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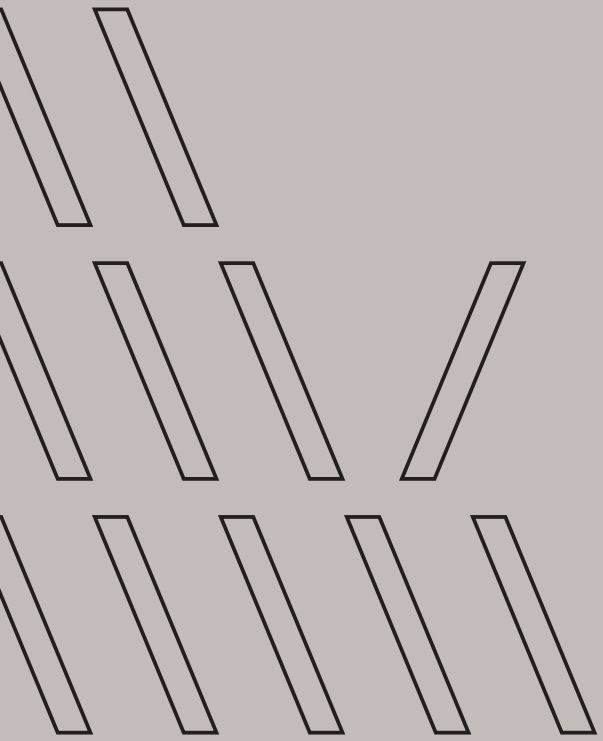
5TH REGIONAL SYMPOSIUM ON LANDSLIDES
IN ADRIATIC-BALKAN REGION

Landslide Modelling & Applications

Book of Abstracts



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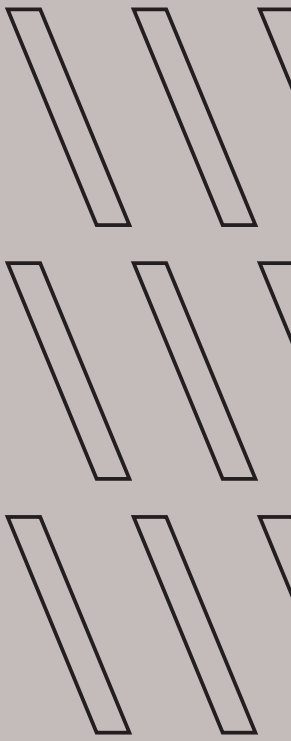

5th Regional Symposium on Landslides in the Adriatic-Balkan Region
'Landslide Modelling & Applications'
Rijeka, Croatia, 23-26 March 2022

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Under the sponsorship of International Consortium on Landslides (ICL)

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Invited lectures

The International Consortium on Landslides for disaster risk reduction and sustainable development

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ABSTRACT: Landslides represent a major threat to human life, property, buildings, infrastructures, cultural heritage and natural environment in mountainous and hilly regions. Their socio-economic impact is strongly underestimated, because landslides usually occur in combination with other natural hazards such as extreme rainstorms, earthquakes, and volcanic processes, in complex multi-hazard chains. Climate change and growing urbanisation are responsible for the growing risk associated with landslides in the last decades, especially in developing and less developed countries.

Landslide hazard mapping and monitoring represent the main tools for landslide risk reduction and sustainable management since they can support the proper definition of prevention and mitigation measures, such as stabilization works or early warning systems.

An established scientific landslide community has flourished in the last decades worldwide, thanks to several international organizations, such as the International Consortium on Landslides (ICL) which leads the International Programme on Landslides (IPL), together with major UN and scientific organizations.

The ICL is the largest and the most authoritative and representative organization for landslide scientific research and risk reduction policies. It has now reached 99 among members, associates and supporters from 35 countries covering 4 continents, plus 12 international supporting organizations.

In November 2020 the ICL launched the Kyoto Landslide Commitment (KLC2020) for global promotion of understanding and reducing landslide disaster risk. The KLC2020 supports the implementation and follow-up of the Sendai Framework adopted at the 3rd World Conference on Disaster Risk Reduction (WCDRR) in Sendai, Japan in 2015, the 2030 UN Agenda for Sustainable Development, the New Urban Agenda and the Paris Climate Agreement as it addresses the adverse effects of climate change.

