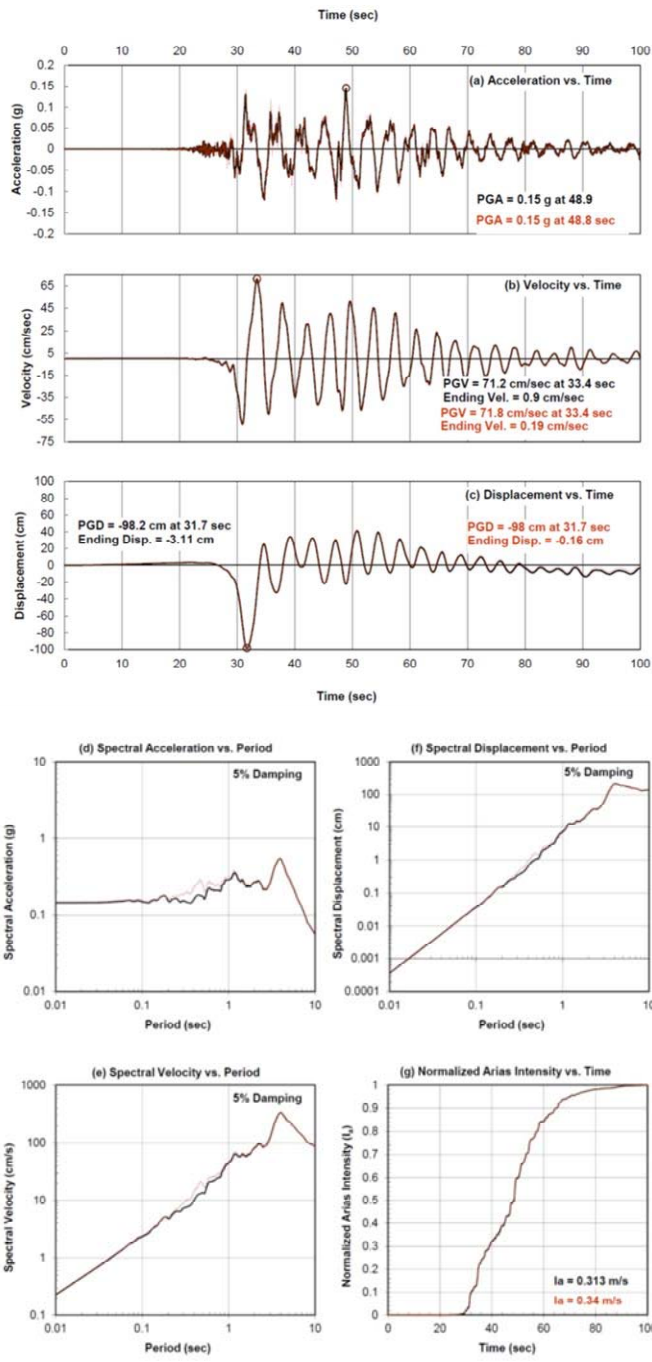
Figure 11 Ground motion and spectral accelerometer, velocity, and displacement data (at 5% damping) from N/S motion of THM station used in the numerical analysis.

Numerical analysis

Dynamic numerical analyses were conducted for different scenarios using non-linear dynamic geo-mechanical analysis utilizing the deconvoluted ground presented in Fig. 11. A quiet absorbing (viscous) boundary was used along the base of the model and free-field boundaries were placed along the edges to minimize wave reflections at model boundaries. SHAKE2000 was used to deconvolute the recorded ground motion and obtain input base velocities Laboratory based hysteresis loops were used for input damping characteristics. The entire analysis was performed using FLAC. Presented in Fig. 12 is the numerical analysis result. As can be observed in Fig. 12, a total displacement of about 1.0 m was observed and the amount and location of the displacement matched well with those observed in the field. The depth of sliding surface was estimated to be 20 m, based on the numerical analysis results, as can be observed in Fig. 12.
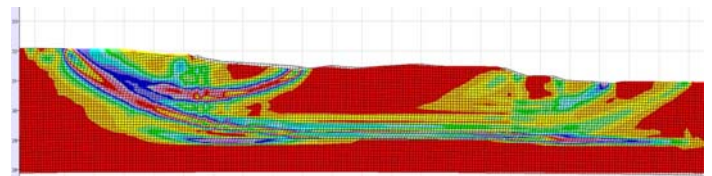
Figure 12 Numerical analysis result obtained for the landslide deformation using FLAC.

Conclusion

The Mw 7.8 2015 Gorkha Earthquake caused a significant damage to infrastructures and scored a death toll of almost 9,000 people. It triggered over 15,000 co-seismic landslides including the Lokanthali landslide in Kathmandu. Laboratory and in-situ test results showed that the lacustrine soft Kalimati soil that was observed in the landslide site is very soft with very low undrained shear strength and lost its undrained strength by 25% under cyclic loading. The laboratory and in-situ test results incorporated into a numerical analysis using FLAC shows that the landslide moved at the depth of 20 m. Moreover, the amount and location of soil deformation matched well with the numerical analysis results.

Acknowledgments

References (in the alphabetical order)

Hashash, Y. M.A., Tiwari, B., Moss, R. E. S., Asimaki, D., Clahan, K. B., Kieffer, D. S., Dreger, D. S., Macdonald, A., Madugo, C. M., Mason, H. B., Pehlivan, M., Rayamajhi, D., Acharya, I., and Adhikari, B. (2015). "Geotechnical Field Reconnaissance: Gorkha (Nepal) Earthquake of April 25 2015 and Related Shaking Sequence." Geotechnical Extreme Event Recon. Report No. GEER-040 V 1.1, GEER.

Moss, R., Thompson, E. M., Kieffer, D. S., Tiwari, B., Hashash, Y. M. A., Acharya, I., Adhikari, B., Asimaki, D., Clahan, K. B., Collins, B. D., Dahal, S., Jibson, R. W., Khadka, D., Macdonald, A., Madugo, C. L. M., Mason, H. B., Pehlivan, M., Rayamajhi, D., Uprety, S. (2015). "Geotechnical Effects of the 2015 Magnitude 7.8 Gorkha, Nepal Earthquake and Aftershocks." Seismological Research Letters, 86, 1514-1523.

Tiwari, B., Ajmera, B., and Dhital, S. (2017). "Characteristics of Moderate to Large Scale Landslides Triggered by the Mw 7.8 2015 Gorkha Earthquake and its Aftershocks." Landslides, in press, DOI: 10.1007/s10346-016-0789-0.

BLISM (Bosnian Landslide Investigation and Stabilization Method)

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e-mail: Azra.Krvavac@unmo.ba

L: Bogatići 2010

R: Zenica 2014

Tuzla 2014

Tuzla 2014

Maglaj 2010

4 7 2010 17-26:12

Tuzla 2010

BLISM (Bosnian Landslide Investigation and Stabilization Method)

This method is based on two variables:

1. Assessment of economic interests for landslide processes

2. Assessment of security interests for landslide processes
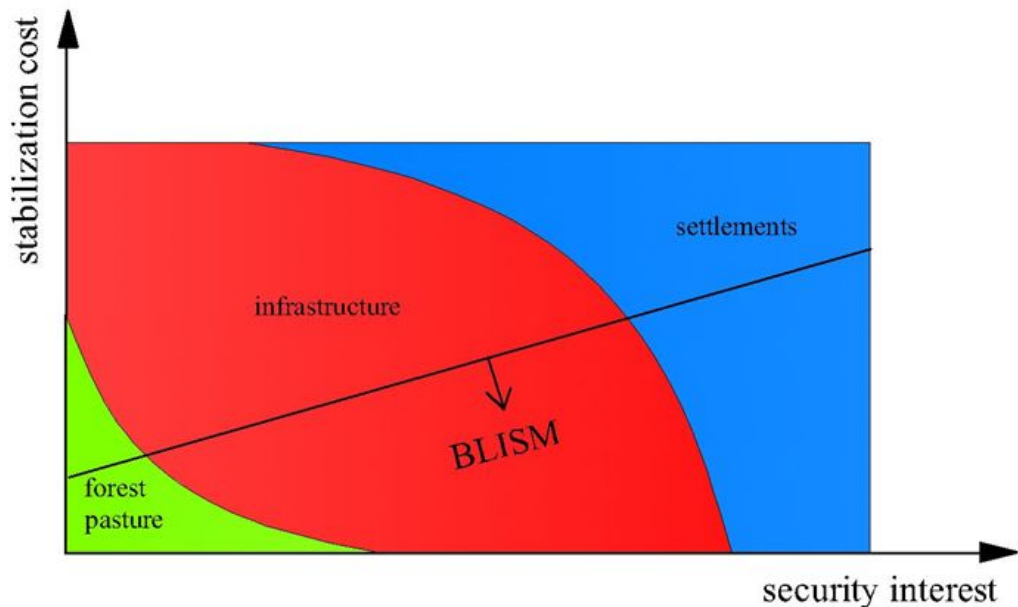
What is BLISM ?

BLISM is the methodology recognizable by investors, researchers, designers and contractors and provide an effective system of control in slope processes, investigation and stabilization of unstable slopes in order to ensure safety of people and property with as less as possible financial expenditures.

The BLISM should be divided in several parts that are to be developed in detail:
- *Slope and urban-planning processes' management;*
- *Pre-investigation and investigation activities on semi-stable and unstable slopes;*
- *Stabilization and post stabilization activities.*

Concept of BLISM

Slope and urban planning manage- ment

Investi- gation

Stabilization and post stabilization activities
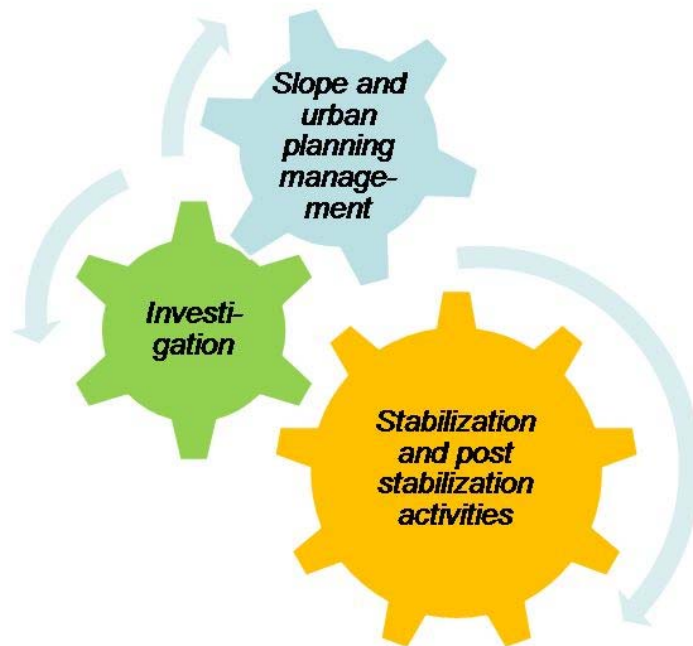
1st PART: The management of slopes and urban-planning processes

should be narrowly related to the definition of the term:
„stable – semi-stable – unstable"

The following basic elements of the methodology need to be clarified for the managment of slopes

- *better understanding of systematization of slope processes;*
- *improvement of urban planning by multifunktional criterion;*
- *assessment of economic interest in the slope process;*
- *assessment of safety interest in the slope process;*
- *quantitatively defined terms: stable, semi-stable and unstable;*
- *stress-strain investigation of the slope in the pre-sliding phase;*

CYCLING OF CLIMATE CHANGE
or ACCELERATION OF CLIMATE CHANGE

(CYCLING or ACCELERATION OF SLIDING)

?   ?   ?   **?**

2010 ₂₀₁₁   ₂₀₁₂   ₂₀₁₃   2014 ₂₀₁₅   ₂₀₁₆   ₂₀₁₇   2018
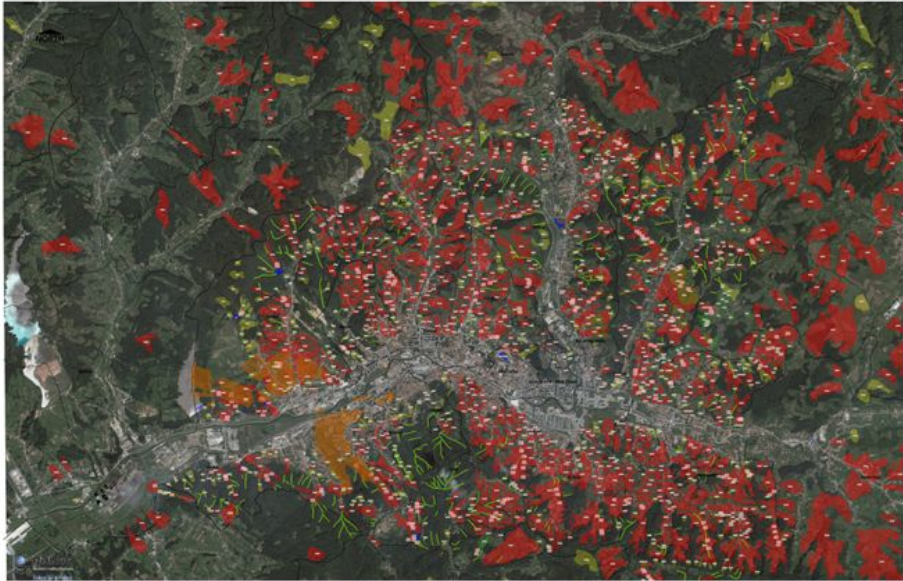
- What is to be done next time?
- How to reduce damage in the future?
- Is it possible to reduce the risk of casualties at semi-stable slopes?
- How much money is needed?
- What types of experts are required?

Answer: BLISM (Bosnian Landslides Investigation and Stabilization Method)

NUMBER OF LANDSLIDES IN BOSNIA AND HERZEGOVINA:

6.000 – 60.000 – 100.000   ????

Landslide as a term, sometimes differ from case to case with more aspects: level of instability, level of urbanization, causes of instability

GIS survey of landslides, Tuzla's urban area

REMARK:

Instability has to be more precise

2nd PART: investigation activities on semi-stable and unstable slopes

should be improve investigation methodology as possible as
„low cost - high level understanding of instability"

The following basic elements of the methodology need to be clarified:
- Investigation stress-strain relations in landslides depending on season weather conditions;
- water-permeability and water-containing of soil - rock (quantitative evaluation);
- Investigation of interaction: structure-unstable slope;
- Definition of the stress-strain status of landslide in the pre-sliding, sliding and post sliding phases
- Definition of the kinematic and dynamic parameters during landslide's movement;
- The scope of field investigation and procedures, as an alternative to the laboratory tests;
- Compliance of laboratory and field investigation tests, scope and type of investigation;
- Advantages and disadvantages of drilling sets and core quality;
- The role of geophysical investigation methods;
- Duration of the investigation and the season;
- The amount of investigation activities;
- Phase procedures in investigation;
- The gradual nature of geospatial investigation from global to local.

manual power drive drillng machine
- mobile on hard and steep terrain
- usable for drilling of soil

mechanical power drive drillng machine
- limited mobility
- usable for drilling of all kind soil-rocks

- Which kind of investigation in-situ methods: drilling with boreholes, geophisics methods, geological mapping, inklinometers, piezometers, GIS monitoring or others ?
- Number of boreholes, inklinometers per landslide ?
- Who has to prepare Program of investigation: (investor or governement office, contractor or consultant, independent consultant)
- Who is responsible for results of investigation ?

BLISM have to make optimum cost of investigation

3rd PART: Stabilization and post stabilization activities

should be improve investigation methodology as possible as
„low cost - high level understanding of instability"

The following basic elements of the methodology need to be clarified:

- Using artificial materials for chemically improvement of soil's strength;
- Optimal design of drainage system in the soil mass;
- Using stone for structures as inexpensive material;
- The new approach in urban areas is design of artificial slopes
- *The possibility of soil strengthening instead of structures supporting;*
- *Development in the production of new materials that are to be used for stabilization;*
- *Establishing the term: Interest towards risk;*
- *Defining the possibility of stabilization in phases;*
- *Reactivation of landslide and legal procedure to establish responsibility;*
- *Post-stabilization observation and monitoring of landslides and semi-stable slopes.*

STABILIZATION MEASURES

Fast for implementation and inexpensive, but low quality

Slow for implementation and very expensive, but high quality
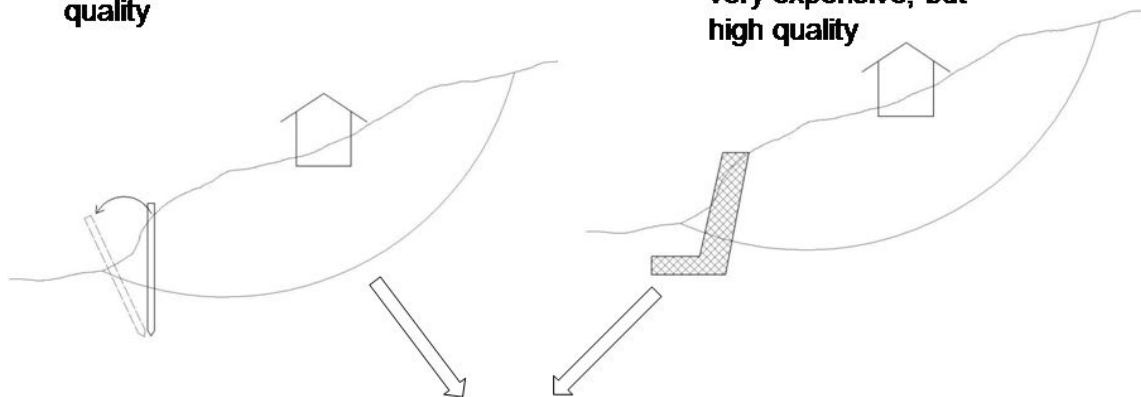
OPTIMUM:

BLISM (Bosnian Landslide Investigation and Stabilization Method)

The goal of BLISM is to save governmental money to stabilize landslides, increase productivity for stabilization and preserve environment acceptable for society.

Landslide Rapid Mapping from Remote Sensing

Ping Lu

Tongji University

IPL Project Proposal 2017

Background
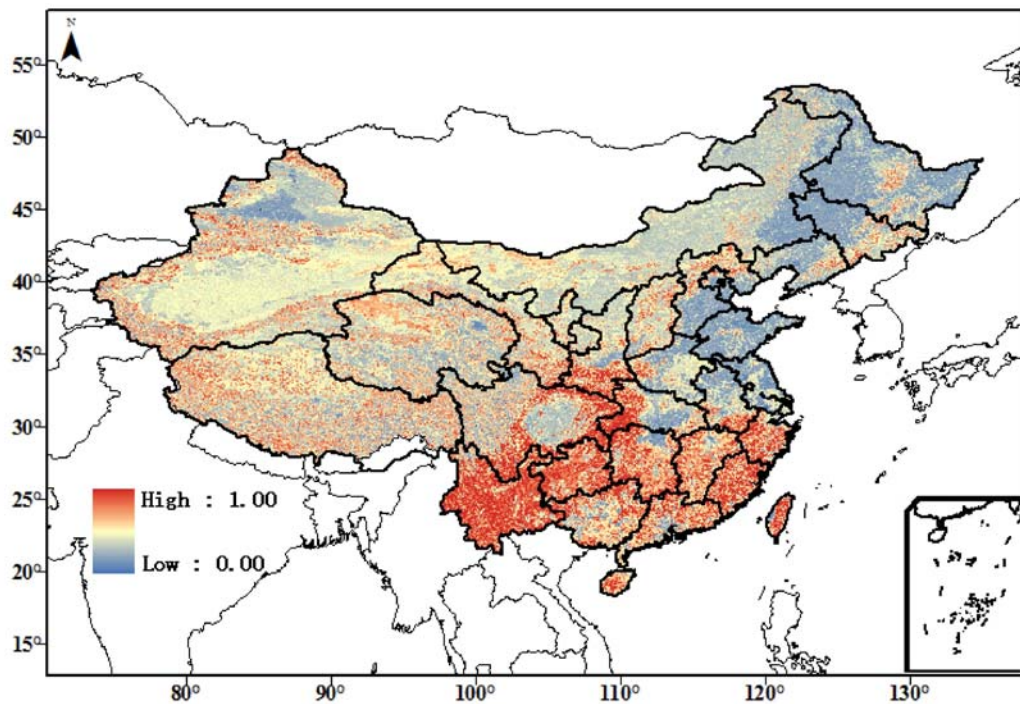
Landslide Susceptibility Map of China (Liu et al. 2013)

Background

Earth-Science Reviews 112 (2012) 42–66

Contents lists available at SciVerse ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Landslide inventory maps: New tools for an old problem

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[c] Kainan University, 1, Kainan Rd., Luzhu, Taoyuan 33857, Taiwan

aperture radar images, and (iii) tools that facilitate landslide field mapping. Next, we discuss the advantages and the limitations of the new remote sensing data and technology for the production of geomorphological, event, seasonal, and multi-temporal inventory maps. We conclude by arguing that the new tools will help to improve the quality of landslide maps, with positive effects on all derivative products and analyses, including erosion studies and landscape modeling, susceptibility and hazard assessments, and risk evaluations.