1. The KLC2020 has been signed by 90 institutions among governmental and international organizations, ICL supporting organizations, full members, associate members and supporters, from 23 countries in 3 continents, with a common commitment for building a common platform for sharing ideas, good practices and policies with key actors and stakeholders concerned with landslide risk at the global level. The signatory organizations have agreed on the following priority actions: Promote the development of people-centered early warning technology for landslides with increased precision and reliable prediction both in time and location, especially in a changing climate context.
2. Advance hazard and vulnerability mapping, including vulnerability and risk assessment with increased precision, as well as reliability as part of multi-hazard risk identification and management.

3. Improve the technologies for monitoring, testing, analysing, simulating, and effective early warning for landslides suitable for specific regions considering natural, cultural and financial aspects.
4. Apply the ISDR-ICL Landslide Interactive Teaching Tools for landslide risk reduction in landslide prone areas and improve them with feedbacks from users in developed and less developed countries.
5. Promote open communication with local governments and society through integrated research, capacity building, knowledge transfer, awareness-raising, training, and educational activities, to enable societies and local communities to develop effective policies and strategies for reducing landslide disaster risk, to strengthen their capacities for preventing hazards from developing into major disasters, and to enhance the effectiveness and efficiency of relief programs.
6. Investigate the effect of climate change on rainfall-induced landslides and promote the development of effective rainfall forecasting models to provide earlier warning and evacuation especially in developing countries
7. Investigate the mechanism and dynamics of submarine landslides during earthquakes that may cause or enhance tsunamis, as well as develop and upgrade its hazard assessment and mitigation measures
8. Promote geotechnical studies of catastrophic megaslides and develop their prediction and hazard assessment.
9. Foster new initiatives to study research frontiers in understanding and reducing landslide disaster risk by promoting joint efforts by researchers, policy makers and funding agencies.
10. Facilitate and encourage monitoring, reporting on, and assessing progress made, through the organization of progress report meetings at the regional and national level, to take place in respective countries, in order to show delivery and performance on progress made towards achieving the Kyoto Landslide Commitment priority actions No.1-9. Participating parties and relevant stakeholders reporting on deliveries and achievements at these meetings are invited to report on this progress in the monthly full colour journal “Landslides” so as to allow viewing progress in addressing landslide risk reduction. They are also encouraged to cooperate, as feasible and appropriate, with countries, the United Nations family, regional organizations, and all other partners and stakeholders concerned with landslide risk in their contribution to the Sendai Monitor System and the Voluntary National Reviews, and in their reporting on relevant key SDGs, notably on resilient and sustainable cities and climate action and on the Paris Agreement follow-up.

The ICL publishes since 2004 the scientific journal “Landslides” as a common platform for the publication of integrated research on all aspects of landslides. The journal has reached an impact factor of 6.578 in 2020, continuously growing.

In the 2021 the ICL has launched a new open access book series titled “Progress in Landslide Research and Technology” for publishing a variety of articles targeted to different and wider landslide communities.

World Landslide Forums (WLF) have been organized every three years after the first forum in Tokyo, Japan, in 2008. The WLF is the main event that brings together scientists, engineers, experts, practitioners, and policy makers who are involved in landslide disaster risk reduction to present their latest progress.

The 6th World Landslide Forum (WLF6) will be held in Florence, Italy, from the 14th to the 17th of November 2023 and is jointly organized by the ICL, the IPL and the UNESCO Chair on Prevention and Sustainable Management of Geohydrological Hazards at the University of Florence.

The WLF6 is entitled “Landslide Science for Sustainable Development”, as a contribution to the KLC2020 for global promotion of understanding and reducing landslide disaster risk. The WLF6 aims to provide a platform to achieve fruitful cooperation among landslide researchers to define shared priority actions for landslide risk reduction on a global scale. The WLF6 will deal with the main aspects related to landslide analysis, focused on the following 6 main themes:

- Theme 1: Kyoto Landslide Commitment for sustainable development
- Theme 2: Remote sensing, monitoring and early warning
- Theme 3: Testing, modelling, and mitigation techniques
- Theme 4: Mapping, hazard, risk assessment and management
- Theme 5: Climate change, extreme weather, earthquakes, and landslides
- Theme 6: Progress in landslide science and applications

Physical modeling of landslides and slopes - Advancements and challenges

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ABSTRACT: Landslides cause a significant loss of lives and properties - globally. Various natural events such as intense rainfall, earthquakes, volcanic activities, etc. trigger landslides - either with one or combination of these causes. With the advancement in landslide investigation, monitoring, prediction, and prevention techniques – specifically with the rapid development of technology and software – our capacity on landslide hazard mitigation has significantly been increased in the past few decades. However, due to the increase in physical infrastructures and marginalization of urban land to serve the increasing population, loss of lives and properties due to landslides have not reduced proportionately with the advancement of technology. Numerical and physical modeling of landslides have been very useful tools in recent years to predict the behavior of slopes during the triggering events such as rainfall and earthquakes. However, it is important to set the parameters for modeling – both numerical and physical – appropriately to get reasonable results from these studies. The author – since more than a decade - has studied slope behavior using a series of numerical and physical models, specifically to study the influence of rainfalls and earthquakes on slopes having different types and densities of soils – predominantly for slopes in southern California, USA. It has been observed that experimental and physical modeling exercises were very helpful to calibrate the numerical models and use the calibrated numerical models in predicting deformation behavior of slopes during earthquake as well as rainfall events. This study also focuses on the impact of rainfall on triggering landslides or causing slope deformation when a slope is subjected to multiple triggering factors, such as rainfall before or after an earthquake event. In this presentation, the author will discuss about the currently available numerical and physical modeling tools, precautions to be made while setting the model parameters as well as instrumentation plan on the experimental models, and challenges as well as limitations of the available modeling methods. The presentation will be followed by a few case studies.

Failure hazard of rockfall sources: some aspects of the hazard quantification

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ABSTRACT: This paper presents two attempts to improve rockfall failure hazards assessment. The first is based on the matrix hazard approach, it tries to assess the failure of medium size rock instability based on two parameters the rockfall activity and the deformation. It assumes that if a rock mass starts to be deformed, which is measured as the displacement divided by the length of the landslide in the direction of displacement. When it is larger 0.001% per year, it starts to be significant. If this is coupled with rockfall temporal frequency above 0.1 per year for boulders larger than 1 m3, the hazard is significant. The matrix is created with four classes numbered 1 to 4 for both activity parameters and higher is the sum of both higher is the hazard level.

The second attempt is a validation of the volume temporal frequency cumulative distribution obtained by comparing the result of inventory of fallen rock volumes and the distribution obtained using the potential unstable volumes. The volume distributions may be obtained by comparing point clouds for the fallen volumes and by using structures or other methods to define the unstable volume and their limits. These methodologies are in an early stage, the results are not yet confirmed, but they may be tested and used in the case of fast risk hazard and risk assessment.

Landslide evidence and spatial prediction - Application of data and information from landslide maps

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ABSTRACT: Landslide maps produced by LiDAR (Light Detection and Ranging) are very clear and detailed representation of the phenomena and in many cases reveal evidence of past landslides that are virtually invisible by other detection techniques due to vegetation cover. Over the last decade, airborne laser scanning (ALS) has been made available and has been used to identify and map landslide. LiDAR elevation data prove particularly effective for mapping of small and shallow landslides in areas that are partially or completely covered by dense vegetation that are difficult or impossible to identify using conventional identification techniques. The first topic covered in the talk is landslide detection and mapping using very high-resolution LiDAR DTM to obtain complete historical inventories of shallow soil slides. Few examples of landslide inventory maps from different geomorphological environment of the Republic of Croatia will be presented to show typical landslide distribution. For landslide spatial prediction, the talk focuses on the results of landslide susceptibility modelling and zonation performed for a range of coverages, starting with the largest encompassing whole territory of Croatia. Landslide susceptibility zonation was also performed for

areas of two counties (Primorsko-Goranska County and Karlovac County) and few smaller pilot areas of cities and municipalities in the Pannonian Basin and in External Dinarides. The main objective of presented susceptibility zoning in different scales (national, regional and local scale) is to enable analysis of usefulness and reliability of map information (i.e., spatial distributions and rating of the terrain units according to their landslide propensity) for application in physical and urban planning. The needs of the decision-makers, planners and other stakeholders involved in landslide risk prevention are analyzed through the series of round-table discussions organized in Croatia in the framework of the project of applied research PRI-MJER (KK.05.1.1.02.0020). The ultimate goal is to create maps depicting information about landslides tailored according to needs of the system of physical planning in Croatia (particularly land use planning), encompassing local and regional level, harmonized at the national level. The research of the mapping methodologies is part of the project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology, LandSlidePlan" (HRZZ IP-2019-04-9900) fully supported by Croatian Science Foundation.