Study Area 1
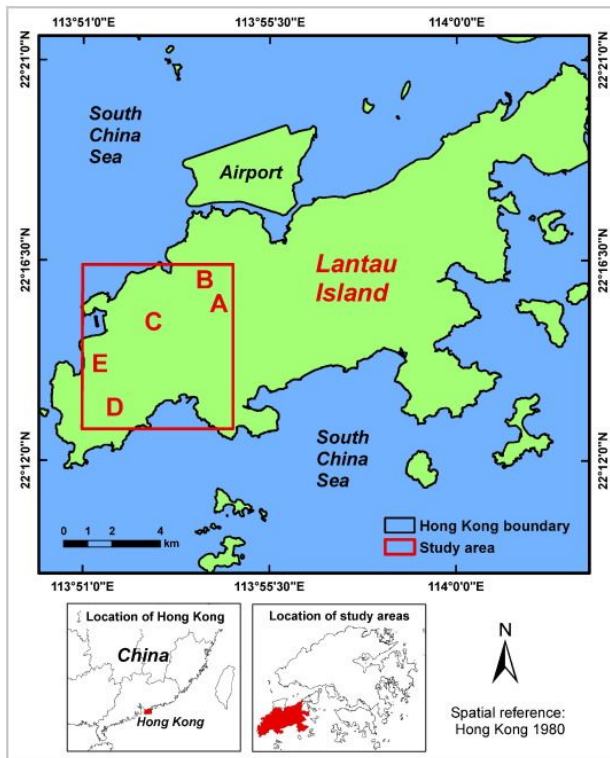
Lantau Island, Hong Kong

Study area (~ 40 km^2) with five sub-areas highlighted

Study Area 2

Danba County, Sichuan Province

Study Area 3
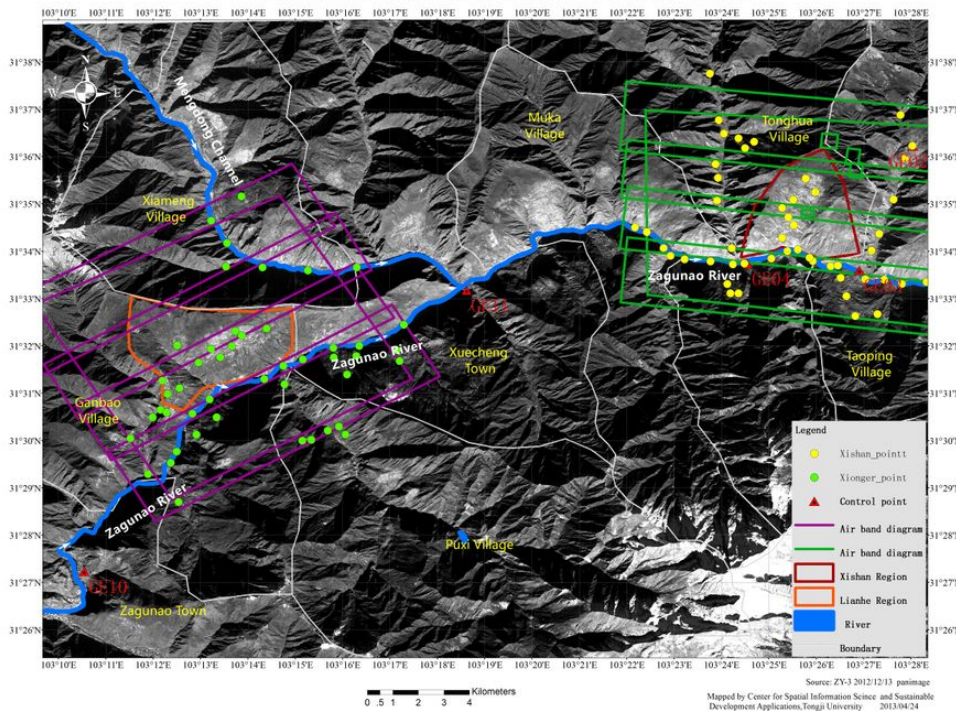
Li County, Sichuan Province

Materials
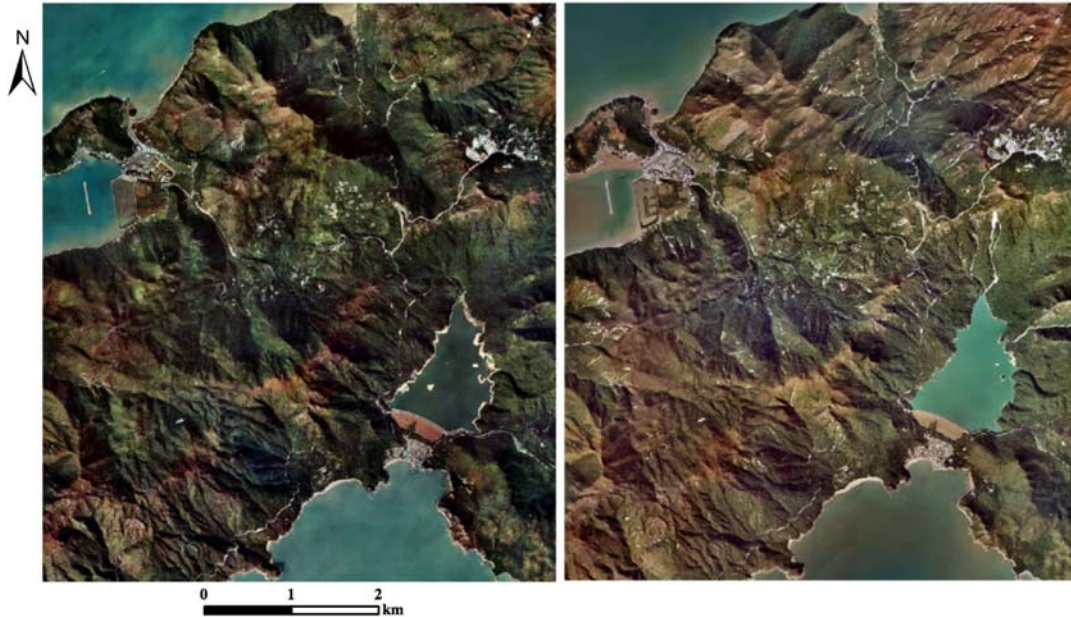
Pre-event and post-event remote sensing images,
e.g. aerials photos and satellite images

Methodology 1
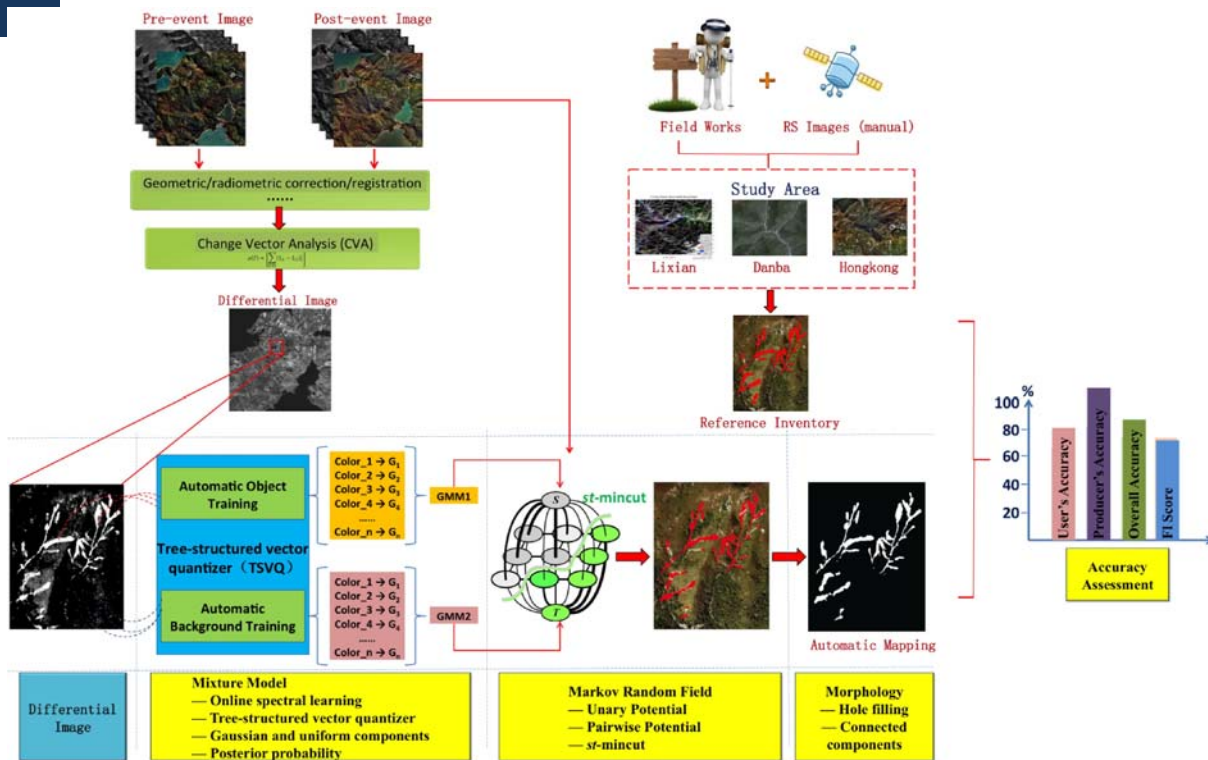
Methodology 2
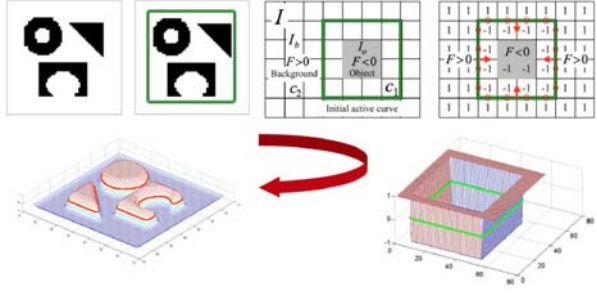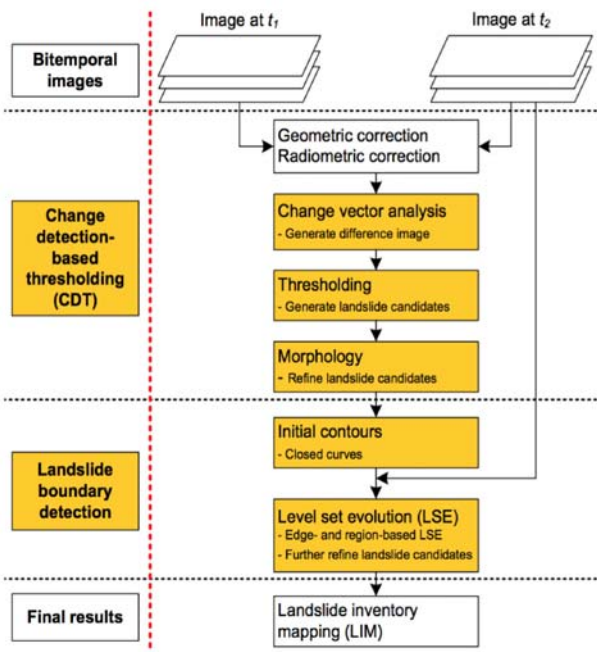
① **The edge-based LSE (ELSE):**

$$\begin{cases} \phi_t = g(I)|\nabla\phi| \\ g(I) = \frac{1}{1+|\nabla G_\sigma * I|^2} \end{cases}$$

② **The region-based LSE (RLSE):**

$$\phi_t = \left[\frac{(c^+ - c^-)(2I - c^+ - c^-)}{\max\left(|(c^+ - c^-)(2I - c^+ - c^-)|\right)} \right] |\nabla\phi|$$

Level Set Evolution

Past Experience

$$mPD = \frac{v_{L1} - v_{L2}}{v_{L2}}$$
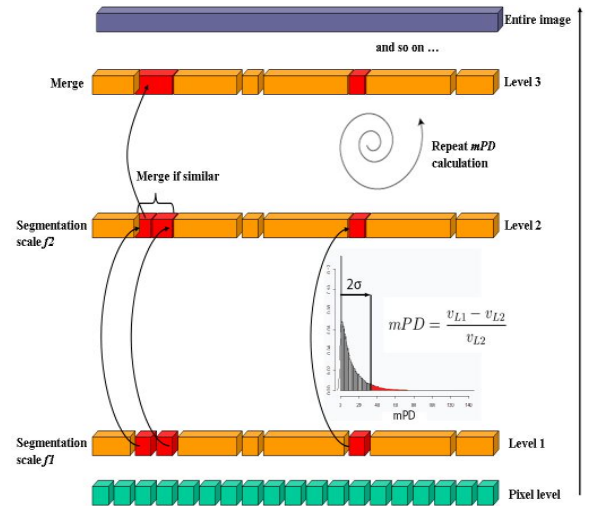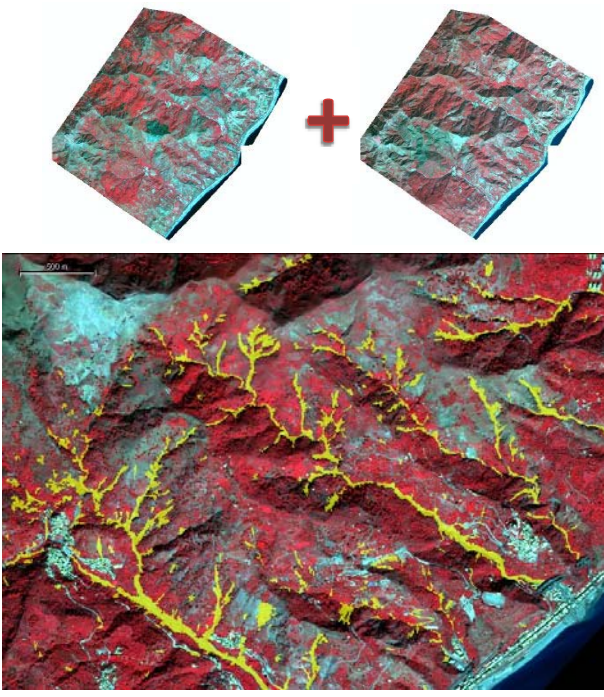
Lu et al. 2011, GRSL

142 cited

Objectives of the Project

To develop newer landslide mapping methods that have the following appealing advantages:

1. to be computationally more efficient (faster);
2. the degree of automation is high (with minimal human interaction);
3. the level of applicability is high (robust and applicable in real mapping applications);
4. the level of generality is high (can handle general landslide objects).

Thank you for your listening!

Questions?
Suggestion?

Rockfall Hazard Identification and Rockfall Protection in The Coastal Zone of Croatia
IPL Project Proposal

Željko Arbanas[1], Snježana Mihalić Arbanas[2]

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[2] University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Croatia

Croatian Landslide Group
IPL World Centre of Excellence

- **PROJECT TITLE: Rockfall Hazard Identification and Rockfall Protection in The Coastal Zone of Croatia**

- **MAIN PROJECT FIELDS**
- **Technology Development:** Hazard Mapping, Vulnerability and Risk Assessment
- **Targeted Landslides: Mechanisms and Impacts:** Landslides Threatening Heritage Sites
- **Mitigation, Preparedness and Recovery:** Preparedness, Mitigation

2017 ICL-IPL UNESCO Conference, Paris, France, 29 November 2017

Croatian Landslide Group
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- **PROJECT LEADER:**
- **Professor Željko Arbanas,** University of Rijeka, Faculty of Civil Engineering

- **CORE MEMBERS OF THE PROJECT:**
- **Snježana Mihalić Arbanas, professor,** University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering;
- **Vedran Jagodnik, assistant professor,** University of Rijeka, Faculty of Civil Engineering, Croatia;
- **Sanja Dugonjić Jovančević, assistant professor,** University of Rijeka, Faculty of Civil Engineering, Croatia;
- **Marin Sečanj, assistant,** University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

2017 ICL-IPL UNESCO Conference, Paris, France, 29 November 2017

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- **OBJECTIVES:**
- **Study of triggering conditions and rockfall mechanisms and run out paths and processes in carbonate rocks and at along the contacts of carbonate rocks and flysch formations in Croatia;**
- **Modeling of typical historical and recent rockfalls in Croatia: back analyses;**
- **Identification of conditions that influence and cause rockfalls in carbonate rocks and at along the contact of carbonate rocks and flysch formations in Croatia;**
- **Recommendations for rockfall hazard identification and rockfall protection in the coastal zone of Croatia.**
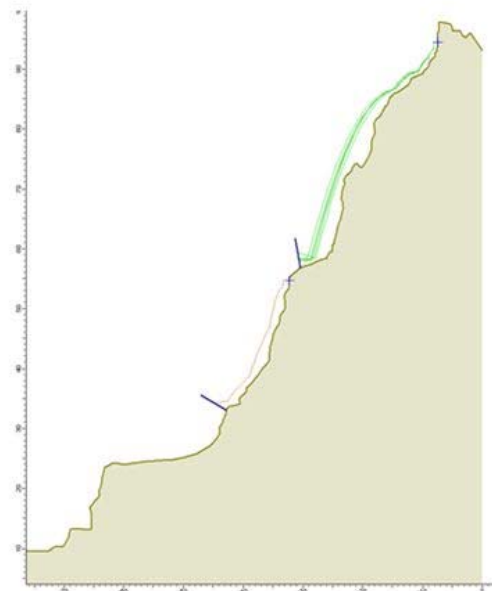
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Croatian Landslide Group
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- PROJECT DESCRIPTION:
- The existing numerous rockfalls in Croatia endangered infrastructure facilities and settlements and towns in the past. There are a lot of still active well known hazardous rockfall phenomena sites that still endanger human lives and structures such as rockfalls above the Town of Omiš in Dalmatia and Grohovo Village near the City of Rijeka; the Raspadalica Cliff above the railway route in Istria, the Stupica location near the road in Dalmatia, the rockfalls below the Trsat Fortress (Rijeka) and Rota Castle (in Istria) cultural heritage sites.
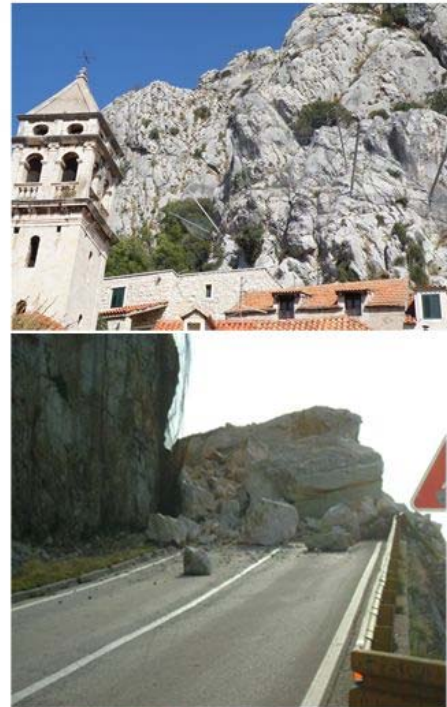
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- **WORK PLAN/EXPECTED RESULTS:**
- **1st phase: Data collection, FIELD INVESTIGATION AND SURVEY.**
- Milestone: Field data base establishment.
- **2nd phase: NUMERICAL MODELING.**
  Milestone: Establishing of typical rockfall models.
- **3rd phase: SPATIAL ANALYSES.**
- Milestone: Rockfall susceptibility and hazard maps for the pilot areas of historical and recent rockfalls in Croatia. Recommendations for rockfall susceptibility and hazard map guides preparation.
- **4th phase: ROCKFALL PROTECTION MEASURES APPLICATION.** Milestone: Assessment of the most effective rockfall protection measures and construction application. Recommendations for rockfall protection measures application guides preparation.
- **5th phase: RESULTS PRESENTATION.** Milestone: presentation of results to the local authorities and stakeholders in the study area.

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University of Zagreb
FACULTY OF MINING, GEOLOGY AND PETROLEUM ENGINEERING

Kostanjek landslide monitoring project (Zagreb, Croatia)

Martin **Krkač**[1], Snježana **Mihalić Arba**nas[1],
Sanja **Bernat Gazibara**[1], Marin **Sečanj**[1], Željko **Arbanas**[2]

(1) University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, Zagreb, Croatia, mkrkac@rgn.hr
(2) University of Rijeka, Faculty of Civil Engineering, Rijeka, Croatia

Project objectives

- development a procedure for prediction of the **Kostanjek landslide** movement in order to mitigate the landslide risks which comprise two steps:

- development of the phenomenological (statistical) model for prediction of landslide movement

- automatization of the landslide prediction process through the development of customized software

University of Zagreb
FACULTY OF MINING, GEOLOGY AND PETROLEUM ENGINEERING

IPL Symposium, Paris, November 29 - December 1, 2017

Kostanjek landslide

- the landslide area is **1 km²**

- the volume of the sliding mass is evaluated to be **32 × 10⁶ m³**

- displaced mass consist of laminated to massive marls

- main cause of sliding: **human activity** (excavation of marl)

- landslide was triggered in 1963
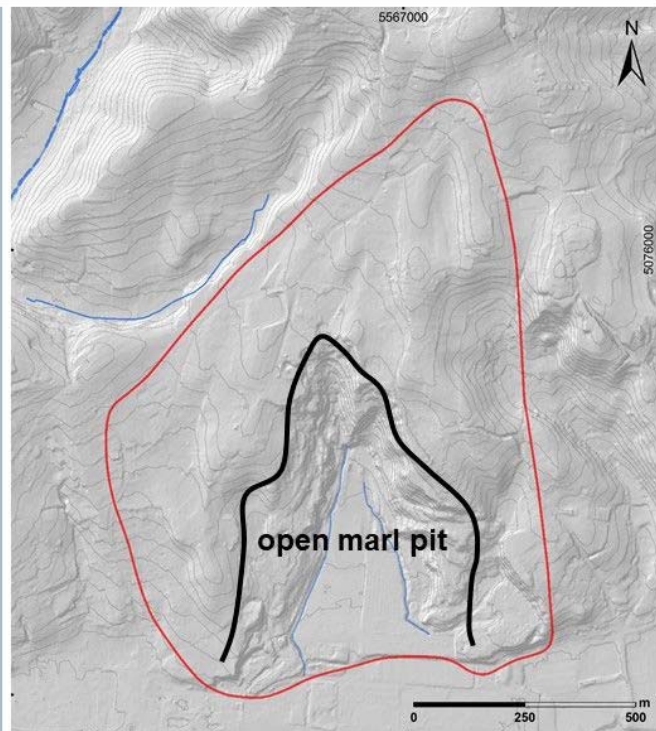
Kostanjek landslide

- **approximately 300 single-family houses** are placed on the moving landslide mass

- **pilot area of the Japanese-Croatian scientific joint-research project** (SATREP Program financed by Japanese Government, 2009-2014)
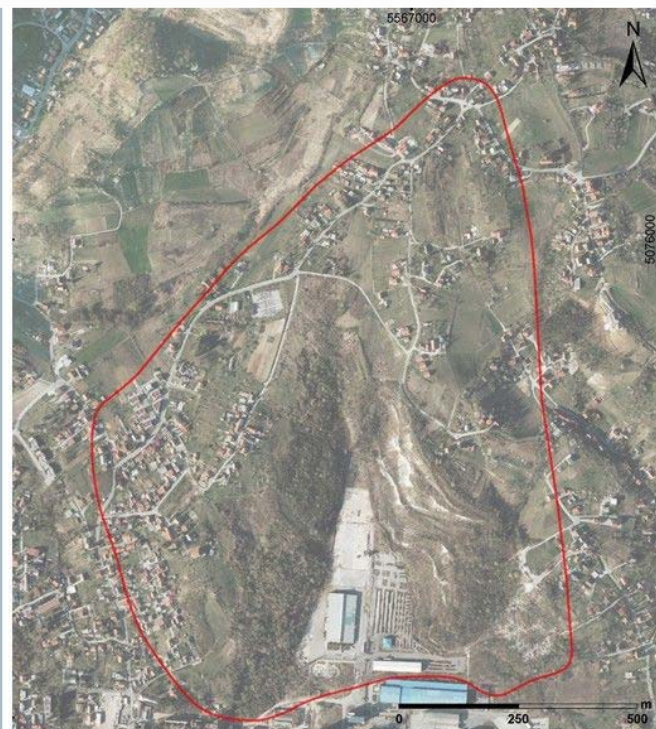
Kostanjek landslide

- **prediction of movements are based on:**

- phenomenological **models established on the basis of 4-year data** series gathered by continuous monitoring of landslide movement groundwater and precipitation

- model are developed with **random forests**, a machine learning algorithm developed by Breiman (2001)
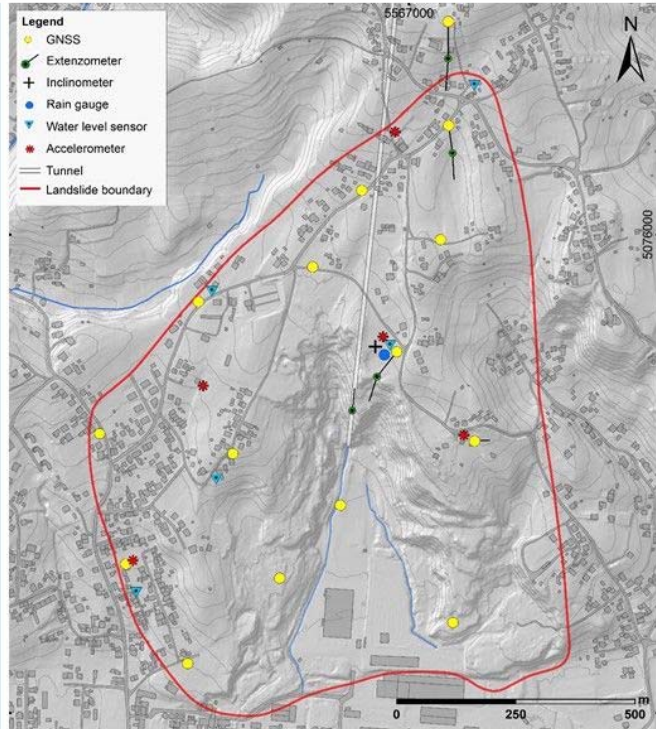
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Random forests

- accurate prediction power, low tendency to overfitting, low computational cost, and the ability to work with very high-dimensional data (Caruana and Niculescu-Mizil 2006; Micheletti et al. 2014)

- all applications of random forests are aimed at landslide susceptibility mapping (Brenning 2005; Stumpf and Kerle 2011; Vorpahl et al. 2012; Catani et al. 2013; Micheletti et al. 2014; Segoni et al. 2014; Goetz et al. 2015; Trigila et al. 2015; Youssef et al. 2015; Pourghasemi and Kerle 2016)

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Combination of radar and optical remote sensing for hazard assessment of the potentially river-damming landslides: cases of the Vakhsh and the Brakhmaputra River basins

Alexander Strom [1] in cooperation with
Andrea Manconi [2] Yueping Yin [3] Nurilo Abdulloev [4]

1) JSC "Hydroproject Institute", Russia
2) ETH Zürich, Switzerland
3) China Geological Survey
4) JSC "Rogun Hydraulic Power Plant", Tajikistan)

Formation and subsequent catastrophic breach of rockslide dams in catchment areas, far upstream of the existing or planned hydraulic project sites can pose a significant threat to these critical facilities if the amount of water that can be released would exceed the storage capacity of the reservoir.