Rainfall-induced landslides and debris flows under the influence of climate change: review of recent Slovenian studies

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M. Jemec Auflič
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ABSTRACT: Climate changes are expected to increase the frequency and magnitude of the most intense precipitation events. In addition, the elements of the hydrological cycle and the seasonal characteristics of climatological and hydrological processes are expected to change in the future. Therefore, these changes will also affect the frequency, magnitude, and impact of landslides, debris flows, rockfalls, and similar natural hazards. This paper reviews recent studies conducted by Slovenian researchers, focusing on Slovenia and other European countries. Special emphasis is placed on the characteristics of precipitation events responsible for triggering mass movements and on an overview of the effects of climate change.

Landslide Investigation

Mountain slopes above Koroška Bela (NW Slovenia) – A landslide prone area

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ABSTRACT: The paper focuses on slope mass movements in the hinterland of a settlement of Koroška Bela, which is located in north western Slovenia in the foothills of the Karavanke mountain ridge. This area is known by numerous landslides, which represent the source area of a potential debris flow. More than 20 landslides have been mapped and five of them exceeded the area of 8,000 m^2. They have been named: Urbas, Čikla, Potoška planina, Malnež and Obešnik landslides. Among them Urbas and Čikla are considered the most active. Both are deep-seated landslides that related to complex geological and tectonic conditions. These landslides pose a threat to the settlement of Koroška Bela, which is very densely populated (about 2000 inhabitants) and has well-developed industry and infrastructure. The settlement itself is located in the area of the torrential fan built from past debris flows. In this regard, the hinterland of Koroška Bela has been studied since 2006 within the framework of various national and European projects. The first projects (before 2017) were mainly for research purposes and focused on the observation of the kinematics of the Urbas landslide. Within these projects, we performed initial geological mapping, first investigations of the Koroška Bela torrential fan and first debris flow modelling. We also implemented different monitoring techniques to observe surface movement patterns and established a cooperative team of decision-makers, response authorities, technical experts and stakeholders to increase awareness and understanding of landslide risk. Unfortunately, all the above activities stopped at the end of the projects due to lack of further funding.

One of the main reasons that attracted attention and led to the first detailed investigations of landslides in the hinterland of Koroška Bela was the (re)activation of a Čikla debris flow of small size (about 5,000 m^3). This event occurred in April 2017 due to heavy precipitation (more than 200 mm in 48 hours). Activities following this event focused mainly on identifying and understanding the landslide dynamics in order to provide the feasibility study for prevention and remediation measures. To achieve this, geological, geotechnical and geodetic investigations were essential. In 2017 and 2020, we drilled several boreholes equipped with inclinometers or piezometers. During the drilling, we also conducted in-situ geotechnical, hydrogeological measurements and geophysical surveys.

As part of the ongoing monitoring we perform periodic inclinometer measurements, tachymetric measurements of object points, hydrogeological monitoring and monitoring of surface displacements using extensiometers and GNSS technology. This paper reports on the main results of the field investigations on landslides in the hinterland of Koroška Bela.

This research is found by Slovenian Research Agency (Research Program P1-0011, J1-8153 project; Z1-2638 project), the Ministry of Environment and Spatial Planning, and the Municipality of Jesenice, GIMS project (European Union's Horizon 2020 research and innovation programme under grant agreement No. 776335).

Recent large-scale gravitational collapses in the Madonna di Puianello mud-volcanoes field calderas (Northern Apennines, Modena, Italy)

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ABSTRACT: Mud volcanoes are quite widespread phenomena in the front "Pede-Apennine margin" of the Northern Apennines within the Emilia-Romagna region. The upward migration of overpressure fluids and/or hydrocarbons can manifest on the surface with the formation of mud volcanoes up to 2-3 m high or gas vents. A mud volcano field is characterized by different eruptive phases alternating with calm phases and it can evolve by sinking into a caldera-like circular pattern. The Madonna di Puianello mud volcanoes field has recently experienced two major large-scale gravitational collapses of significant magnitude in two different locations in 2015 and 2020. Both events started suddenly and developed rapidly during less than 12 hours. In February 2015, at the "Possessione field", normal fractures with up to 25 cm of vertical displacement rimmed an area as large as 0,5 km^2 area. At first the uphill normal fractures were identified as possible evidence of a deep-seated landslide. Later on, thanks to field surveys, aerial photo interpretation, the phenomenon was better identified as a possible gravitational collapse feature. Recently, in December 2020, in the "Traino field" located less than 1 km eastward, another similar event took place affecting an area of 0,15 km^2. In this second case, sub-vertical fractures rimming the collapsed area showed displacements as high as 5-7 m, evidencing quite uncontroversially the caldera-like collapse nature of the phenomenon. With respect to the timing of the evolution of these phenomena, both periodic GNSS surveys ("Possessione field") and permanent GNSS monitoring ("Traino field") and InSAR analysis performed after the events, evidenced that movements had substantially return to extremely slow rates within a few days after the main events (i.e. to displacement rates in the order of 2 mm/year that MTI SAR interferometry shows as long-term trend in both areas). Actually, the possible causes of these sudden impulsive evolution are still substantially unknown. The geological setting of the area is highly complex, and for a number of tectonic reasons highly fractured sandstones of the Pantano formation lay in depth underneath clay shales of Ligurian and Epi-ligurian sequence. Thus, at least in principle, a rapid degasification or reduction of deep-water fluxes inside the sandstones, could trigger normal faulting inside the clay shales cap and determine the caldera-like shape observed in the field. Nevertheless, there is no direct evidence of any sudden degasification before the events, and as a matter of fact the mud-

volcanoes in the field did not show any increased activity prior to the collapses. Furthermore, water sampled in wells located in the area have mostly a gravitational origin, since they do not show the distinctive isotopic signature of mud-volcanoes fluids (i.e. absence of Tritium and depleted oxygen $\delta^{18}O$ and hydrogen δD stable isotopes). Nevertheless, this does not exclude possible changes of pressure in deep fluids. This contribute aims to describe the geomorphic and kinematic characteristics of these events on the basis of GNSS monitoring, SAR-MTI processing, field and Uncrewed Aerial Vehicle multi-temporal surveys and to discuss potential causes with respect to the abovementioned geological and geochemical constraints.

Paroxysmal reactivation of a large-scale earth flow documented by multitemporal UAV photo surveys and Robotic Total Station

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ABSTRACT: The Valoria landslide is a complex earth slide-earth flow located in the Northern Apennines of Italy, in the upper Secchia River basin of the Emilia Romagna Region. It affects a surface of 1.6 km2 over a length of 3.5 km and has a vertical development of about 900 m having the source zone at 1413 m above sea level. In the period 2001-2009, landslide reactivations caused repeated interruptions of the traffic along a local road. This led local authorities to build in 2009 an overpass bridge in the track zone to preserve the viability in case of further reactivation. From October 2020 to March 2021, the Valoria landslide experienced the first paroxysmal reactivation since overpass bridge construction, which has caused concern for the infrastructure itself. This recent event, as previous ones, has started as a retrogressive rotational slide in the source zone and then evolved into an earth-slide and earth-flow along the track and accumulation zone. The downhill propagation was characterized by multiple impulses within the period from October 2020 to March 2021. In order to follow the evolution of the phenomenon, from November 2020 onward a total of 18 prisms have been monitored by using a Robotic Total Station (RTS) installed on the overpass bridge itself. Monitoring points are located in-between the source and track zone and some of them scored a total cumulative displacement of about 300 m over the 4 months period and showed distinctive acceleration and deceleration patterns in response to changing geomorphic and meteorological forcing factors. At the same time, repeated Uncrewed Aerial Vehicle (UAV) surveys were performed in order to obtain updated orthophotos which would allow to follow the evolution of the landslide in unmonitored sectors and, eventually, quantify movements. To do so, two acquisition strategies have been used: i) rapid mode surveys covering the whole re-activated landslide area characterised by low resolution and accuracy but useful to map the evolution of the landslide; ii) photogrammetric mode surveys (PS), covering smaller areas but delivering highly reliable results that can be coupled to pointwise data obtained by the contextual RTS results. The aim of this contribution is to describe

the recent Valoria landslide reactivation, pointing out the peculiarities of the displacement patterns evidenced by RTS monitoring and highlight the polyhedrality of UAV application as a tool for an effective landslide evolution characterization using rapid mode surveys and a quantitative estimate of displacement by photogrammetric mode acquisitions.