The proposed project is aimed to select sites where such phenomena might occur and to provide initial data for their further monitoring and for elaboration of the reasonable protection and/or prevention measures.

Two regions were selected for such analysis: Vakhsh River basin in Tajikistan where several hydraulic schemes, including the 300 m high Nurek dam (N), are under operation and 335 m high Rogun dam (R) is under construction. Rockslide site is marked.
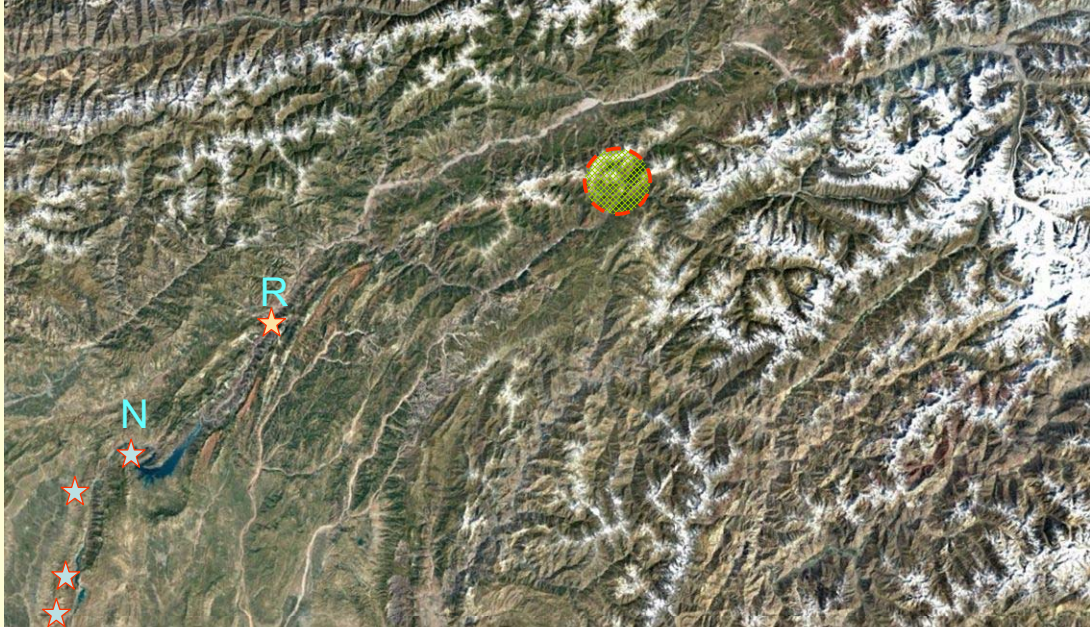
And the Brakhmaputra River basin where the 2000 Yigong disaster (Y) had occurred in China with peak discharge up to 120 000 m³/s and several large hydraulic schemes are planned downstream in India (orange star). Rockslide site is marked.

Considering the remoteness and hard attainability of these regions, identification and the preliminary analysis of the suspicious sites will be performed by combination of optical and radiometric remote sensing data – old and recent aerial and space images and INSAR technology.

Analysis of optical images allows identification of the geomorphic evidence of slope deformations and selection of sites where large-scale catastrophic rockslides might occur in future being triggered by climatic phenomena or earthquakes. Rough estimates of the unstable rock masses volumes, of the parameters of the blockage that could be formed and of the amount of water that could be stored upstream will be provided.

The Ragnow-mouth rockslide in the upper reaches of the Vakhsh River basin, about 150 km upstream of the Rogun dam site.
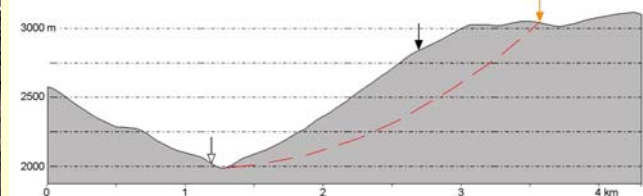
System of fractures on top of the ca. 1 km high slope and schematic profile of the Ragnow River valley

3D Google Earth views

Use of the successive images, if available, is especially efficient since it allows estimates of the character and rate of slope deformations within the time span of several decades.
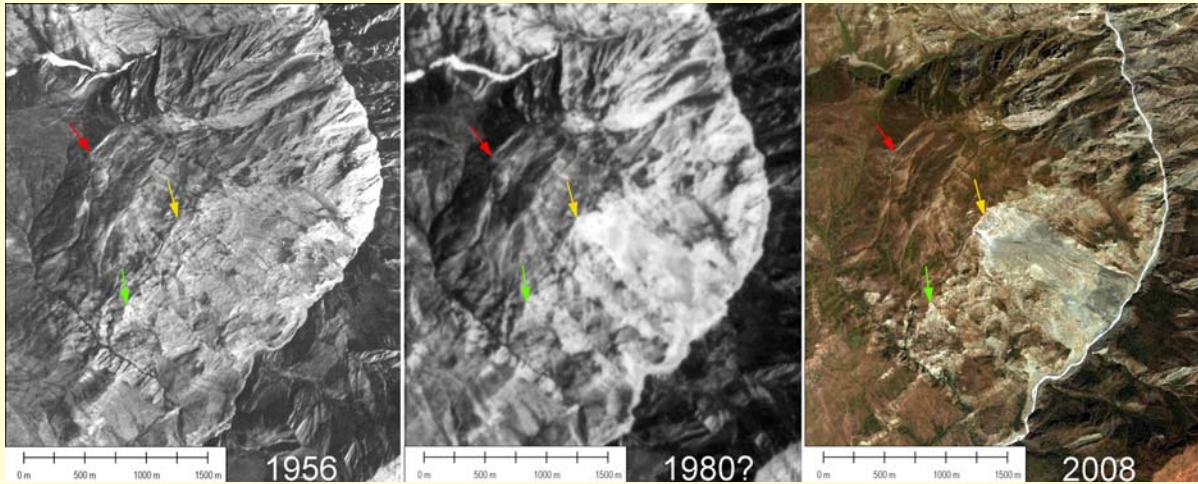
Air photo   KFA Space photo   Google Earth image

Ongoing slope deformations of the 1.5 km high slope in the upper reaches of the Yigong River, about 100 km upstream of the 2000 blockage site.
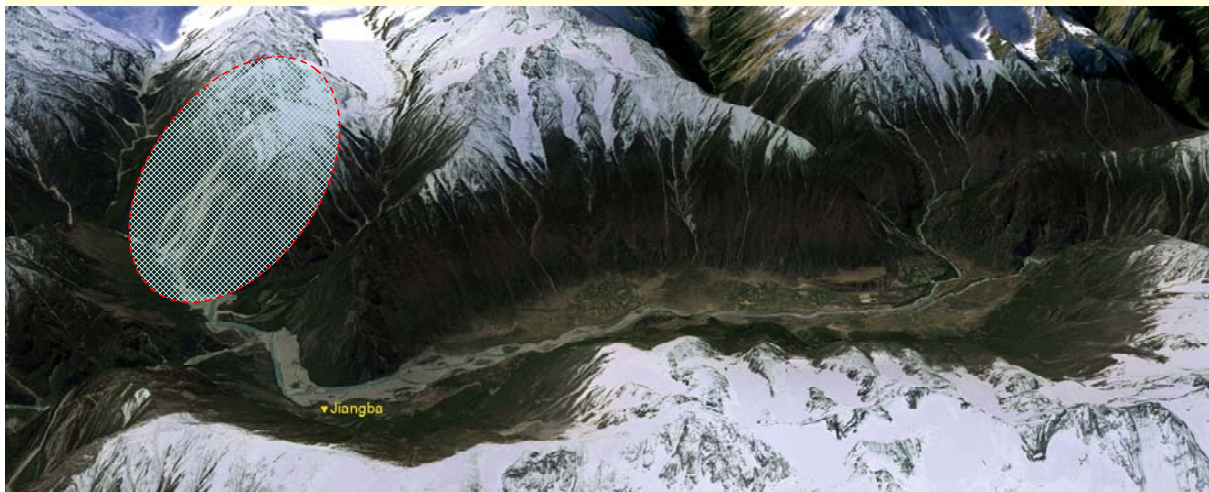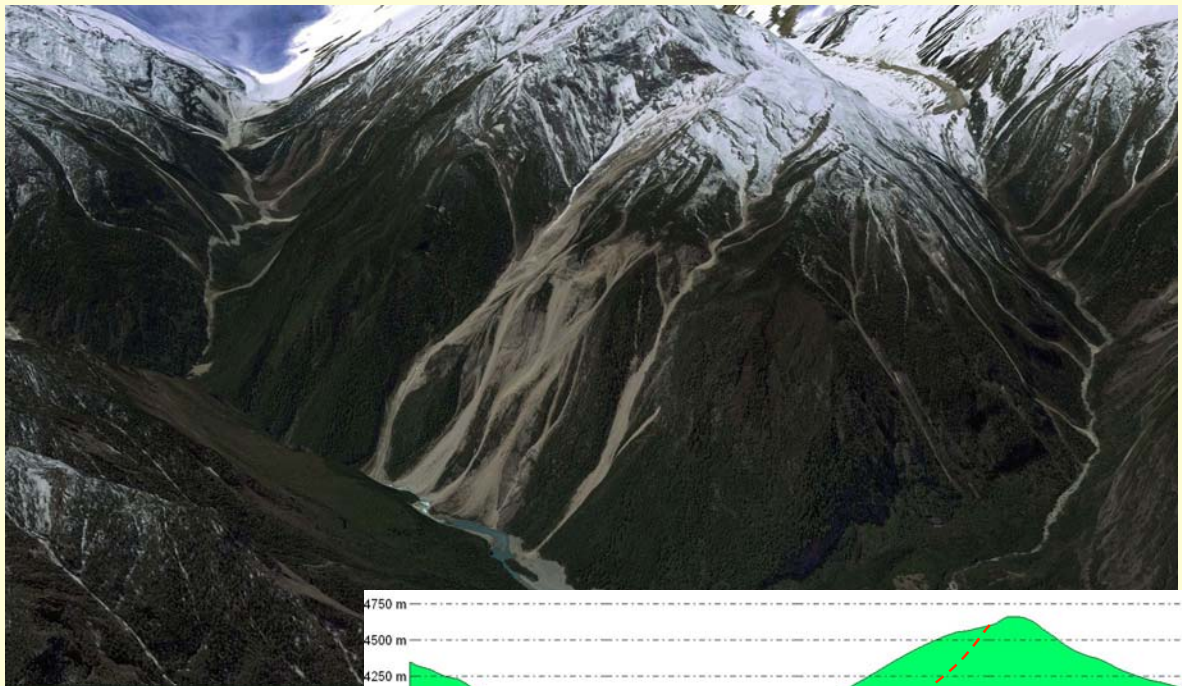
3D Google Earth view of the site and schematic valley profile

Possible dammed lake dimensions

Dams' height ~350 m; Lake volume ~6 km^3

Dams' height ~200 m; Lake volume ~2.2 km^3
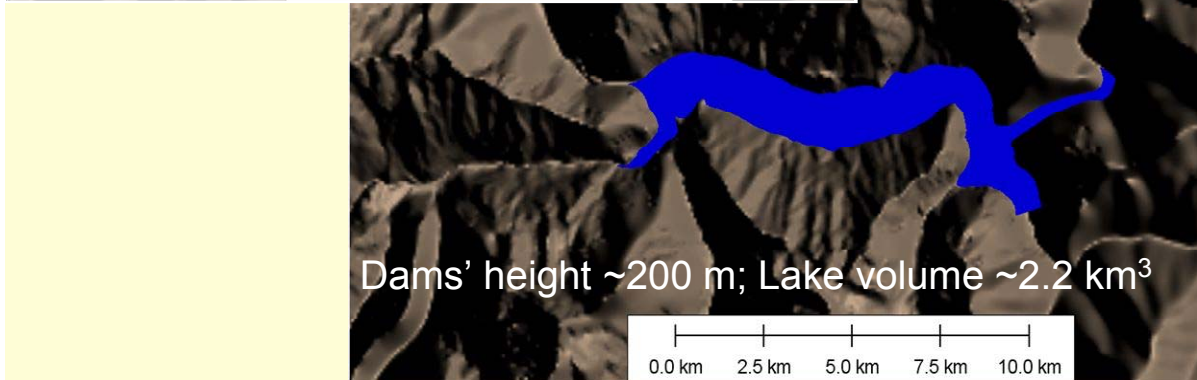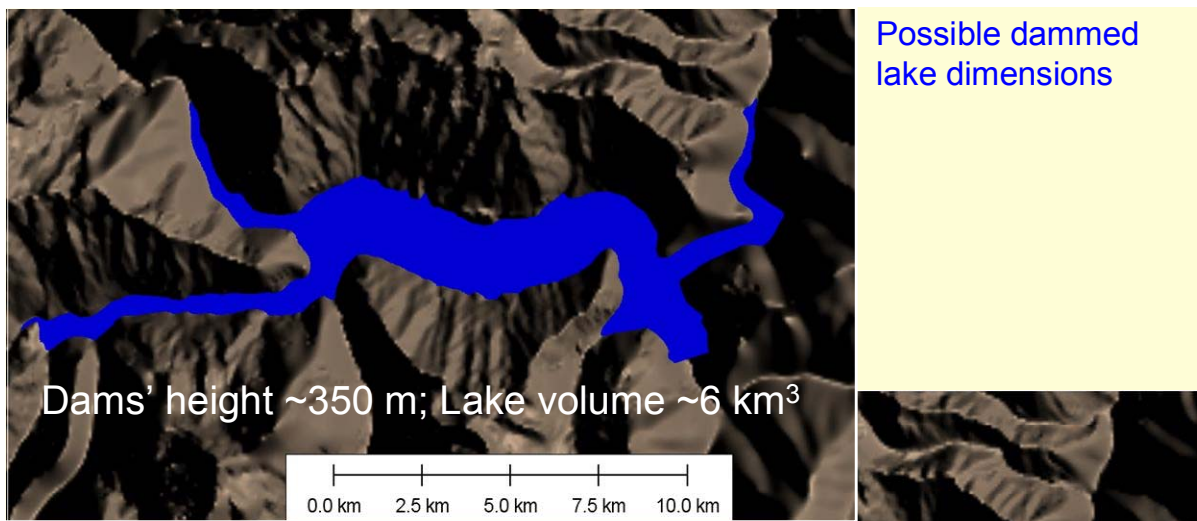
Analysis of radiometric satellite images (INSAR) will provide data on the present-day behavior of the landslide-prone slopes, on the localization and rate of the ongoing slope deformations and will form basics for further monitoring of these potentially hazardous sites.

Preliminary INSAR data on the Ragnow-Mouth area
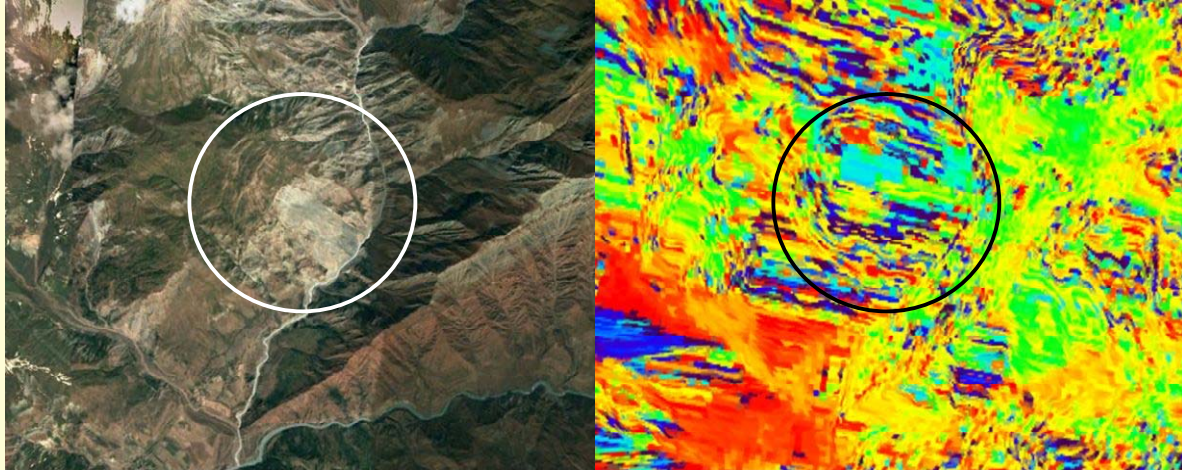
Realization of the proposed IPL Project will provide data that will help owners and designers of the hydraulic projects in the study river basins in Tajikistan, China and India and to emergency agencies responsible for peoples' safety at the local, regional and state levels to estimate hazards caused with large-scale rockslide damming in the catchment areas and related risks with open mind.
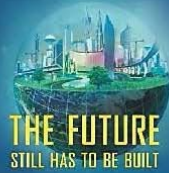
International Programme on Landslides Symposium
UNESCO, Paris, 29 November 2017

Recognition of potentially hazardous torrential fans using geomorphometric methods and simulating fan formation (IPL-225)

M. MIKOŠ, T. PODOBNIKAR, J. SODNIK, M. MAČEK
Faculty of Civil & Geodetic Eng., University of Ljubljana

M. JEMEC AUFLIČ, Geological Survey of Slovenia

Presentation Outline

- **General introduction.**

- **Hypothesis.**

- **Motivation, state-of-the-art, challenges.**

- **Work plan, expected results.**

- **Discussion and general conclusions.**

THE FUTURE STILL HAS TO BE BUILT **UL FGG**   25.10.2017   2

General introduction

- **Basic goal of the proposed project**
  - Automatic determination and classification of torrential fans, with an emphasis on their potential for the development of debris flows in their catchment areas.
- **Definition**
  - Debris flows resulting from torrential events (torrential debris flows)
  - Developed from landslides (slope debris flows)
- **Background for our project**
  - Fans are layers of coarse and poorly sorted debris (rocks, stones, gravel, or sand) at places where debris-flow torrents or rivers exited from narrow valleys into a broader or another valley
  - A fan's conical shape is formed due to a rapid decrease in flow velocity and, consequently, due to lower transport power to continuously transferring debris material

THE FUTURE STILL HAS TO BE BUILT **UL FGG**   25.10.2017   3
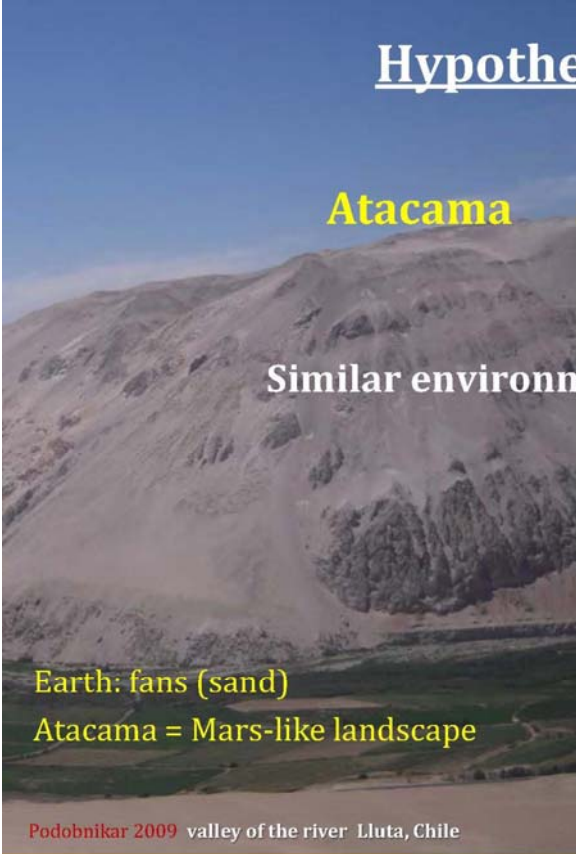
Hypothesis - 1