Field investigation of the landslide that occurred during the construction of the dam "Svračkovo"

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ABSTRACT: Svračkovo dam site is located in western Serbia, on the Veliki Rzav River, 8 km upstream of Arilje town. About 26 million m^3 reservoir capacity shall be formed by the construction of the embankment dam with the clay core - 60 m high and with the dam crest elevation of 423.60 m a.s.l. The area of the dam site and of the appurtenant structures comprises approximately 0.4 km^2. For the purpose of construction of the stilling basin for the diversion tunnel, within the left abutment downstream from the dam crest and up to the location of stilling basin, the terrain is steeply cut in storeys, and the upper access road S1 and the lower access road S2 were executed, up to the stilling basin at the elevation of 369.20 m a.s.l. During construction of the S2 road slopes, contemporary scars resulting from the movement of the terrain were detected at the upper access road, and in the vicinity. During the execution of these access slopes, there were no heavy rainfalls, so the occurrences of terrain instability had not been initiated by bad weather conditions. The upper boundary, i.e. landslide scar, is above road S1 at the elevation 420.00 m a.s.l., while the bottom, i.e. the toe of landslide is below elevation 369.20 m a.s.l. The landslide had affected the Middle Triassic rock complex, which consists of tectonic limestone blocks lying over completely altered tuffs, tuff breccias, and porphyrites, and partially underlying marly limestones of the Lower Triassic. Heterogeneous geological composition is further complicated by overthrusting of the Lower Triassic sediments over the younger rocks within this complex. For the requirements of rehabilitation of this part of the terrain, multidisciplinary geotechnical investigation of the terrain had been conducted, which included: detailed engineering-geological mapping of the executed slopes, drilling with coring, emplacement and monitoring of geodetic benchmarks and inclinometers, geophysical seismic and geo-electric testing, and laboratory tests of the samples. During the initial phase of research, it was established that the rock mass is heterogeneous and anisotropic along with the depth. Irregular relationships between lithological members within this complex are the rule, rather than the exception at this location. The most important conclusion related to these investigations is that the results cannot be considered individually, but only integrally. Based on the conducted investigations and tests, complex geotechnical zoning of the terrain was conducted, for the requirements of the stability analysis. As a rehabilitation measure, it was proposed to unburden moving rock material, in combination with preloaded geotechnical anchors that are executed in phases, i.e. by sections.

Probabilistic modelling of HVSR results for 3D mapping of rock-slides subsurface

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ABSTRACT: When dealing with the structural mapping of large landslides, high heterogeneity and a limited number of direct observations lead to uncertainties in the definition of a suitable geological conceptual model. In this abstract, we show a probabilistic model based on HVSR recordings dataset collected on a large-scale, deep-seated rock-slide in Northern Apennines (Italy). We addressed the representativeness and performance of the model by comparing it with the interpretation of existing surveys and by the means of cross-validation analysis. We first defined a reference landslide model based on the interpretation of 1000 m of P-wave seismic refraction tomography and 900 m of DC electrical resistivity tomography. We constrained the interpretation by evidences provided by boreholes and an airborne Lidar survey. We then performed an indicator kriging 3D interpolation based on 129 S-wave velocity vertical profiles obtained by the inversion of each of the HVSR recordings. As required by indicator kriging, we modelled three significant velocity cut-offs, namely 300, 450 and 600 m/sec, chosen by comparison between borehole stratigraphy logs and nearest S-wave velocity vertical profiles. Cross-validation analysis was employed to optimize the kriging settings. As result, we obtained three interpolations expressed in terms of a probability for the velocity value at a given location of being below the given cut-off. The interpolation based on the 600 m/sec cut-off showed a better match with the reference model, providing a good estimate of low rigidity and mobilized material. Despite being an indirect observation, HVSR recordings proved to be a good way to extend information from existing boreholes. Moreover, the probabilistic approach provides a basis to access the uncertainty in the conceptual model.

Statistical relationships for characterising rock avalanche mobility: state of the art and perspectives

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ABSTRACT: Statistical analysis of various rock avalanche databases provides relationships that link parameters, characterizing the collapsing slope (volume, slope height, maximal height drop), and parameters characterizing rock avalanche mobility (runout, angle of reach, total affected area, area of the deposits). Judgement on these relationships' reliability and on the preferability of their use for practical applications can be based on a comparison of the correlation coefficients of corresponding regression equations. It is obvious that such analysis is most efficient not for the entire database but for samples that take into consideration some important external or internal factors influencing rock avalanche motion. At present most relevant relationships were derived for three samples selected according to the confinement conditions – for unconfined, laterally confined and frontally confined cases. Each of these samples from the Central Asian database include from ca. 70 to more than 300 cases. Correlation coefficients for some of such regressions exceed 0.9. It was also found that the best correlation is between the total affected area (dependant parameter) and the product of rock avalanche volume and its maximal height drop that is proportional to the potential energy released during emplacement. Further progress in such a research field could be achieved if a larger rock avalanche database will be used. Besides higher representativeness of regressions derived according to the same sampling criteria as described above, it will allow selecting samples with more strict characteristics based on multi-level morphological classification proposed at 5th World Landslide Forum (volume 5 of Forum Proceedings). The particularly promising is to analyze factors causing variable shapes of unconfined rock avalanches that either move strictly forward, forming narrow tongues of debris, or spread sidewise significantly, creating fan-shaped or isometric aprons whose width can be comparable with length. Interrelation between such unconfined rock avalanche bodies and substrate seems to be the simplest one and their statistical analysis can provide interesting results. Samples selection using other classification criteria such as compactness of frontally confined rock avalanche dams or change of debris motion direction after collision with an obstacle can be performed as well. The database enlargement that is needed for such sampling can be provided by quantification of the remaining ca. 400 cases from the entire Central Asian inventory including more than 1000 cases, for which it has not been done yet and, also, by expanding the inventory to a much larger area. Compilation of a global database will be the best, though quite a laborious solution. Anyway, it is the aim we should pursue to.

Landslide Monitoring

Statistical literature analysis of combined GNSS-InSAR landslide investigation

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ABSTRACT: The Synthetic Aperture Radar Interferometry (InSAR) is a technique capable to detect ground deformation, by comparing the phase difference between two images over the same area acquired in two different times, since the 70s. The InSAR approach has evolved over time and several algorithms for elaborating more than two images were developed, namely Multi-Temporal InSAR (MT-InSAR), allowing the analysis of ground deformation evolution. The MT-InSAR approach has some limitations, to which (i) the recognition of movement along a Line of Sight (LoS) of the satellite, with a consequent record of a component of the real movement, (ii) a temporal limit depending on the used datasets and (iii) the assessment of a relative deformation since the MT-InSAR approach needs a Reference Point for calculating displacement and velocity of deformation.

In order to overcome these limitations, several researchers improved the landslide analysis and investigation with the use of the GNSS (Global Navigation Satellite System) data. The GNSS family, comprehending GPS (Global Positioning System), Galileo, and GLONASS (GLObal'naya NAvigatsionnaya Sputnikovaya System), allows having precise worldwide information about the positioning, timing and navigation of elements on a receiver that, with a standardized procedure, commute the information in a precise location. Differently from the MT-InSAR, this technique provides three-dimensional and absolute deformation data but works better for regional deformations for the usual large distance between adjacent stations. The sparse network of receivers limits the applicability in remote zones or the investigation of local patterns or movements.

The combination of GNSS and InSAR approaches has proved to be very useful in several issues reducing the drawbacks of each technique. Their integration may improvedifferent phases of the InSAR and MT-InSAR processing, atmospheric corrections, volcanic event investigation and analysis, as well as tectonic and seismic studies. Several advantages were demonstrated also in the field of ground deformation detection and assessment, such as subsidence, uplift, and landslide phenomena.

A literature analysis conducted using Google Scholar's freely accessible web search engine allowed gathering more than 40 scientific contributions published, among peer-reviewed articles, international congresses, and book chapters, that considered both InSAR and GNSS data for landslide investigation. The research was conducted using keywords recalling the use of the two techniques combined with, one by one, the European countries.

The research on Google Scholar search engine identified publications since 2006 over 14 European countries. The collected scientific contributions were critically analysed to identify the scope, the used radar satellite constellations as well as the spatial and temporal distribution of the publications. The state-of-the-art of InSAR and GNSS data integration for landslide investigation can

be a relevant starting point considering that in the mid of 2022 MT-InSAR data, yearly updated, will be freely available over Europe thanks to the European Ground Motion Service (EGMS) as well as the EPN (European REFerences - UEREF - Permanent GNSS Network) freely provide GNSS data of more than 300 continuously operating stations referenced to the ETRS89 (European Terrestrial Reference System) benchmarks over the European territory.