- **By using a high-resolution DTM, and the characteristic spatial variables (indicators), it is possible to distinguish between torrential fans caused by debris flows and the alluvial fans where debris flows are not expected and where only fluvial torrential processes take place**

- **Comparison of two completely different methodological approaches, i.e. the geomorphometrical analyses and the simulations of fan formation on the basis of mathematical modelling to simulate the triggering and movement of debris flows will accelerate the search for optimal solutions**
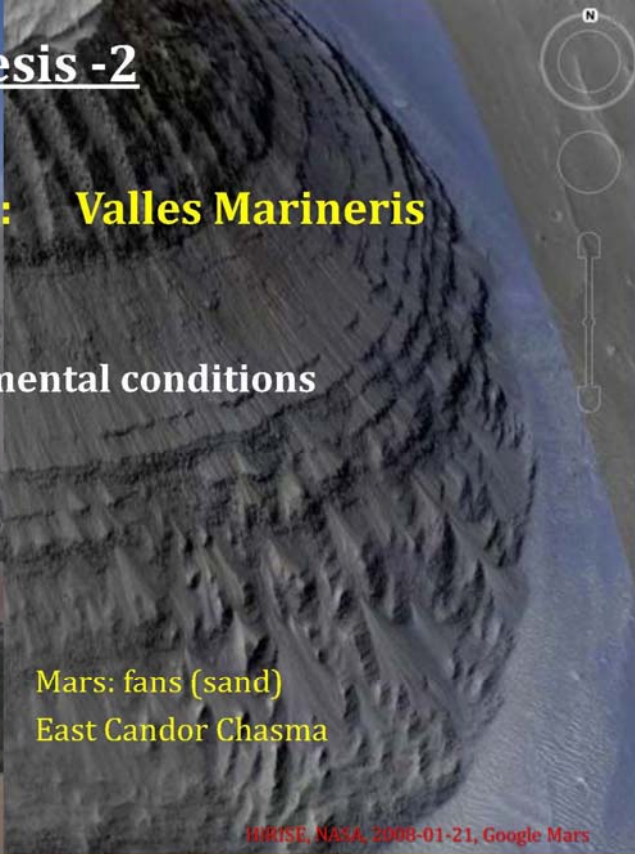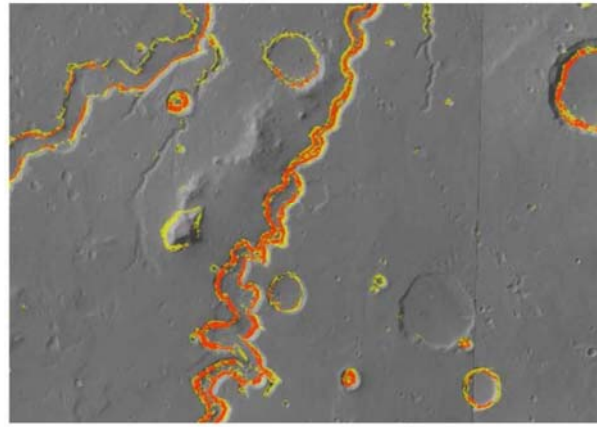
THE FUTURE STILL HAS TO BE BUILT **UL FGG**   25.10.2017   4

Project study area

▪ **Selected torrential fans in Slovenia to develop the model and the Sava Dolinka River valley in NW Slovenia**

(Geo)morphometric methodological approach

▪ **The study will based on:**

  – **Developing and realisation of different geomorphometric methods**

  – **Innovative indicators**

  – **Prediction with specific approaches**

    • **raster and object**

    • **empiric, geostatistic, including machine learning approach**

    • **multi-scale**

Work plan, expected results - 1

- **WP I Project management:**
  - Task (1) Interim reports and a final report.
  - Task (2) Addressing practical issues arising from the project.
- **WP II Spatial data acquisition and pre-processing:**
  - Task (1) DTM and DSM acquisition, quality control, gross and systematic error removal, improving quality.
  - Task (2) Obtaining other information about the fans (based on fieldwork, geological maps, etc.).
  - Task (3) Data homogenization.

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Work plan, expected results – 2

- **WP III Geomorphometric analysis for fan determination:**
  - Task (1) Classic geomorphological fan mapping in selected areas, and field sedimentological inventory to define the fan's genesis; selection of key geomorphological characteristics of certain fan types.
  - Task (2) Processing variables (factors) for geomorphometric analysis.
  - Task (3) Analysis/modelling with spatial data, rheological information, and other relevant descriptive information.
  - Task (4) Comparison of the classical and developed methodology results.

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Work plan, expected results - 3

- **WP IV Applying the mathematical model to simulate triggering and movement of debris flows:**
  - Task (1) Application of 2D debris-flow models (RAMMS, triggering phase: LS-RAPID).
  - Task (2) Soil samples rheological analysis using large rheometer ConTec Viscometer 5.
  - Task (3) A comparison of both groups of analysis and a sensitivity analysis.
  - Task (4) Comparison of geomorphometric analysis and numerical simulations of the formation of torrential fans.

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Challenge: different quality, multi-resolution DTMs

Sava Dolinka River valley, Slovenia

DTM 12.5 (GURS)

same resolution

Lidar DTM, resampled to 12.5 m (Flycom)

resampling

Lidar DTM 1 m (Flycom)

THE FUTURE STILL HAS TO BE BUILT **UL FGG**   25.10.2017   14
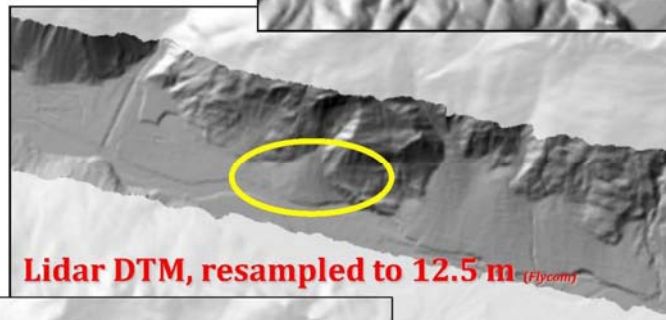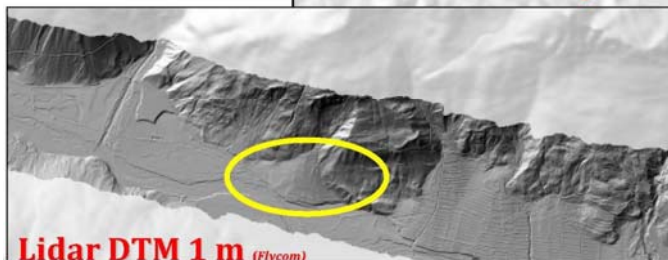
Discussion & general conclusions

- **Fan's surfaces can be automatically detected: expert knowledge + predictive modelling**
- **Balance between robust and sensitive geomorphometric methods vs. problems with different aspects of the DTM quality and uncertainties**
- **The proposed methodology needs to be tested in other test sites with known debris-flow historical records, and then applied as a tool for debris-flow hazard assessment and mitigation on a national or regional level (large scale) together with debris-flow susceptibility models**

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Discussion & general conclusions

- **There is a twin IPL-226 project, proposed by the Geological Survey of Slovenia (GeoZS) entitled: „Studying landslide movements from source areas to zone of deposition using a deterministic approach", where UL FGG is a core member of the project.**
- **Both projects are financed by the Slovenian Research Agency for 3 years & by 100 k€ per annum: J7-8273 (IPL-225) & J1-8153 (IPL-226), running from May 2017 to April 2020.**

THE FUTURE STILL HAS TO BE BUILT **UL FGG**   25.10.2017   16

International Programme on Landslides
UNESCO, Paris, 29 November 2017

Studying landslide movements from source areas to zone of deposition using a deterministic approach (IPL-226)

M. Jemec Auflič, T. Peternel, J. Jež, M. Janža

Geological Survey of Slovenia

M. Mikoš

Faculty of Civil & Geodetic Eng., University of Ljubljana

Contents

- Objectives

- Problem identification

- Study area

- Work Plan/Expected Results

- Project Beneficiaries

- Conclusions

2

Objectives

- Low speed landslides may cause failure of structures but are not usually dangerous for humans. While a highspeed, long-runout and wide-spreading landslides may cause a greater disaster.

- To reduce human loss from landslides and assess landslide hazard the following questions are pursued:

    - **where** can landslides occur (place of origin),

    - **when** (rheological properties of material, rainfall),

    - **how** extensive can they be (magnitude), and

    - **where** can landslides act (place of action)?

GeoZS
Geološki zavod
Slovenije

3

Objectives

- Developing a interdisciplinary methodology for risk assessment of landslides and debris flows, which will include

    - landslide origin (source areas) modelling,

    - assessment of deposition volume,

    - determination of rheological characteristics of the material, and

    - modeling of the runout distance and the zone of deposition.

GeoZS
Geološki zavod
Slovenije

4

Problem identification

- This IPL project is focused on **landslide investigations, deposition areas**, and the **geomechanical** and **rheological conditions** required for **mobilization** into a **debris flow**.

- The **landslide and debris flow origin** (source areas) was **determined** by previous studies using **spatiotemporal factors**.

- **Rainfall, velocity, volume** of deposit, **sliding**/flow **path**, and **deposition area** were not yet considered in studying the **dynamics of the landslide**.

GeoZS
Geološki zavod
Slovenije
5

Problem identification

- The following **key parameters** will be studied:
    - geological structure,
    - slope inclination (relief),
    - geomechanical characteristics of the soil,
    - catchment area of surface water and groundwater,
    - rainfall threshold.

GeoZS
Geološki zavod
Slovenije
6
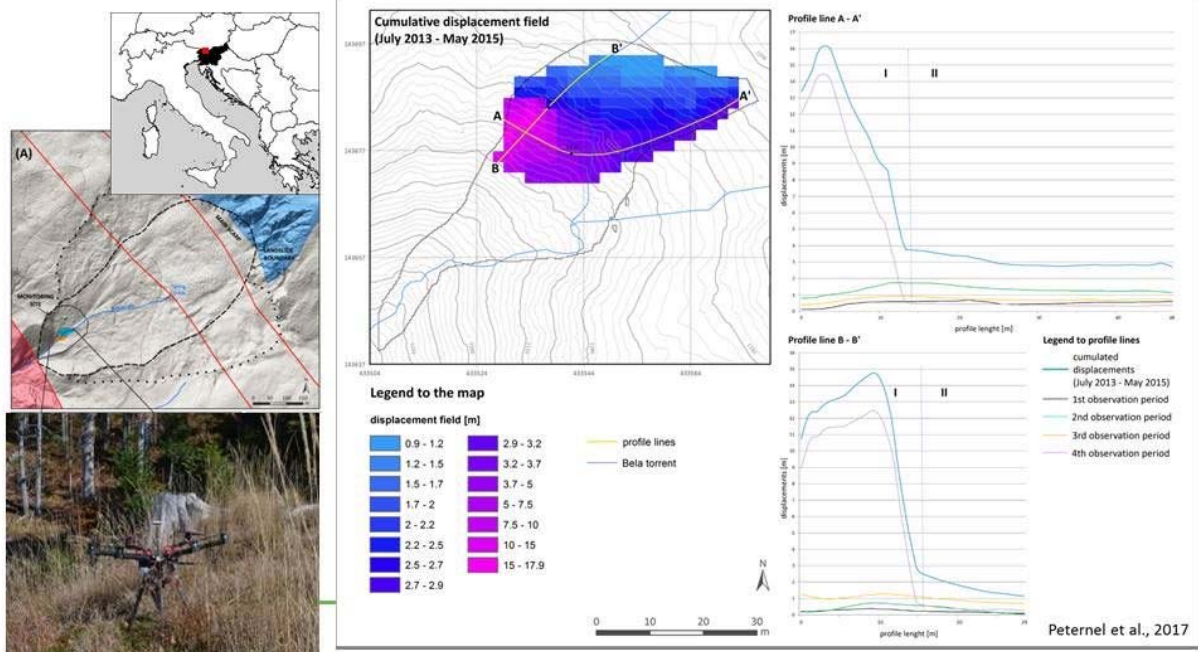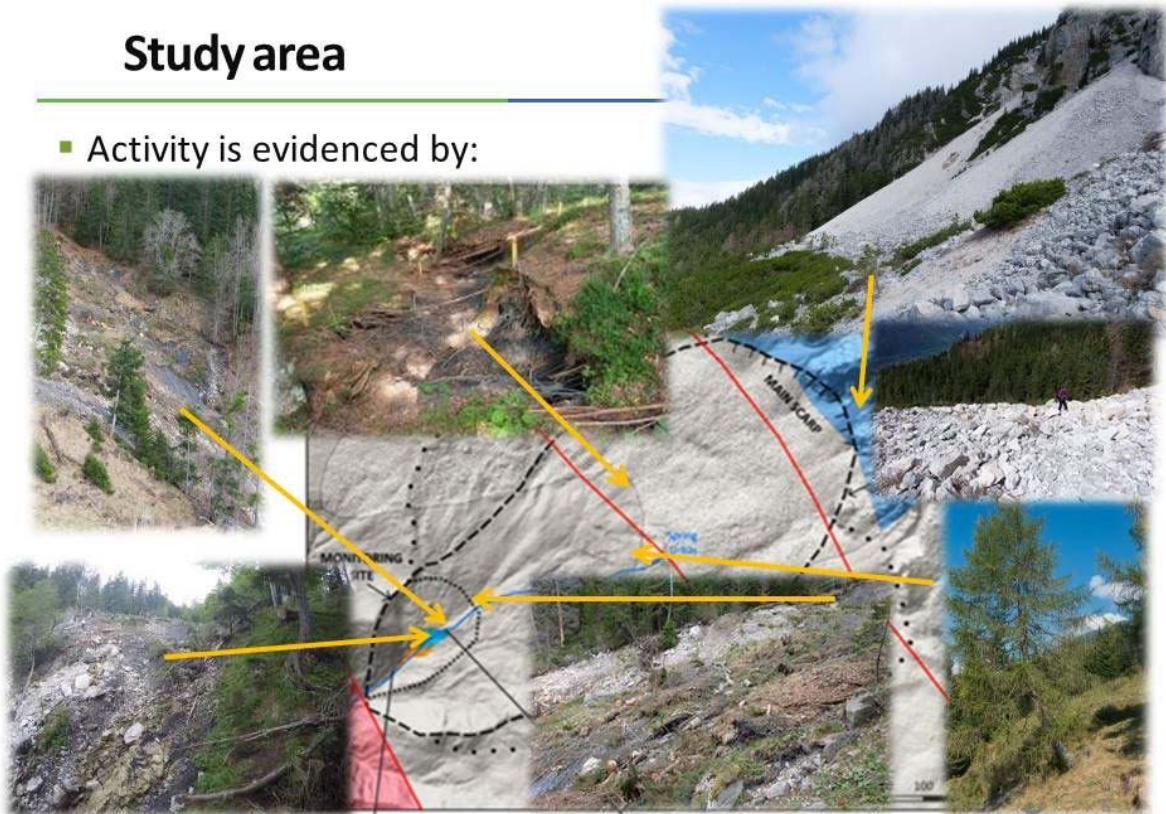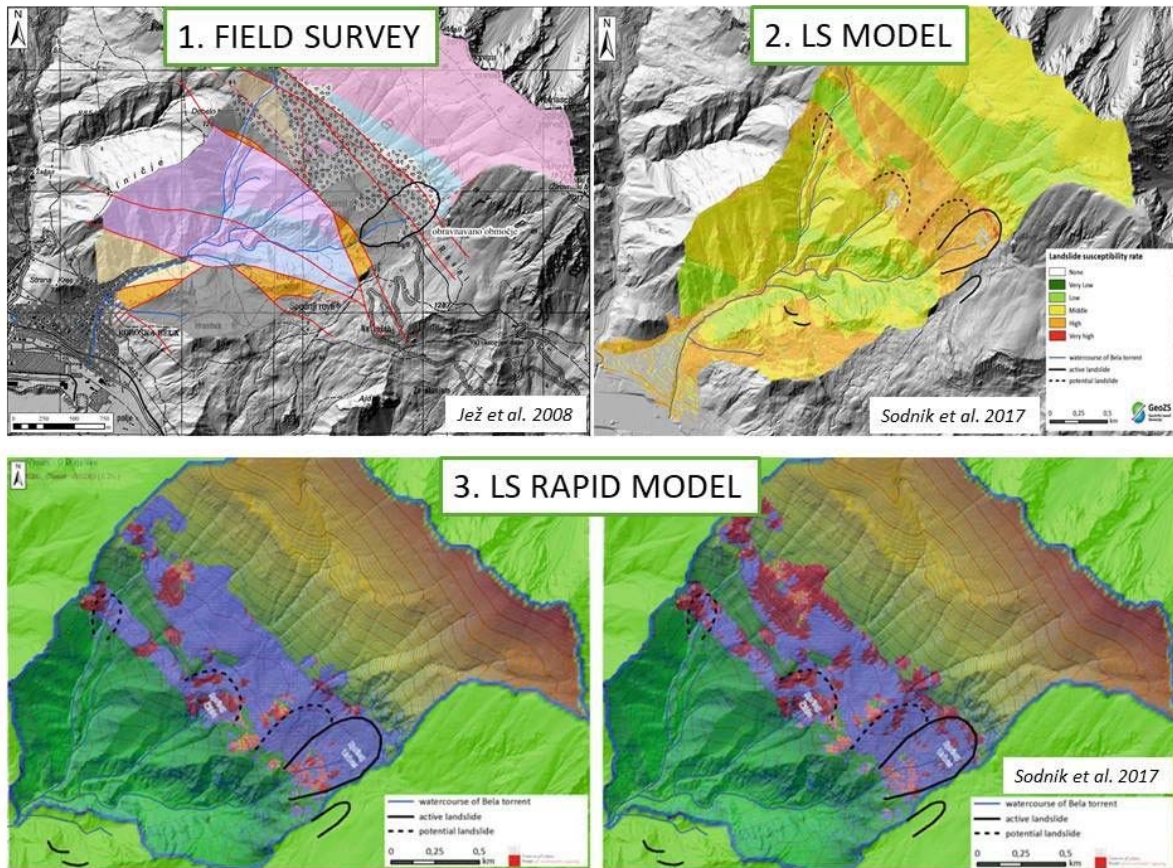
Study area

- Village of Koroška Bela that lies on the alluvial fan with more than 2,200 inhabitants

- Maximum flow depths of potential debris flow on Koroška Bela fan (Sodnik et al., 2012)
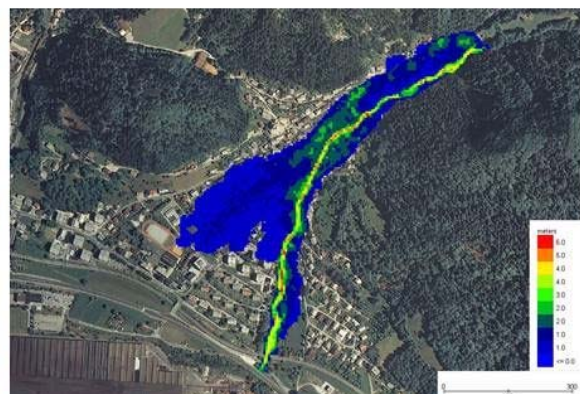
Work Plan/Expected Results 1

▪ **WP1 Geological, geomorphological, geophysical, geotechnical and hydrogeological investigations in pilot areas**

- Geological mapping of the Stože landslide and the wider Koroška Bela catchment
- Shallow excavation, boreholes and sampling
- Lithological and geomechanical characteristics of material
- Geophysical measurements
- Hydrogeological measurements (infiltration, groundwater table)

▪ **WP2 Rheological investigations of materials in pilot areas**

- Rheological characteristics of the material

GeoZS
Geološki zavod
Slovenije

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Work Plan/Expected Results 2

▪ **WP3 Analytical and model-based prediction of landslide movements**

- Geological maps of the Stože landslide and the wider Koroška Bela catchment
- Landslide source area identification using LiDAR-derived DEMs
- Hydrological modeling
- Impact of rainfall on landslide prediction models
- Modelling of landslide initiation, movement, and spreading (LS-RAPID)
- Modelling landslide volume (Flo-2D)

GeoZS
Geološki zavod
Slovenije

12

Work Plan/Expected Results 3

- **WP4 3D landslide hazard maps**
  - Determination of a conceptual model for hazard maps
  - 3D landslide hazard maps in different scales

- **WP5 Project management and reports**
  - Project management
  - Intermediate annual reports and final report
  - Dissemination

GeoZS
Geološki zavod
Slovenije

13

Project Beneficiaries

- The results concerning the volume and deposition modelling will provide:
  - an effective tool for the work of Civil Protection when dealing with landslides,
  - improving the existing or creating a new Early Warning System (EWS),
  - creating risk assessments of unpredicted natural disasters,
  - basis for spatial planning and proper placement of infrastructures in relation to potential risks due to landslides and debris flows.

GeoZS
Geološki zavod
Slovenije

14

Conclusions

- The integration of different disciplines has a prospect for effective solving of problems related to landsliding.

- Another goal is the transferability of the achieved results and methodology used, so that they can be applied to other areas where similar problems occur.

- Experience and modeling results will globally enable the improvement of software models for prediction of landslide source areas and their dynamic (as for example LS-Rapid).

GeoZS
Geološki zavod
Slovenije

15

Conclusions

- Project is financed by the Slovenian Research Agency, approved in 2017, the total project budget is 300.000 EUR (J1-8153).

- Project duration 3 years (1 May 2017 – 30 April, 2020).

- Participating institution: Faculty of Civil & Geodetic Eng., University of Ljubljana (UL FGG).

GeoZS
Geološki zavod
Slovenije

16

Development of a Web Based Landslide Information System for the Landslides in Sri Lanka

K. M. Weerasinghe[1], J. M. K. Herath[1], K. B. Attapattu[1], A. A. Virajh Dias[1]

(1) Centre for Research & Development (CRD), Central Engineering Consultancy Bureau, No. 11, Jawatta Road, Colombo 05, Sri Lanka, kmweera@yahoo.com

Objectives

The objective of this research is to develop a web based database on landslides for Sri Lanka by collecting information through online tools such as 'Google alert' (https:/www.google.com/alerts), other available databases (www.desinventar.lk) and field verification, and organizing the data in an user friendly manner.

Background

❖ Landslide information have been collected, at one's desired level, for several decades.
❖ Since they are not shared, those who require landslide related information for decision making or for further research often face difficulties.
❖ The Des Inventar database published by the Disaster Management Center of Sri Lanka (www.desinventar.lk) is the only online disaster database available in the country.
❖ In there also, landslide related information have not been updated after the year 2011.
❖ Therefore, development of an online comprehensive landslide database has become a timely necessity.

Study Area

Mountainous area of Sri Lanka covering the Central, Sabaragamuwa, Uva, Western and Southern administrative provinces.

cec | LANDSLIDE INFORMATION SYSTEM

Home   Statistics   NRM&LS

Click the a district to view details

Country profile at a glance

Number of major landslides	1000
Number of deaths	3000
Number of houses destroyed	500
Number of families affected	50000
Length of roads affected	750 km

District Profile

District	Number of major slides
Badulla	150
Galle	20
Hambantota	10
Kalutara	75
Kandy	90
Kegalle	85
Kurunegala	10
Matale	70
Matara	25
Monaragala	15
Nuwara Eliya	250
Ratnapura	200

Technical and non technical details

Pahiyangala (Jayalathgoda) landslide

Location	
District	Kalutara
DS Division	Bulathsinhala
GN Division	Niggaha
GN Code	823 A
Coordinates	6°38'52.08"N 80°12'54.00"E

Date and time of Occurrence	
Date	26th May, 2017
Time	4:20 Hrs

Type	Landslide

Triggered by	Heavy rainfall

Extent of landslide (approx.)
Scarp

Height	15 m
Width	60 m
Length of debris deposit	400 m
Affected area	0.3 ha

Damage

Deaths	23
Wounded	None
Houses destroyed	05

Other damages:
Additional 03 houses in Jayalathgoda had been partially damaged. The debris had completely dammed the Nagahadola, crating huge flood impact in Yatagampitiya village on the opposite bank. As a results another 3 lives had been lost. 11 houses, and tea plantation had been destroyed. Several persons had been wounded.
Properties at Risk:
Yatagampitiya – Amaragoda road and houses are at risk.

Variations in Monthly rainfall

Source: Department of Meteorology

Sample No	Description	Depth	Cohesion (kPa)	Ǿ$_d$ Deg.
S1/R/3	Weak soil pre-determined shear plane	4.5	0	21^0

Deliverables/Time Frame

February 2018:   Mysql database on landslide information available at CECB
August 2018:   Preliminary user interface for retrieving landslide information
February 2019:   Improved user interface for retrieving landslide information
August 2019:   Improved user interface with basic tools for data analyses at the users' end, Enriched database with appropriate legend for representing different accuracy levels
February 2020:   Launching beta version of the landslide information system
August 2020:   Launching final version of the comprehensive landslide information system

Estimated Cost

Item	Description of Personnel and Facilities	Cost USD	Mode of Contribution
1	Database server and associated peripherals	200.00	By CECB
2	Field data collection	2,500.00	By CECB
3	Dissemination of Information	3,000.00	Research grant
	Total USD	5,700.00	
	Total grantee contribution (USD)	2,700.00	By CECB
	Total expected through funding (USD)	**3,000.00**	**Through a grant**

Project Beneficiaries

The landslide professionals, academics, researchers, planners and people residing in landslide prone areas in Sri Lanka are the beneficiaries of this project.

LANDSLIDE SUSCEPTIBILITY MAP OF DURRES AND KAVAJA REGION, ALBANIA

By

Hasan Kuliçi[1], Olgert Jaupaj[1], Mentor Lamaj[1]

1) Albanian Geological Survey, address "Myslym Keta", hkulici@yahoo.com

Introduction

Landslide susceptibility is useful tool in urban planning, specifically for the definition of the land use zones and for the design of future construction projects and is very necessary due to the strong impact of landslide processes on people and their goods

Abstract

➢ The study area is prone to landslides due to geological features, diverse terrain topography, high intensity spring-autumn rainfall, deep weathering associated with the humid climate and man-modified slopes

➢ In the study area 157 landslides are described and the heuristic approach is used to obtain the Landslide Susceptibility Map.

➢ On the basis of these results, recommendations about landslide risk are given to take into account landslides in the land-use planning

GEOGRAPHY OF STUDY AREA
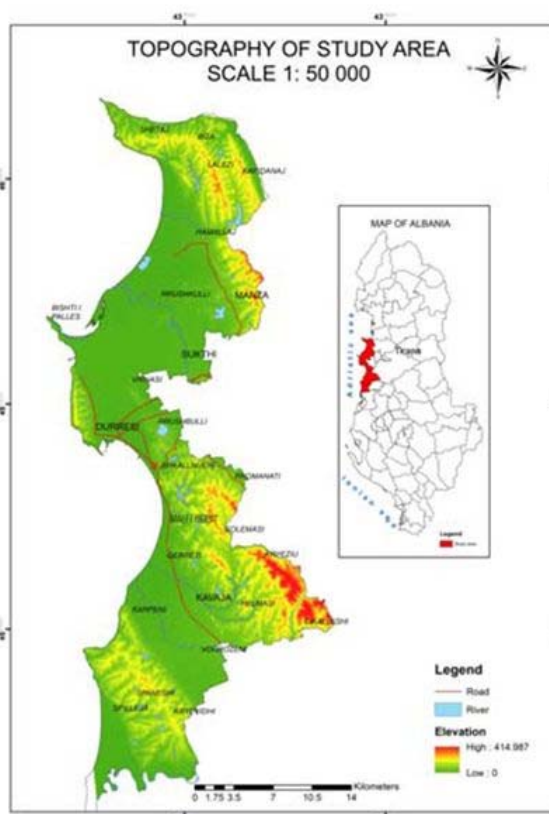
Geographically, the study area is located in central-western part of Albania between latitudes 40° 59' 59" to 41° 35' 14"North, and longitudes 19° 23' 25 " to 19° 42' 14"East.

This area represents anticline structures. The elevation ranges from 0 to 414.9 m above sea level, while the annual rainfall is around 1100 mm/Year.

The study area is about 619 km2 and belongs to Kavaja district. An estimated 250 000 people live and work in this area.

GEOLOGY OF STUDY AREA

GEOLOGY MAP OF STUDY AREA
SCALE 1: 50 000
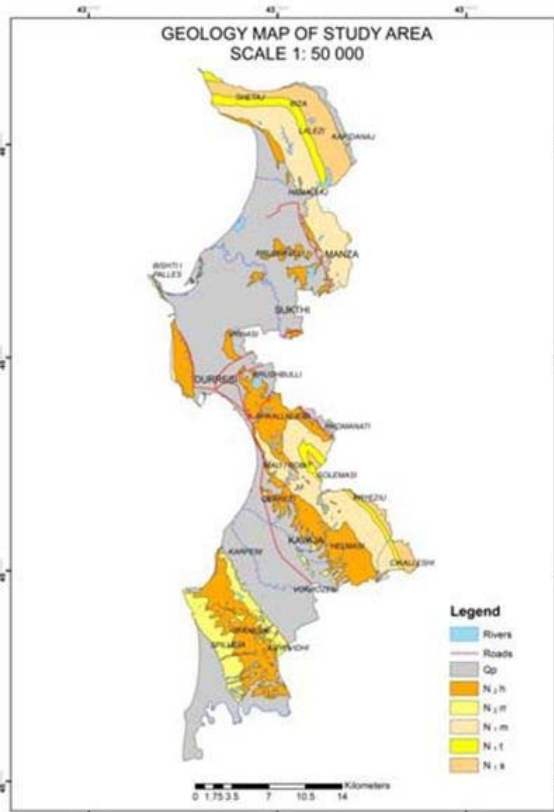
This area, which belongs to pre-Adriatic depression of Albania geological terrains consists entirely of molassic formations which lie transgressively on underlying formations of the Ionian and Kruja zones.

The main geological formations that crop out in the Kavaja region are represented by:

a) **Quaternary deposits:** consist of clay, sandy clay, silt, silty sand, sand, gravel

b) Pliocene molasses

c) Mesinian molasses

d) Tortonian molasses

e) Serravalian molasses

PLIOCENE MOLASSES

HELMASI FORMATION (N$_2$H)

The molasses of this formation are represented by massive clay with very rare sandstone layers and constitute the core of the anticlines. Their thickness is over 1 000 m

Rrogozhina formation (N$_2$R):

Molasses of this formation constitute the syncline structures.
This formation is divided into three layers from the bottom to the top:
N$_2$R (a) - clays, siltstone. Thickness 250m.
N$_2$R (b) – siltstone - sandstone, Thickness 50 to 100 m.
N$_2$R (c) - mostly conglomerate and sandstone. Thickness 300m

Messinian N₁m

Mesinian depositions continue stratigraphicaly up to Tortonian. The molasses of this formation are represented by sandstone intercalated with argillite layers.. Their thickness is over 1 100 m

Tortonian N₁t

Tortonian depositions in generally continue normally up to Serevalian and are represented by masive sandstone. Thickness 700m

Serravalian N₁s

Serravalian formations are represented by massive clays. This depositions are divided in three packets starting form bottom to top their thickness is over 1750m

MATERIALS AND METHODOLOGY

➤ Data collection.

➤ Selection of the landslide causative factors on the basis of previous fieldwork survey and landslide inventory analysis in the study area.

➤Evaluation of the role of landslide causative factors in the study area and preparation of the input factor maps for landslide susceptibility mapping.

➤ Apply heuristic approach for deriving landslide susceptibility map of the study area.

➤Based on the final map of the study area, recommendations are given on the landslide hazard prevention measures in order to help the local community to be prepared and to respond adequately to disasters.

DATA COLLECTION

Archive data: Gathering all information from Central Archive of **Albanian Geological Survey**

Field surveys: Looking new landslides, evaluate the landslide evolution, present state and activity

Interpretation of landslide occurrences from aerial photographs according with field verification.

LANDSLIDE INVENTORY

Around 157 landslides are observed in this area. This study was carried out from the project Landslide Inventory Map of Albania, in order to reduce the landslide risk

Nr in landslide inventory	Y	X	AzimutH	Location
1	4551566	4376010	179	Adhjare, Kryevidh, Kavaje
2	4551700	4376006	355	Adhjare, Kryevidh, Kavaje
3	4551681	4376227	30	Adhjare, Kryevidh, Kavaje
4	4551564	4376395	5	Adhjare, Kryevidh, Kavaje
5	4551552	4376774	311	Kryevidh
6	4551687	4376891	280	Kryevidh
7	4551862	4376555	247	Kryevidh
8	4552112	4376515	302	Kryevidh
9	4552229	4376669	284	Kryevidh
10	4552607	4376553	233	Kryevidh
11	4552655	4376546	36	Kryevidh
12	4552891	4376367	267	Kryevidh
13	4553129	4376253	185	Kryevidh
14	4553134	4376131	343	Kryevidh
15	4553004	4375751	330	Kryevidh
16	4552927	4375622	355	Kryevidh
17	4552772	4375597	265	Kryevidh
18	4552801	4375626	88	Kryevidh
19	4552889	4375773	204	Kryevidh
20	4553263	4376614	173	Kryevidh

| PROJECT 2010-20014 | **Title:** Compilation of the landslides susceptibility map, for the whole territory of Albania at scale 1:200.000 based on the regional maps at scale 1:50.000. | Albanian Geological Survey Department of enginering geology, geophysic, geodesy | Author: Mimoza Jusufati, Mentor Lamaj, Edlira Plaku, Albert Avxhiu |

| Alphanumeric code | | | | | | Landslide ID | 1 | 1 |

GENERAL INFORMATION

Date of report:	Location	
	Region:	Province:
Reporter's Name:	Municipality:	
Public istitution:	The coordinates of the crown	X-	Y-
Topographic Map, scale:	Nomenklatura	Place name:

Landslide Geometry

Crown elevation (m):	Horizontal length L(m) :	Total area (m²):
Toe elevation (m):	Length La (m):	Volume of displaced material. (m³):
Slope angle (°):	Depth of surface of rupture. (m):	Azimut:

GEOLOGY

Geology of the body to move					Geology of the plan skates					Geology of the immovable foundations		
O	Magmatic rock	O	Debris		Description by (C)		Description by (φ)			Struktura	O	Magmatic
O	Carbonates	O	The compressed	O	Cohesive soil	O	< 10°	O	Massiv	O	Carbonates
O	Sandstone rock	O	Un compresed	O	Soft cohesive soil	O	10 - 15°	O	monoclinal	O	stratified
O	Clayey rock	O	Cohesive soil	O	Without cohesion	O	>15°	O	Sinclinal	O	sandstone
O	Evaporate	O	Without compresio n	Note:				O	anticlinal	O	average clay
O	Breccia	O	Organic soil					O	tectonic	O	The soft clay
O	Deluvium							O	with cracks	O	conglomerate
O	Eluvium	O	Very wide (>2 m)	O	Close (0.06 – 0.2 m)			O	friable	O	chaotic
O	Clay	O	Wide (0.6 – 2 m)	O	Very close (<0.06 m)			O	caotice	O	Evaporate
O	Debris	O	Moderate (0.2 – 0.6 m)	O	without gaps						

Joint spacing

Morfology data

Drejtimi i renies se shtresave		Pershkrimi i shpatit			Klasifikimi i territorit				Shkalla e errozionit	
O	Horizontal	Crown		Toe	O	Urbane areas	O	Dam	O	Hight
O	vertical	O	>45°	O	O	Road	O	Fruit trees	O	moderate
O	Paralel to slope	O	30 – 45°	O	O	House	O	Arable land	O	weak
O	The opposite slope	O	15 – 30°	O	O	Mineral deposit	O	Forest tree	Shenim:
O	transverse	O	5 – 15°	O	O	Water bodies	O	Natural grassland	

HYDROGEOLOGY

Superficial water	O	Absent	Spring	O	Absent	Groundwater	N.U.N.
Distance from slide body			Distance from slide (m):			Rock complex	
flow (l/min):			Prurjet (l/min):			Quaternary cover	

Rainfall

| O | 649-1060 | O | 1061-1471 | O | 1472-1883 | O | 1884-2294 | O | 2295-2705 | O | 2706-3117 |

Engineering geology data

Type of moviment		State		Distribution		Material		Water content	
O	flow	O	active	O	Moving	O	Rock	O	Dry
O	slide	O	reactiv	O	Enlarging	O	Debris	O	Moist
O	Rock fall	O	suspended	O	I izoluar	O	earth	O	Very wet
O	tooples	O		Worked					

ALBANIAN LANDSLIDE DATA SHEET

LANDSLIDE OCCURRENCE MAP

Landslide Occurrence Map
Scale 1: 50 000

Legend
— Roads
— Rivers
— Landslides

Kilometers
0 1.75 3.5   7   10.5   14
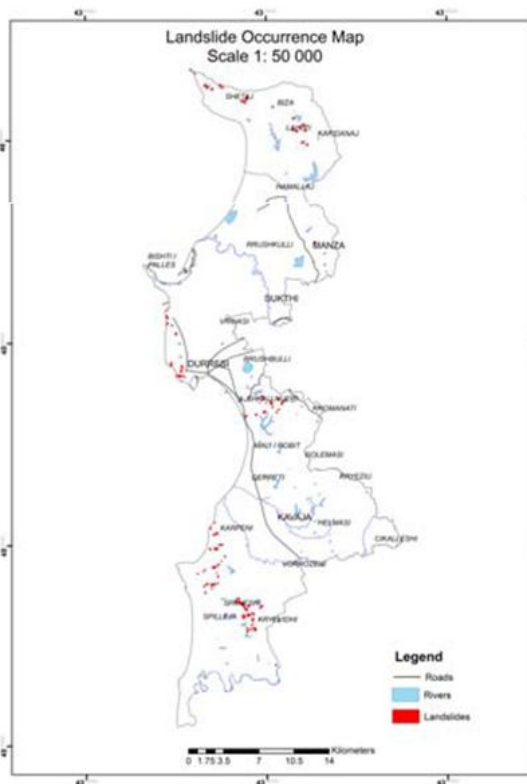
Based on the analysis of the landslide inventory and field work, three major types of slope movements can be identified:

1. Rotational landslides, which occur principally in Quaternaty deposits and Helmasi formation

2. Translational landslides, We can find this type of landslides in Kryevidhi hills in the Rrogozhina formations and in Tortonian mollases

3. Earth flows are a rapid or slower movement of plastic, clayey earth. These are usually associated with heavy rains and occur. This types of landslide occur in Helmasi formation and Serravalian formations

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LANDSLIDE INFLUENCING DATA LAYERS

GEOLOGICAL FACTOR

Geology	Nr_Ls	Lsarea Km^2	Area %	Area Km^2	Sip ne %	Wij
Qph	6	0.01	1	318.58	52	1
N$_2$h	93	1.06	59	113.43	19	5
N$_2$r	19	0.14	8	31.57	5	4
N$_1$m	11	0.15	8	96.38	16	2
N$_1$t	11	0.18	10	21.28	3	2
N$_1$s	17	0.27	15	37.88	6	3
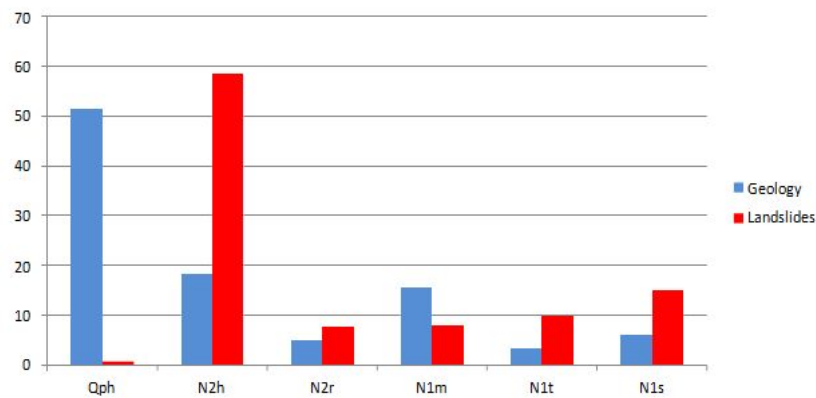
SLOPE FACTOR

Slope Angle	Nr_Ls	Ls area Km^2	Area %	Area Km^2	Sip ne %	Wij
0°-10°	55	0.29	15.93	448.47	73.21	3
10°-20°	94	1.31	71.97	142.24	23.22	5
20°-25°	5	0.14	7.69	17.68	2.89	4
25°-30°	1	0.08	4.40	3.85	0.63	2
30°-40°	1	0.00	0.01	0.48	0.08	1
>40°	1	0.00	0.00	0.00	0.00	1
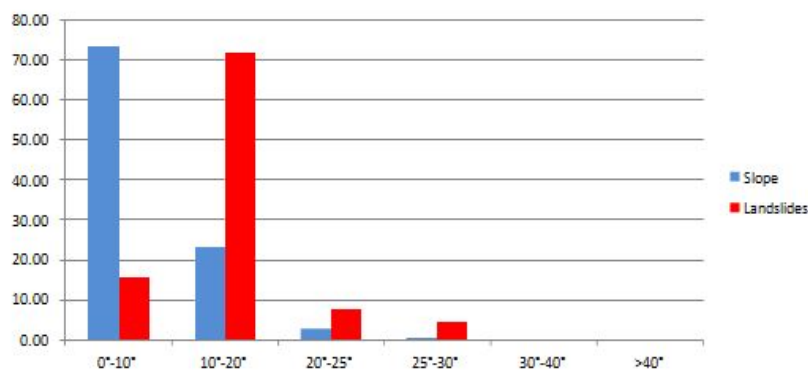
ASPECT FACTOR

Aspect	Nr_Ls	Ls area Km^2	Area %	Area Km^2	Sip ne %	Wij
Flat	0	0.00	0.00	47.08	7.69	0
North	11	0.26	14.28	65.71	10.73	2
Northeast	18	0.15	8.05	68.21	11.13	2
East	19	0.23	12.75	71.21	11.62	3
South	27	0.30	16.40	75.04	12.25	4
Southeast	20	0.22	12.32	71.18	11.62	2
Southwest	26	0.34	18.85	67.03	10.94	5
Northwest	11	0.15	8.47	72.92	11.90	1
West	16	0.16	8.89	74.21	12.11	2
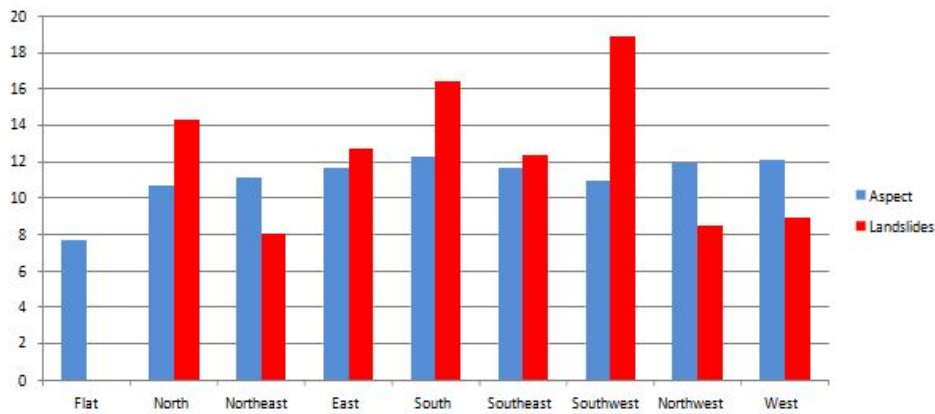
LAND-USE FACTOR

Landuse	Nr_Ls	Ls area Km2	Area %	Area Km2	Sip ne %	Wij
Agriculture area	67	0.59	32.60	337.70	54.6	3
Forest	9	0.29	15.98	120.91	19.6	2
Urban area	46	0.45	24.76	79.88	12.9	3
Not forested	27	0.29	16.16	53.33	8.6	4
water body	0	0.00	0.00	9.70	1.6	1
Shrub	8	0.19	10.50	16.76	2.7	5
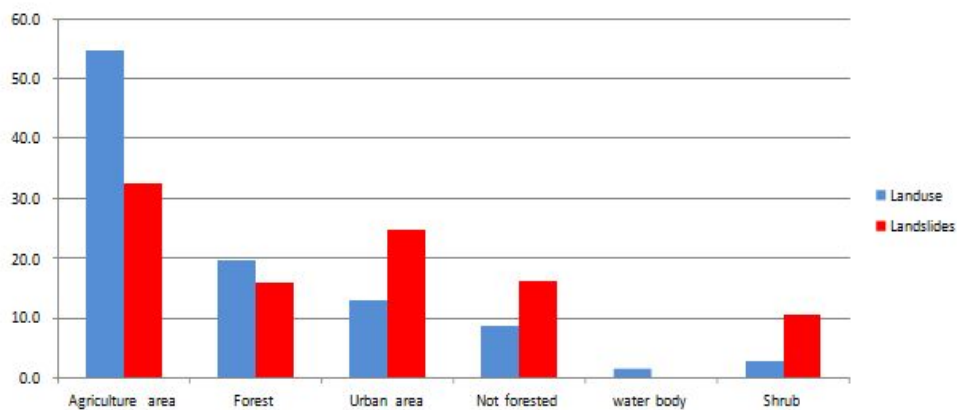
INDEX-BASED METHOD (IBM)

For this study heuristic approach or **Index-Based Method** (IBM) is used. This approach uses a simple ranking and rating technique for landslide susceptibility zonation. for this study 4 factor were considered : geology, slope, aspect and land use which are chosen after a careful bibliographical review and field investigations

The relative importance of each parameter map for slope instability is evaluated according to subjective experts' knowledge. In this way, we assigned weights for all subclasses in each parameter. The weight of subclasses range from 1 to 5, where 1 represents the lowest influence and 5 indicates the highest impact on the landslide hazard

All Wij layers for all the causative factors created in Arc_GIS are summed in raster calculator in Arc_GIS to obtain landslides susceptibility index map .

Index-based Method (Ibm)
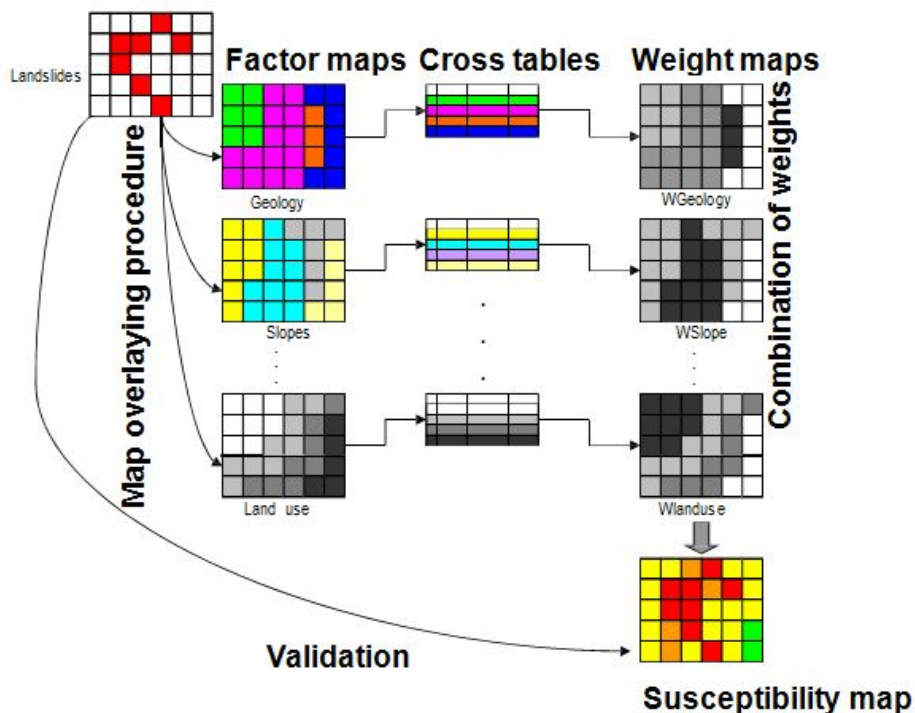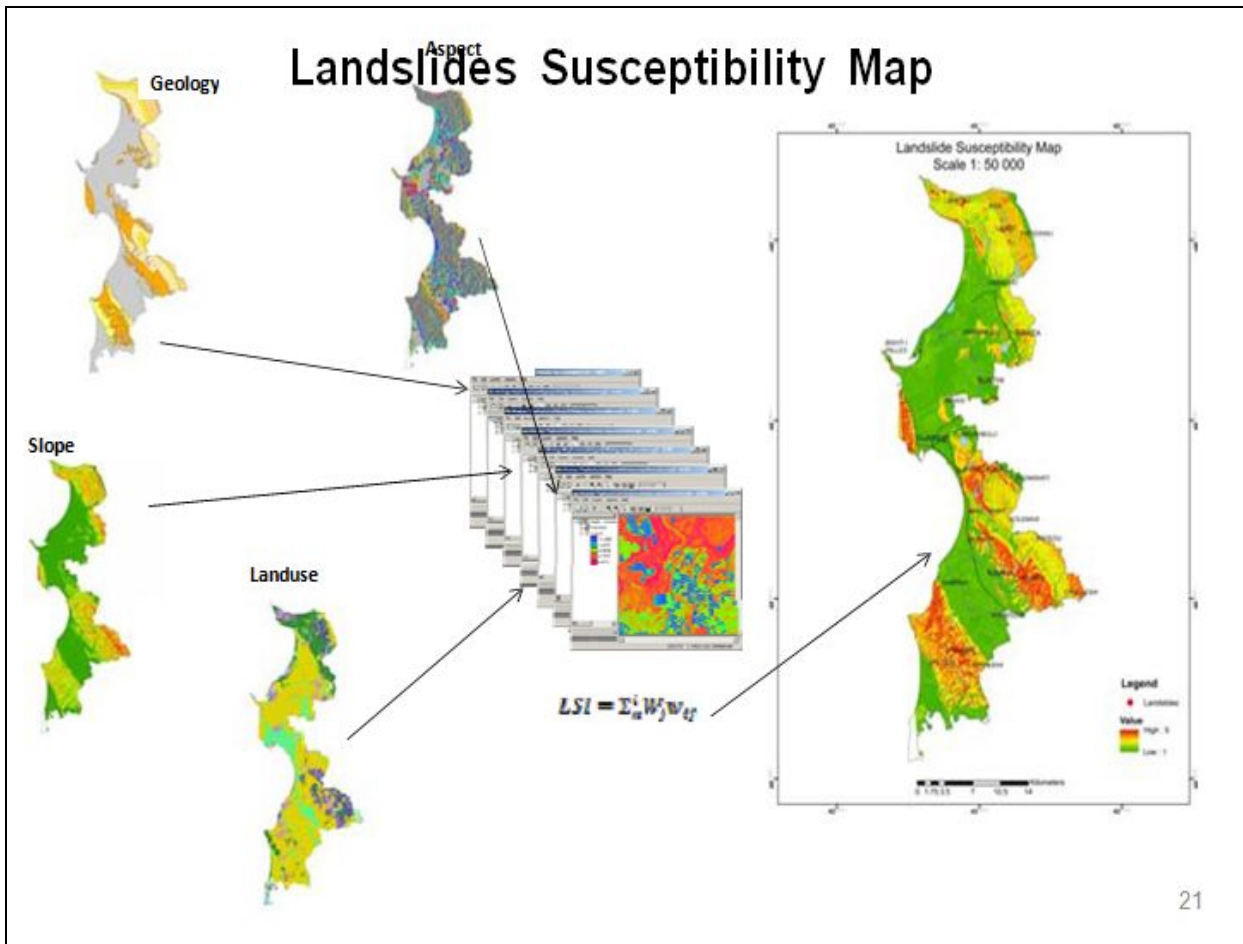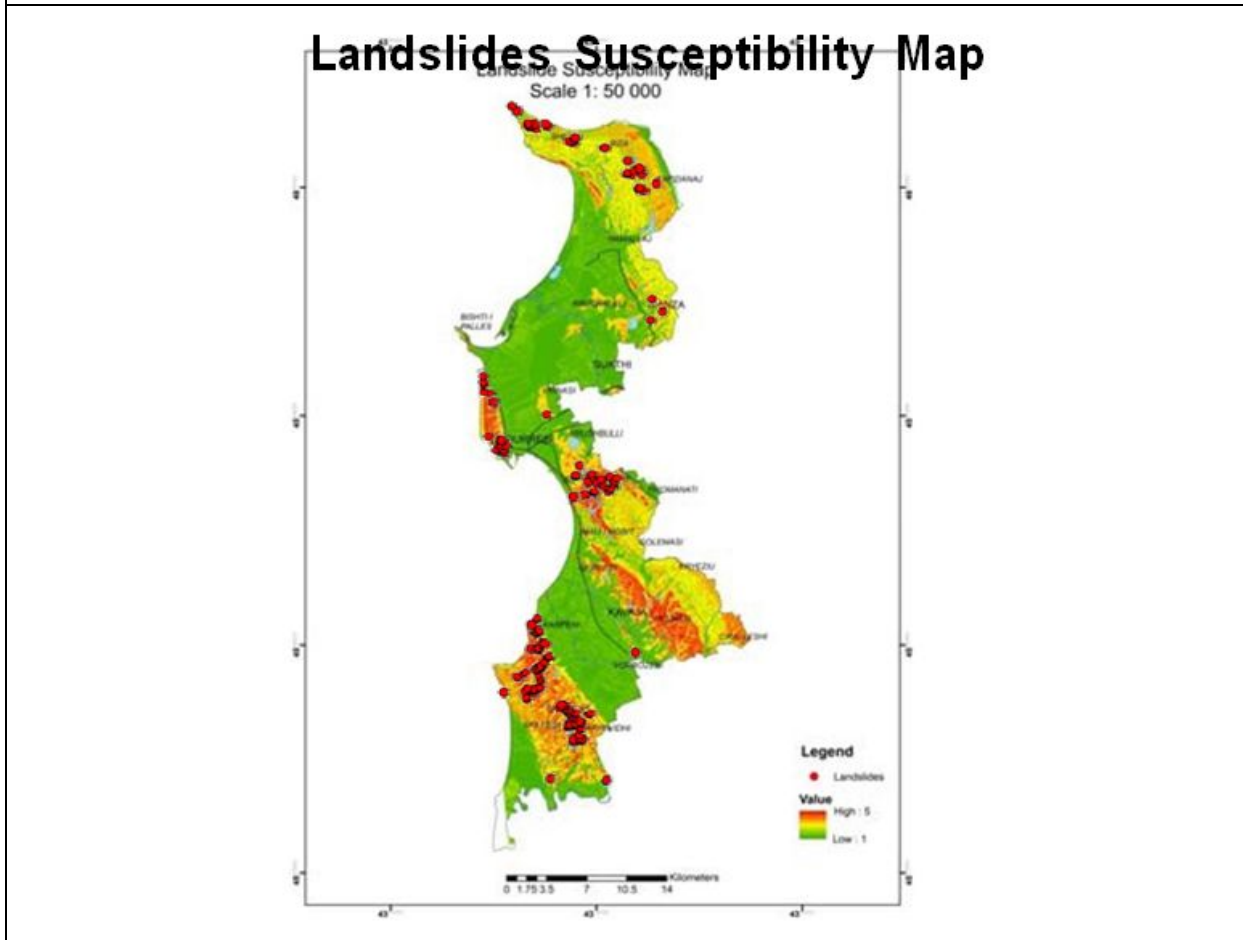
CONCLUSIONS

$N_2^1 h(c)$ and $N_2^t rr(a)$ formation are more favorable for land sliding compared to the other geological formations.

Analysis shows that slopes from 10˚-25˚ are prone to landsliding. It is a fact that fewer landslides occur on mild and steep slope angles

Southwest facing slope and Southfacing slope are more favorable for landsliding compared to the other slope aspect.

Urban area and non forested area are more prone to landsliding compared to the other landuse because human activities and modification of the landscape play an important roles in triggering landslides.

FUTURE WORKS

Extend the susceptibility map of this study area to all the territory of Albania with similar geological conditions as Kavaja which can provide useful information for government in order to develop policies for landslide reduction, buildings codes and land-use planning

Preparation of hazards maps from susceptibility maps

Vulnerability assessment of elements at risk in this study area as a pilot-project in order to prepare risk map

Objectives

- To strengthen the <u>IPL</u> through new approaches for hazard and risk mapping and their proper communication to the local communities.
- Contribute for the <u>Global Network</u> through maintaining the world wide **databases of glacial lake outburst floods (GLOFs)** and establish new world wide **database of giant landslides on oceanic island volcanoes**.
- To meet the <u>Sendai Partnership</u> mainly in analysis of combined effects of **landslide triggering factors**, and with open communication with society through integrated research and capacity building (e.g. in Peru, Ethiopia and recently opened cooperation in Colombia).

Landslide hazard research - Location of the study site and other slope failures on the south-facing slope of the Krušné Hory Mts.
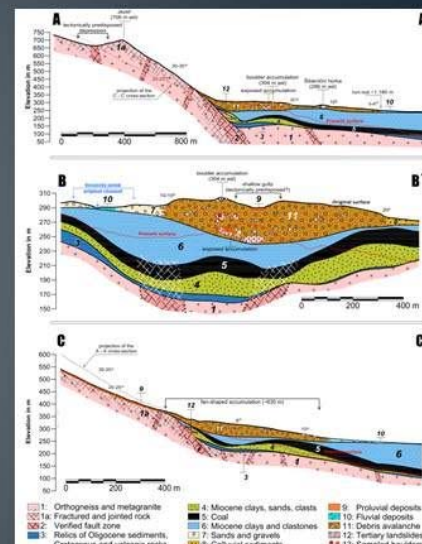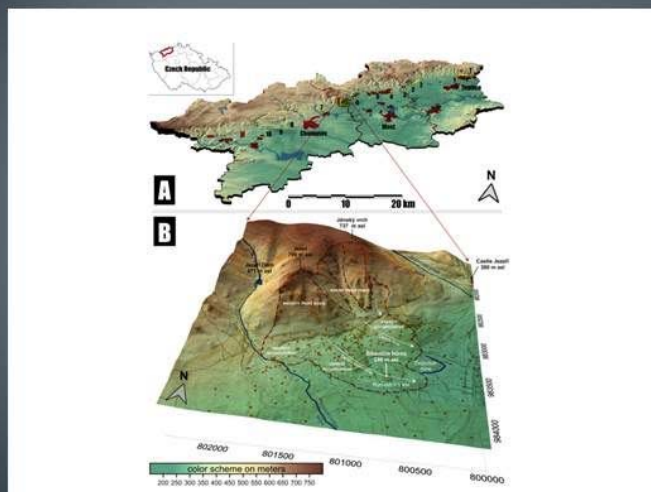
The gneiss block was separated along a tectonically predisposed plane or bedding planes and then the rocksliding occurred. The accumulation toe reached up to 1,200 m from the mountain foothills due to the rolling motion .
(Burda et al., online first)

Landslide hazard research - Reconstruction of the Quaternary deposit from the boreholes

216 boreholes drilled between 1950 and 2008.
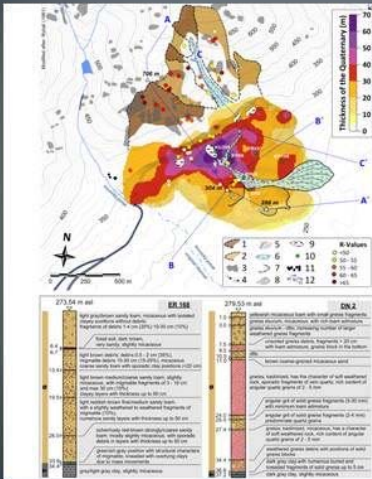
	Váně (1960)	Špůrek (1974)	Marek (1979)	Rybář (1981)	Růžičková et al. (1984)*
Total volume:	-	17 - 20 mil. m³	> 20 mil. m³	26.9 mil m³	17 - 20 mil. m³
Total surface:	-	635 000 m²	-	-	635 000 m²
Accumulation length:	~ 1 000 m	1 000 and 500 m	1 150 m	-	-
Accumulation width:	~ 1 200 m	350 and 300 m	~ 950 m	-	-
Max. thickness:	70.2 m	70 m (ø 47 m)	up to 75 m	70 m	70 m (ø 47 m)
Altitude at crown:	706 m a.s.l.	684 m a.s.l.	738.4 m a.s.l.	730 m a.s.l.	-
Classification:	Rockslide	Two debris flows	Rockslide	Rockfall	Large toppling
Type of movement:	Sliding of a large gneiss block along bedding planes	First rocksliding along bedding planes changing into rolling	Gravitational spreading passing to rocksliding	-	large block separation and its overtopping during the movement activity
Age:	-	Pleistocene	Pleistocene	Pleistocene (Würm)	Pleistocene (stadial)

The main landslide morphometric characteristics

Burda J, Veselý M., Řehoř M., Vilímek V. (on-line first): Reconstruction of a large run-out landslide in the Krušné hory Mts. (Czech Republic). **Landslides**

Cooperation between two WCoE in Prague and Florence: The database of 51 cases of landslide dams in the Cordillera Blanca, Peru
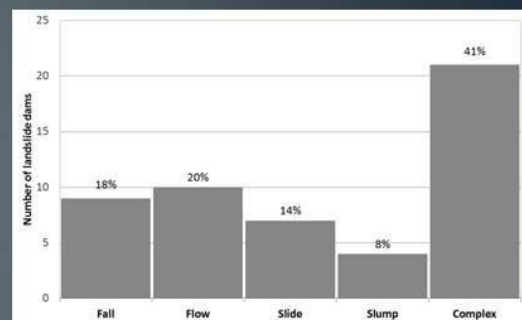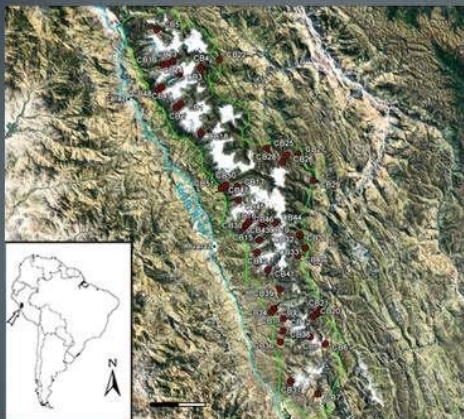
The results of the Cordillera Blanca analysis has been compared with a large Italian landslide dam inventory

Tacconi C., Vilímek V., Emmer A., Catani F. (on-line first): Morphological analysis and features of the landslide dams in the Cordillera Blanca. **Landslides**

Cooperation between two WCoE in Prague and Florence: landslide formed-stable dams from the
Cordillera Blanca have a slightly different distribution
and are more shifted toward instability.
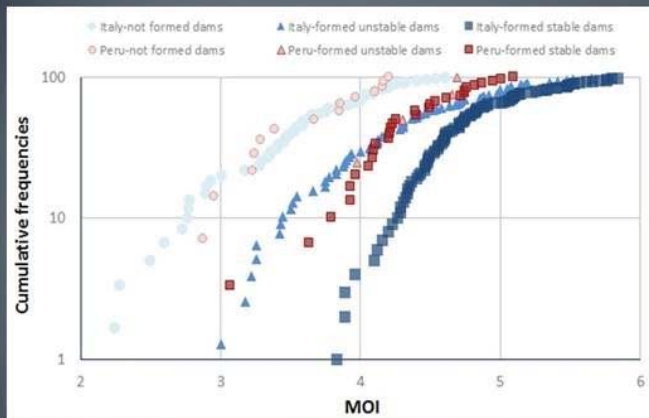
Nevertheless high similarity between the results of the geomorphological indexes application on datasets coming from different geographical contexts (Italy and Peru), is an encouraging result for the indexes reliability.

Tacconi C., Vilímek V., Emmer A., Catani F. (on-line first): Morphological analysis and features of the landslide dams in the Cordillera Blanca. **Landslides**

Project: „Landslide research for **risk reduction** and climate change adaptation in high mountain environments of Peru", 2016 - 2017

Aims:
- **Communication** of the landslide hazard to the local inhabitants
- Landslide **risk mapping**
- **Civil protection** plan
- Landslide **monitoring**

Joint project:

Location of the landslide monitoring sites operated by the WCoE in the Czech Republic (Klimeš et al., 2017)

Data source	2011	2012	2013	2014	2015	Dated/Total
Web	22	10	27	16	14	89/121
Roads	N.A.	60	94	51	39	244/244
Survey	8	2	163	4	0	177/473

Number of landslides detected by web search „Web" (Klimeš et al., 2017, Landslides)

Series of documentary movies initiated by the IRSM as a part of Strategy 21: dissemination of scientific knowledge to help the society

3 parts finished (landslides, earthquakes, space threats), 2 more in preparation

Public projection of Norwegian catastrophic movie „The Wave" followed by discussion with Norwegian and Czech researchers

Giant landslides on oceanic island volcanoes – Atlantic Ocean (IPL 212)
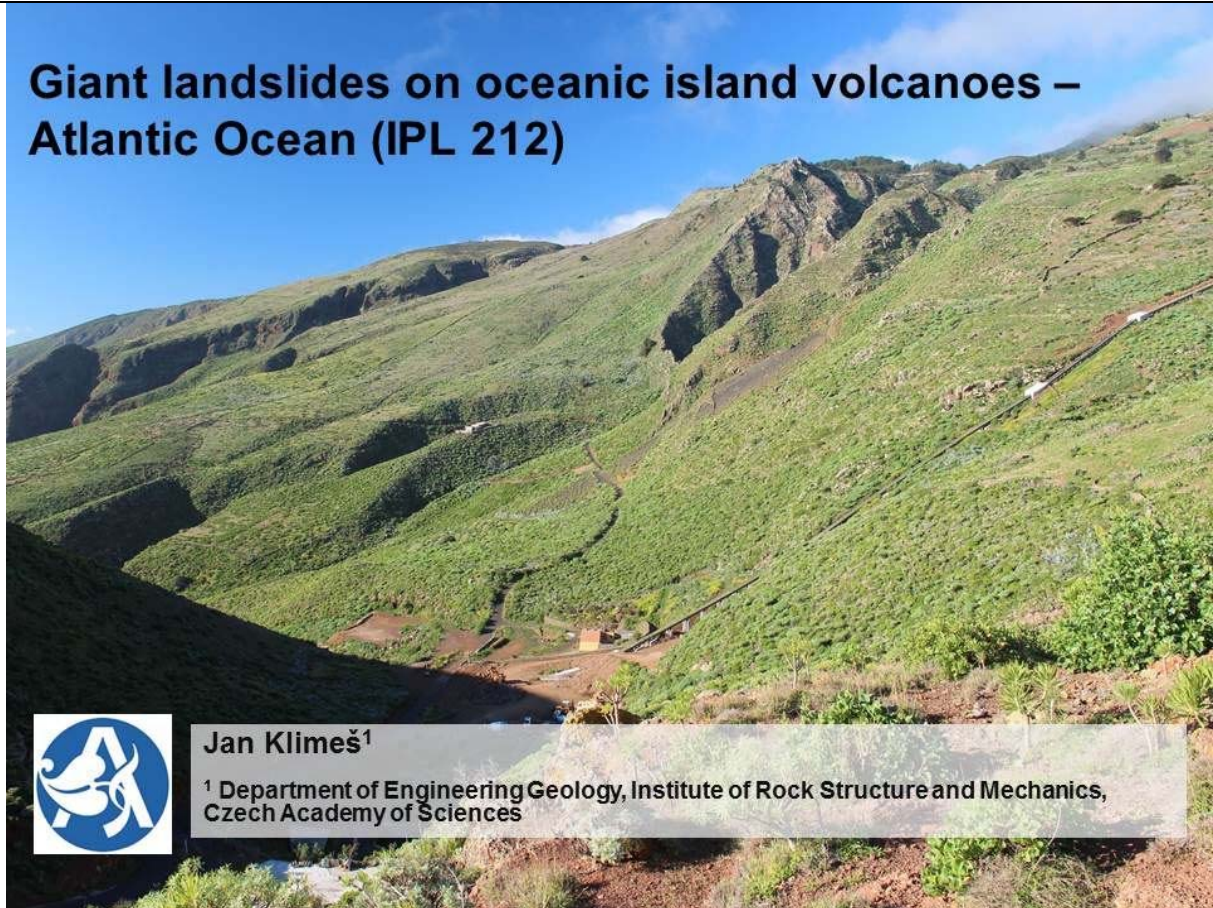
Jan Klimeš[1]

[1] Department of Engineering Geology, Institute of Rock Structure and Mechanics, Czech Academy of Sciences

INSTITUTE OF ROCK STRUCTURE AND MECHANICS
Academy of Sciences of the Czech Republic

Why to study giant landslides

- **Giant landslides** on the margins of oceanic island volcanoes are the **largest formations** which can be generated in a single geological moment

- Their occurrence would not only cause **immense losses** its immediate vicinity, potential tsunami may devastate coastal regions thousands of kilometers away

USMH

INSTITUTE OF ROCK STRUCTURE AND MECHANICS
Academy of Sciences of the Czech Republic

USMH

Why to study giant landslides

- They remain **poorly understood** :
  - occur so infrequently
  - much their accumulation rest at considerable depths in the ocean
- No efforts to **synthesise** the literature at **global scale** have yet been made

INSTITUTE OF ROCK STRUCTURE AND MECHANICS
Academy of Sciences of the Czech Republic

USMH

Objectives

- To construct the first **global database** of **giant landslides** on oceanic island volcanoes
- To investigate **spatial and temporal** patterns of landslide **occurrences and reactivations**
- To contribute to the **assessment of hazard** and potential risks posed by the giant landslides

Structure of the database

Location

ID	ML name (alternative names)	Site	Island	References
1	Abona		Tenerife	Dávila et al. 2011

Volcanic island characteristics

Height of island above sea floor (m)	Type of volcanic acitivty	Rate of island uplift	Presence of rift zones on the island

Qualitative ML description

Type of ML according the literature	Type of ML according our classification	Trigger of paleo-ML	Preparatory factors of ML occurrence	Age of ML	Age determination method	Previous ML occurrences (Yes/No)	Number of preceeding MLs	Age of the oldest ML	Presence of defined sliding surface(s) Yes/No and main geometry	Historical/recent reactivations of main detachment planes (Yes/No)	Main triggeres of historical/recent reactivations	Displacement during historical/recent reactivation events (m)	Secondary landslides/rockfalls/debris flows within the ML body on shore	Tsunami related with the ML development (Yes/No)	Fatalities /damage related to ML activity
debris-avalanche		explosive eruption	phonolite dome growth	733±3 ka	40Ar/39Ar					no					

Quantitative description

Total volume (km3)	Total area (km2)	Sub-aerial volume (km3)	Sub-aerial area (km2)	Sub-marine volume (km3)	Sub-marine area (km2)	Method of sub-marine part mapping	General dip - sub-aerial	General dip - sub-marine	Max sub-aerial length (km)	Highest point of ML (m) - sub-aerial	Lowest point of ML (m) - sub-aerial	Max sub-aerial width (km)	Max sub-marine length (km)	Max sub-marine width (km)	Max sub-aerial depth of ML (m)	Max sub-marine dept of ML (m)
		267**							23**	2467*	0	20.4				50

Giant landslides on the Canary Islands
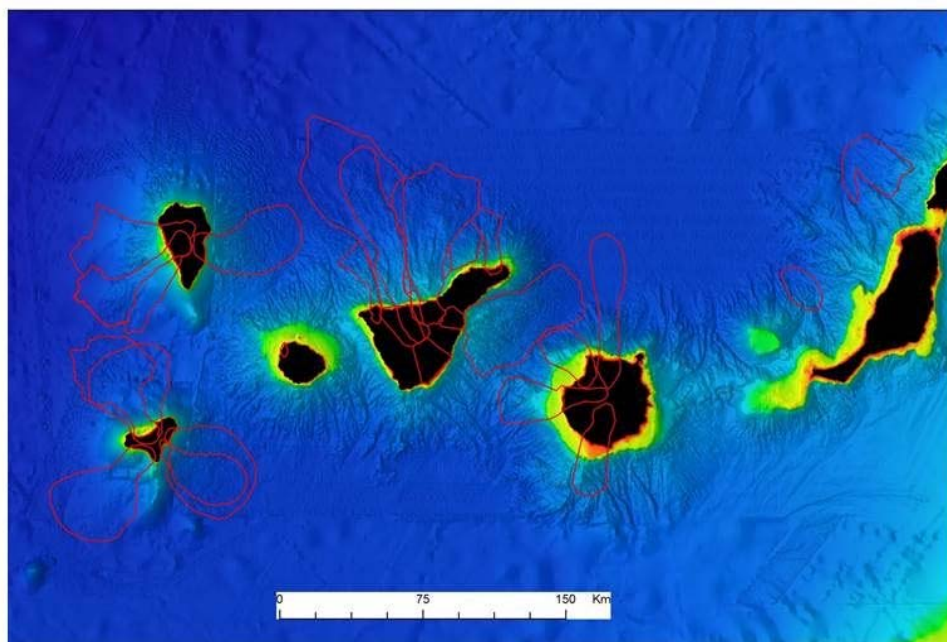
0   75   150 Km

Landslide hazard assessment and mitigation measures in geothermal fields

Teuku Faisal Fathani, Ph.D. and Dr. Wahyu Wilopo

Center for Disaster Mitigation and Technological Innovation (GAMA-InaTEK)
Faculty of Engineering, Gadjah Mada University, INDONESIA

ICL-IPL UNESCO Conference 29 Nov – 1 Dec 2017

www.ugm.ac.id

Scope of Activity

❖ Site investigation (field survey and laboratory testing)

❖ Development of hazard map and risk map

❖ Detailed Engineering Design for structural landslide and fast flood mitigation

❖ Design and implementation of online monitoring and warning system:

- Aerial photogrammetry

- Monitoring device: Extensometer, Tiltmeter, Raingage, Ultrasonic sensor, IP Camere

- Telemetry system: local server, website, level of warning

- Mitigation control: structural and non-structural

www.ugm.ac.id
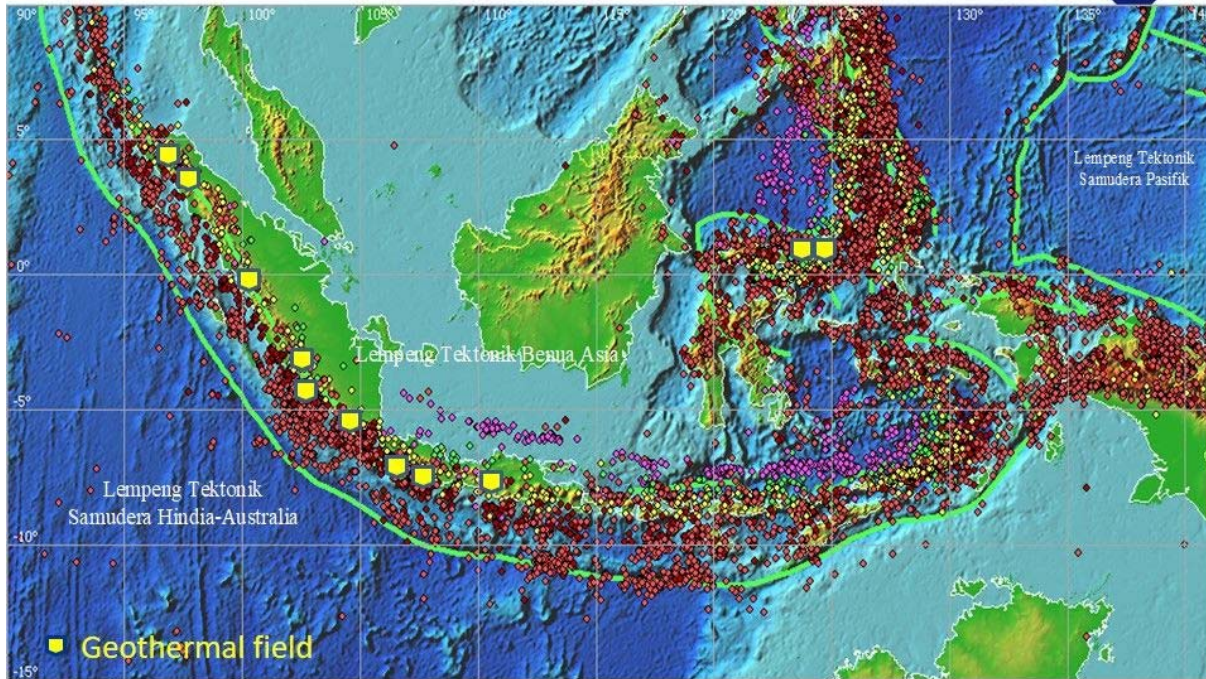
Online Landslide Monitoring – Geothermal Fields in Indonesia
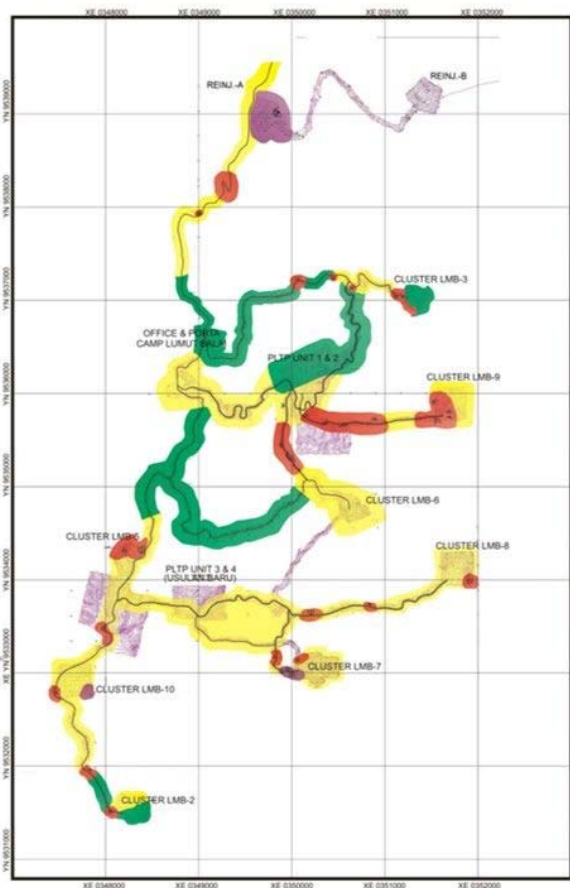
Landslide Vulnerability Map at a geothermal field
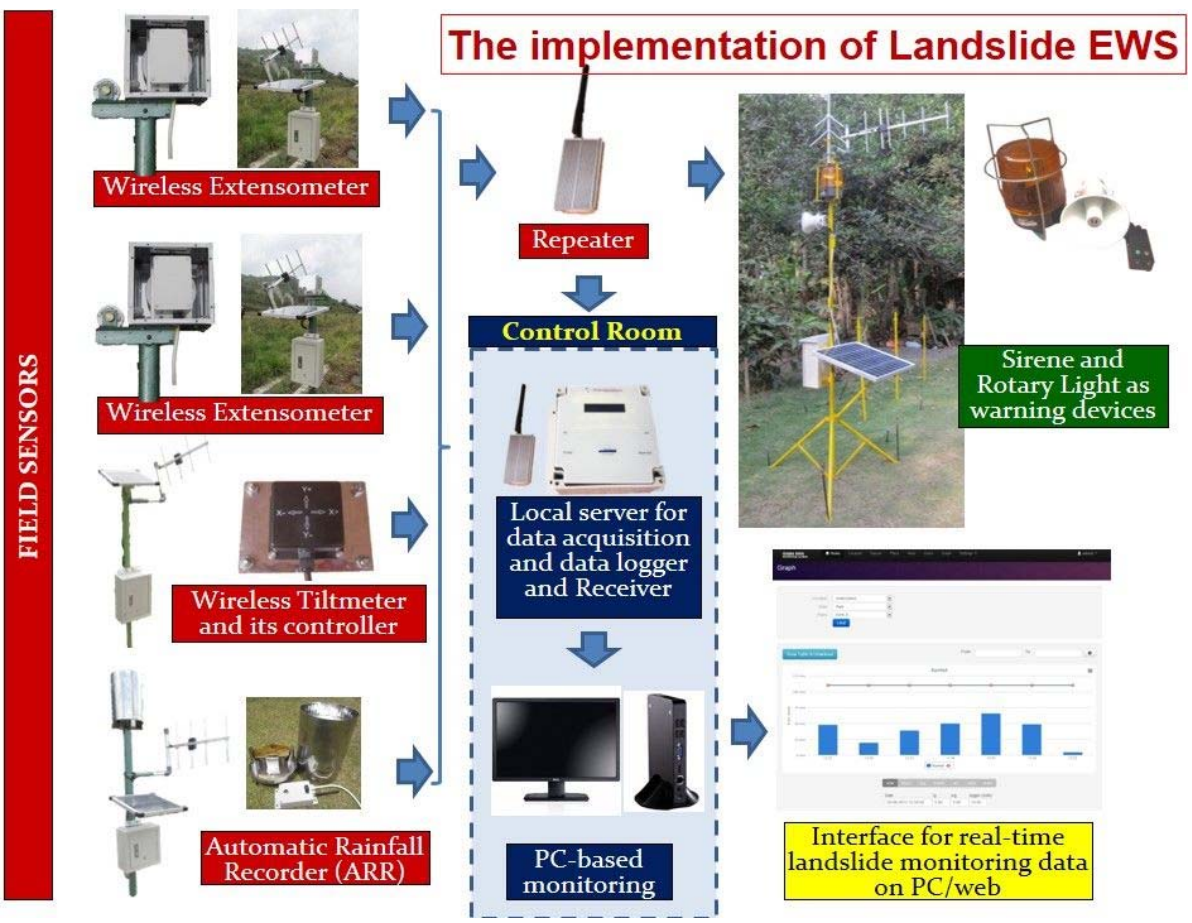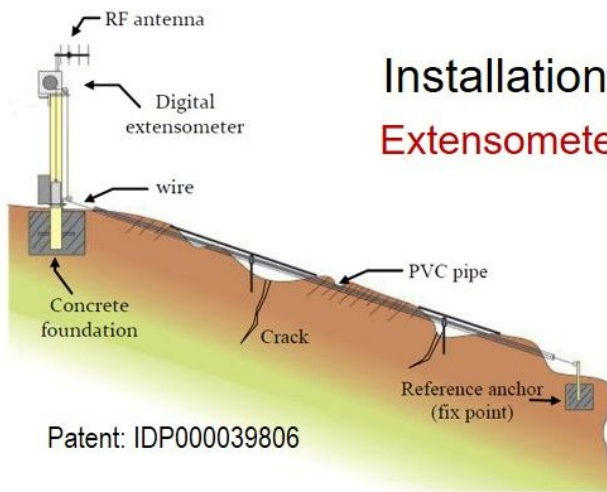
Installation of Monitoring Devices

Ultrasonic water level meter
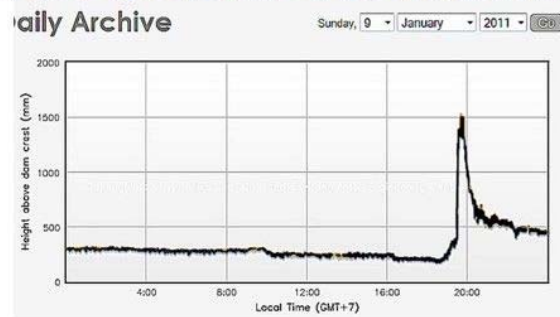
Data

Raingauge
- Rain count put in Database every 1 minutes
- Unit: mm (Graph shows mm/hour)

Extensometers and Tiltmeter
- Data collected every 10 seconds (Unit: mm)
- Collected displacement put into Database every 1 minutes

Ultrasonic water level sensor
- Measured and converted to water/debris depth in meters
- Data read and put into database every 1 minutes
- Unit: meters (Graph shows depth)

- Data is entered into database every 1 minutes
- Every 1 minutes the collected data is transferred to the Server
- Every 30 sec the latest image from IP camera is transferred to Server

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Landslide EWS installation (2007-2017) in Indonesia

Legend:
- ● UGM in cooperation with BNPB, BPBD and KPDT
- ■ UGM in cooperation with Private Mining Company
- ▲ UGM in cooperation with Pertamina Geothermal Energy (2013)
- ★ UGM in cooperation with International Consortium on Landslides (ICL-UNESCO)

- BNPB & UGM 2015 ●
- BNPB & UGM 2016 ●
- BNPB & UGM 2017 ○
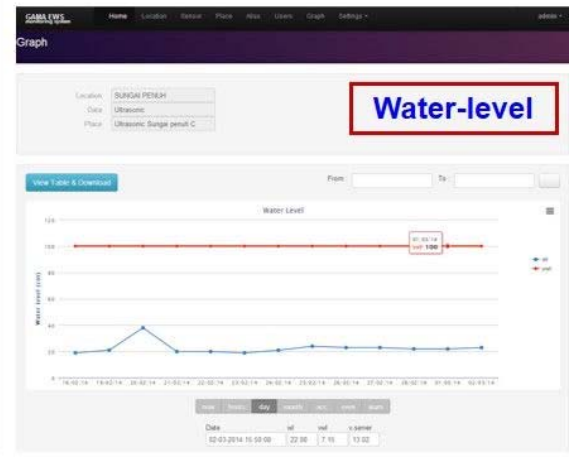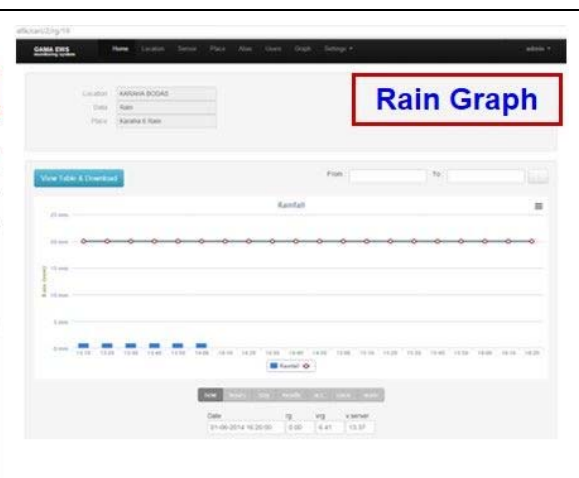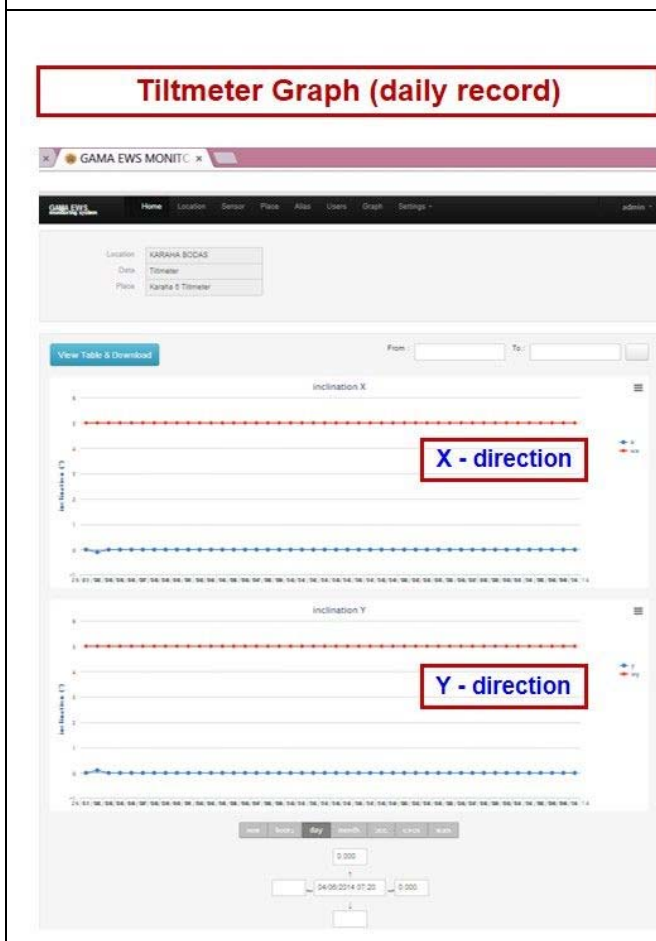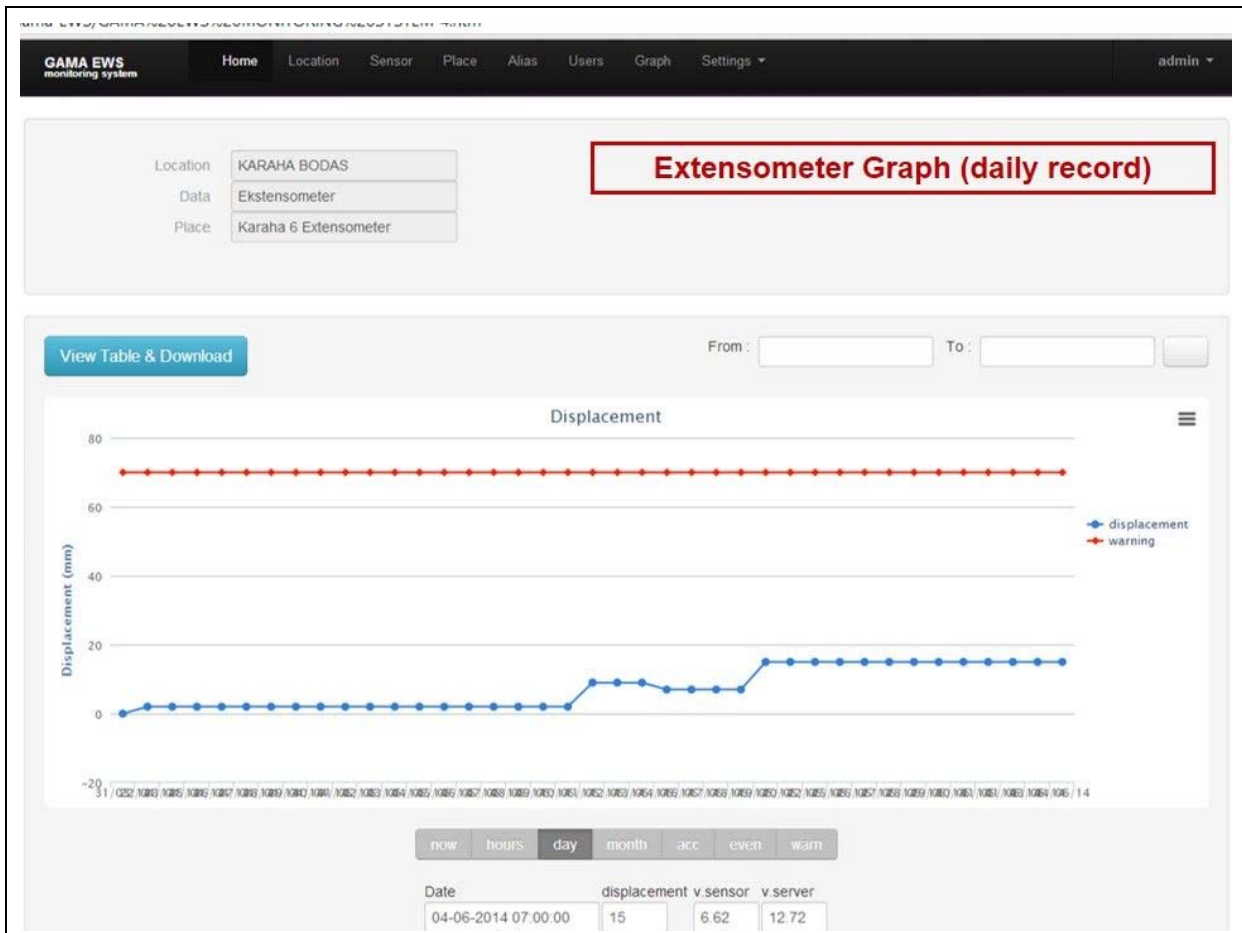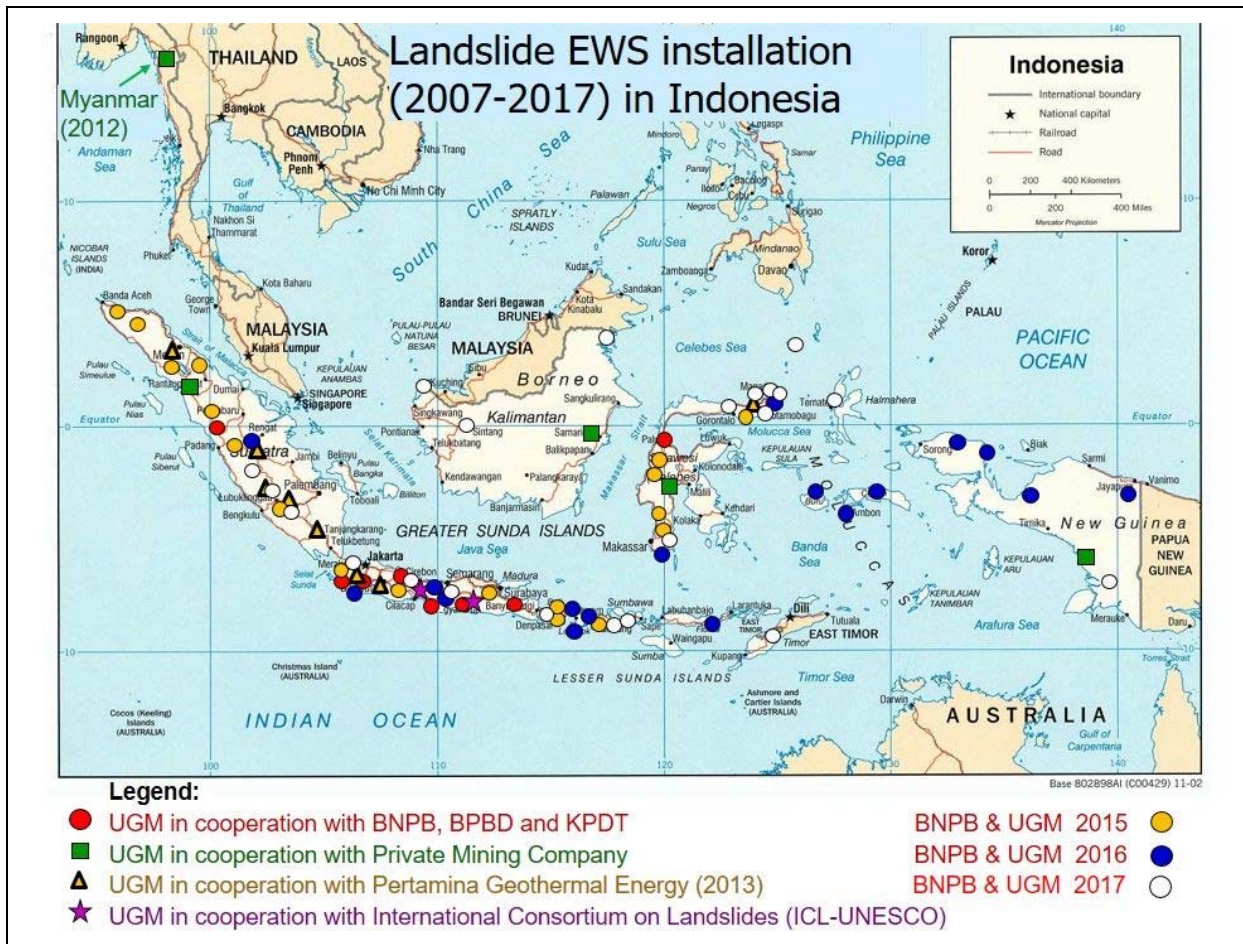
4 key element for people-centered EWS
(UN-ISDR, 2006)

RISK KNOWLEDGE

Systematically collect data and undertake risk assessments

Are the hazards and the vulnerabilities well known?

What are the patterns and trends in these factors?

Are risk maps and data widely available?

MONITORING & WARNING DEVICE

Develop hazard monitoring and early warning services

Are the right parameters being monitored?

Is there a sound scientific basis for making forecasts?

Can accurate and timely warnings be generated?

DISSEMINATION & COMMUNICATION

Communicate risk information and early warnings

Do warnings reach all of those at risk?

Are the risks and warnings understood?

Is the warning information clear and useable?

RESPONSE CAPABILITY

Build national and community response capabilites

Are response plans up to date and tested?

Are local capacities and knowledge made use of?

Are people prepared and ready react to warnings?

www.ugm.ac.id

First application of GB-InSAR for landslide monitoring(2000)

LiSAmobile™ 5th generation (Linear Synthetic Aperture Radar)

Radar interferometry

1st Level Statistical Model

Statistical analysis of Intensity-Duration Data
Massive CUMulate Brisk Analyzer

First level of alert

- Intensity-duration
- Automated analysis
- Standardized approach
- Definition of local thresholds
- Balancing between false and missed alarms
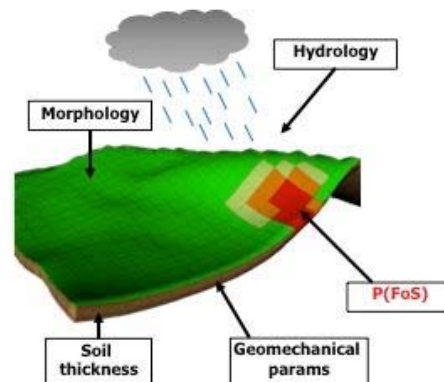
2nd Level Deterministic Model

HIgh REsolution Slope Stability Simulator

On areas with Level-1 Alert

- Physically based, high resolution model
- Large scale operativity
- Coded for real-time applications
- Fast parallel computational scheme

HIRESSS

Hydrology

Morphology

Soil thickness

Geomechanical params

P(FoS)

4. Multi-sensors drone for geohazards monitoring and mapping
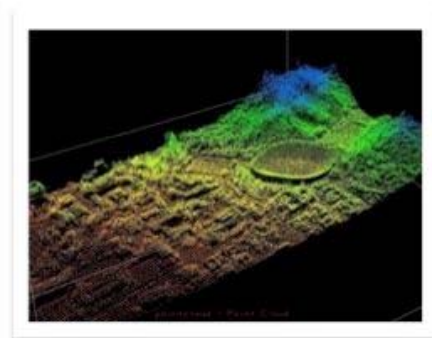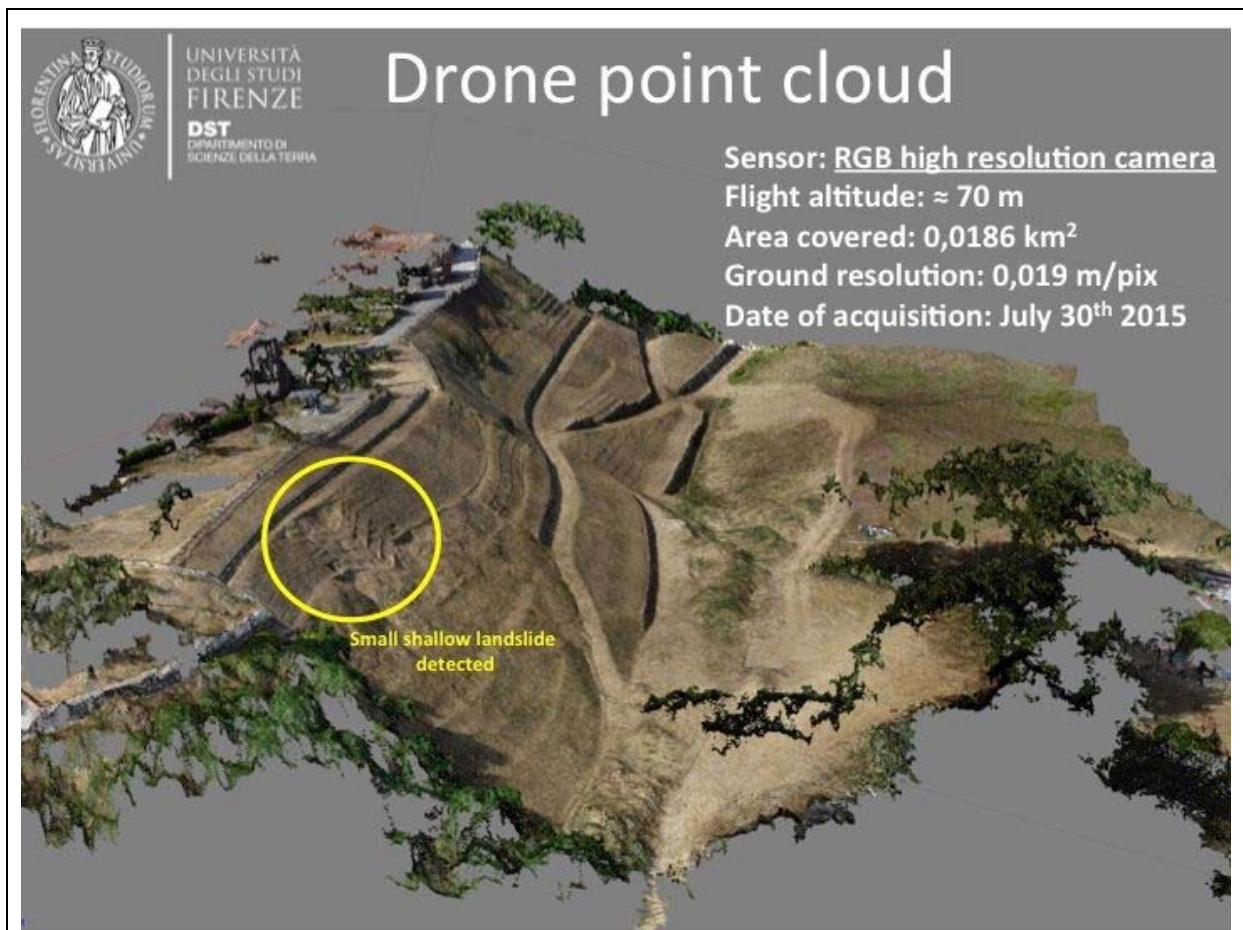

SATURN Drone

- Mission flexibility
- Light solution
- No constraint for cargo area
- Optimal placement of any sensor
- Improved and flexible flight time
- High payload mass
- Powerful computation and acquisition unit

Multi-sensors drone
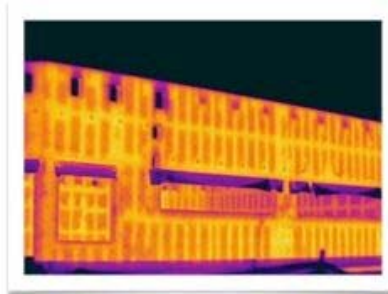
- hi-res camera
- multispectral camera
- hyperspectral sensor
- thermal camera
- radar
- up to 17 kg of payload

University of Ljubljana
Faculty of Natural Sciences and Engineering
Faculty of Civic and Geodetic Engineering

IPL-216 Project Annual Report for 2017

Diversity and hydrogeology of mass movements in the Vipava Valley, SW Slovenia

Timotej Verbovšek*, Tomislav Popit, Jernej Jež, Ana Petkovšek, Matej Maček

*Department of Geology, University of Ljubljana, Faculty of Natural Science and Engineering,
Privoz 11, 1000 Ljubljana, timotej.verbovsek@ntf.uni-lj.si

ICL meeting, Paris, 29 November – 1 December 2017

Study Area

× SW Slovenia, the upper Vipava Valley
× Mesozoic carbonates overthrusted on the Eocene flysch
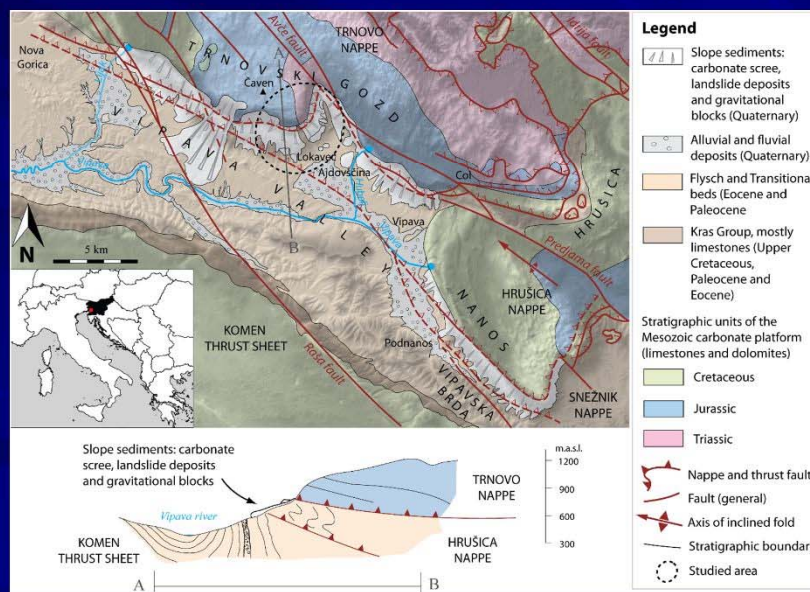
Project duration and objectives (from 2016 application)

- **Project Duration: 3 years:**
  - Year 1 (2017): Data collection and literature review of the mass movements in the Vipava Valley. Engineering-geological mapping of the area, creation of a GIS geodatabase.
  - Year 2 (2018): Continuation of previous year activities, plus hydrogeological measurements.
  - Year 3 (2019): Continuation of previous year activities, plus monitoring and geotechnical investigations.

- **Objectives:**
  - *T*o create a landslide inventory (database) of the Vipava Valley in GIS environment.
  - Use of Cruden and Varnes classification, plus the use of updated Varnes classification (Hungr et al., 2014)
  - *T*o perform a hydrogeological analysis of selected springs in this area, which are related to landslides.
  - *T*o monitor the movement of some of the selected landslides, according to available budget.

2017 Activities – WLF4 and ReSyLAB

- **4th World Landslide Forum (WLF4)**
  - Study tour in the Vipava Valley (3 June 2017)
  - landslides Stogovce, Slano blato, Podboršt and Selo
  - + Summer School Natural Disasters students

- **3rd Regional Syposium on landslides in the Adriatic-Balkan Region (ReSyLAB 2017)**
  - Study tour in the Vipava Valley (13 October 2017)
 - landslides Stogovce, Gradiška gmajna, Slano blato, Podboršt, Hubelj spring

2017 Activities – Papers

- published papers in 2017 for Vipava Valley:
    - **Landslides** - Jemec Auflič, M, Jež, J, Popit, T, Košir, A, Maček, M, Logar, J, Petkovšek, A Mikoš, M, Calligaris, C, Boccali, C, Zini, L, Reitner, J, Verbovšek, T. The variety of landslide forms in Slovenia and its immediate NW surroundings. Landslides 14(4), 1537-1546.
    - **Landslides** - Verbovšek, T, Košir, A, Teran, M, Zajc, M, Popit, T. Volume determination of the Selo landslide complex (SW Slovenia) : integrating field mapping, ground penetrating radar and GIS approaches. Landslides 14(3), 1265-1274.
    - Acta Geographica Slovenica – Kocjančič M, Popit T, Verbovšek T, Gravitational sliding of the carbonate megablocks in the Vipava Valley, SW Slovenia
    - Geologija - Novak, A, Verbovšek, T, Popit, T. Heterogeneously composed Lozice fossil landslide in Rebrnice area, Vipava Valley. Geologija 60(1), 145-155
    - WLF4 - Verbovšek, T, Kočevar, M., Benko, I., Maček, M., Petkovšek, A.: A Mass movement processes of Quaternary deposits in Vipava Valley, SW Slovenia
    - WLF4 - Popit, T., Jež, J., Verbovšek, T. *Mass movement processes of Quaternary deposits in Vipava Valley, SW Slovenia*
    - WLF4 - Verbovšek, T, Kočevar, M, Benko, I, Maček, M, Petkovšek, A. Monitoring of the Stogovce landslide slope movements with GEASENSE GNSS probes, SW Slovenia.
    - WLF4 - Mikoš, M, Logar, J, Maček, M, Sodnik, J, Petkovšek, A. Mechanisms of landslides and creep in over-consolidated clays and flysch (WCoE 2014-2017).
    - WLF4 - Maček, M, Smolar, J, Petkovšek, A. Influences of rheometer size and the grain size on rheological parameters of debris flow.
    - WLF4 – Study tour book
   - ReSyLAB 2017 – several extended abstracts from project team members   **+ more local publications**

2017 Activities – Mapping

- Production of GIS map of landslides in the project area, compilation of all known mass movements (in progress)
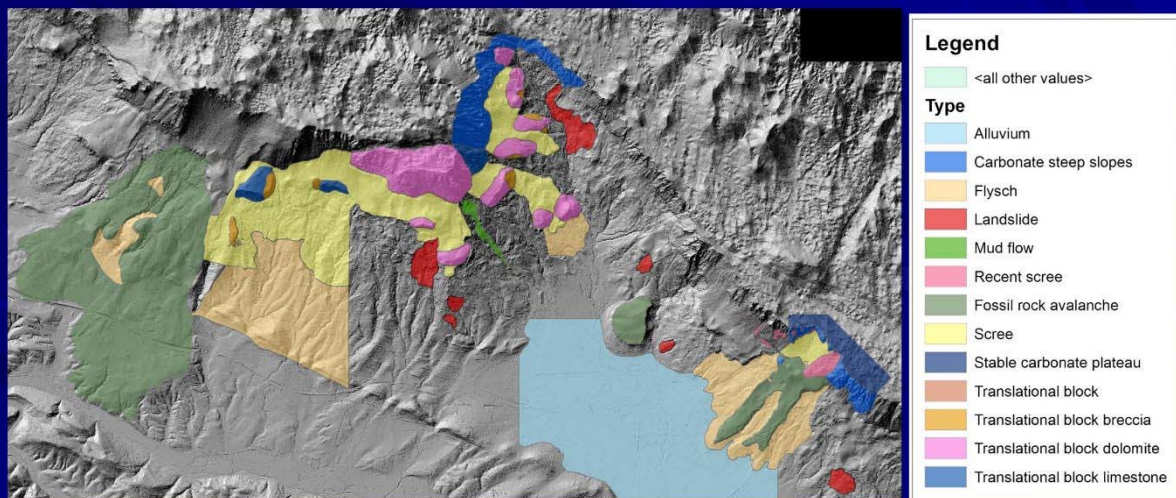
2017 Activities – Groundwater

- Monitoring of groundwater in Stogovce landslide
  - temperature, electroconduvity, water level (CTD diver)
  - example: inclinometer SS-1, time period 31 August – 13 September 2017
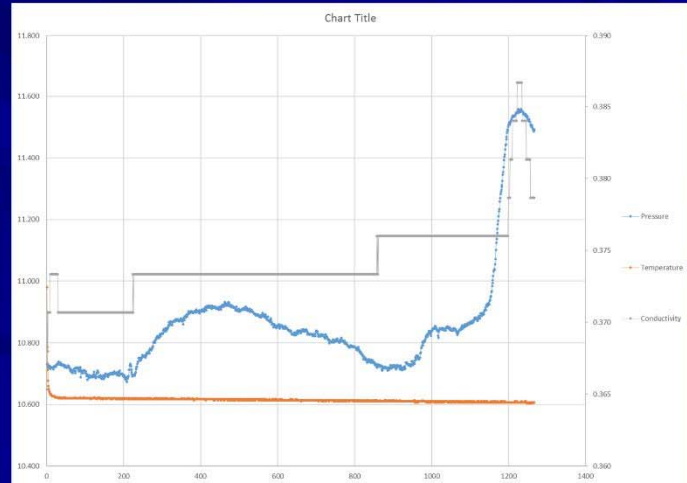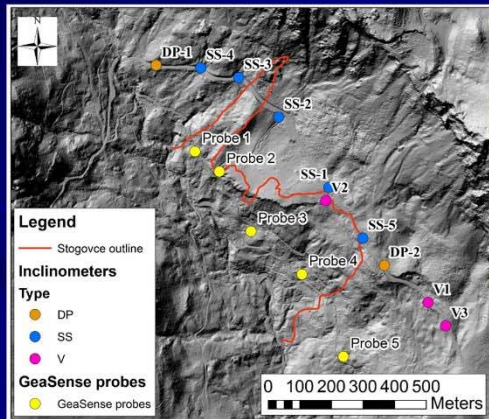
2017 Activities – Other

- Sampling of sediments for determination of rheological properties in Stogovce (and Stože) landslide (Ana Petkovšek, Jasna Smolar and Timotej Verbovšek), August 2017

- Field work with students of University of Ljubljana + University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering (Adriatic-Balkan network ICL ABN) to Stogovce, Slano blato and Podboršt landslides, 9 June 2017

- Promotion of ICL during the Engineering geology lectures, University of Ljubljana, NTF