Ground deformation monitoring service of Veneto region (NE Italy) by means of Sentinel-1 data

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ABSTRACT: Spaceborne Earth Observation represents nowadays consolidated tools for the monitoring of a wide range of natural and anthropogenic displacement events occurring on the Earth's surface. The use of SAR (Synthetic Aperture Radar) sensors, since the early '90s, and the development of Interferometric and Multi-Temporal Interferometric techniques (InSAR and MTInSAR) has enabled constant and continuous worldwide observation for 30 years. Moreover, the launch of the Sentinel-1 mission by the ESA (European Space Agency), characterized by a low revisit time (6 days), open policy and rapid product delivery has fostered even more the Earth observation practices, making operational monitoring services possible. In particular, three Italian regions implemented a continuous monitoring service based on the exploitation of MTInSAR Sentinel-1 data: Tuscany started in 2016, followed by Valle d'Aosta and Veneto regions, in 2018 and 2019, respectively. Here, the operational service of Veneto region (NE Italy) is depicted: the service benefits from regularly updated deformation maps (every 12 days), generated by means of the SqueeSAR algorithm (Ferretti et al. 2011), to detect trend variation in the time series of displacement, defined as anomalies of deformation. In detail, any change in the deformation pattern (Δv=10 mm/yr) occurring in the last 150 days is identified, by setting a breaking point and calculating the average deformation before and after this. Once the anomalies are identified, if classified as persistent (i.e., repeated in the same place in subsequent acquisition) and relevant (in terms of element at risk and intensity of the movement), they are delivered to the regional authorities in charge of territorial management for defining the risk mitigation strategies. From July 2020 to April 2021, about 20'000 anomalies have been collected on the Veneto territory. Each anomaly has been classified according to the process (mainly SI, Slope Instability, S, Subsidence and MA, Mining Activities, plus ND and N, Not Determined and Noise, respectively, i.e. anomalies without any real cause assigned). All the anomalies collected were also statistically analysed, by coupling them with several types of factors, related to territory. In detail, SI anomalies were intersected with the existing landslide inventory, slope gradient, slope aspect and elevation in order to evaluate their impact over the Veneto territory. In the period of analysis, two main anomaly cases were reported to Veneto regional authorities, both related to landslides in urban setting in the Belluno province: (i) Lamosano and (ii) Rivamonte Agordino. As a consequence, field surveys and further investigations were carried out, and regional authorities undertook the proper actions to mitigate the risk. Therefore, the interferometric information along with ancillary data and the interpreter expertise are fundamental to correctly analyse the automatic highlighted anomalies. Hence, the prompt identification of anomalous movements for the early identification of any acceleration of ground deformations and the implementation of regional-scale services may represent a step forward in the prevention of natural disasters.

Monitoring the Slano blato mudflow using InSAR and UAV photogrammetry (preliminary results)

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ABSTRACT: Monitoring landslides is one of the foundations for understanding their activity. The complexity of each landslide requires different approaches for efficient monitoring, often resulting in high costs and logistical difficulties. The latter is usually directly proportional to the efficiency and accuracy of the measurements: the more money and time we invest in monitoring campaigns and equipment, the more trustworthy and accurate information we obtain. Fortunately, modern technology offers a variety of different approaches. Remote sensing techniques have become non-expensive, practical tools for an easy approach to dangerous or inaccessible large areas and provide time- and resource-efficient solutions. In this paper, we present preliminary results of monitoring the Slano blato mudflow (Vipava valley, SW Slovenia) using remote sensing. The landslide was reactivated during a major rainfall event in November 2000 during the same event two other large landslides occurred (Log pod Mangartom and Macesnik landslides). The current activity of the landslide is relatively unknown, as there have been no monitoring activities in the last decade. Morphological signs such as cracks on the surface, bent trees and minor mass displacements, show obvious evidence of active movements, therefore the need to monitor the activity is immense. The use of remote sensing to detect displacements is a logical choice due to the size of the landslide, with a length of 1.3 km and a width of up to 250 m, with a height difference of approximately 300 m between the scarp and toe. The mudflow reaches and flows through the bed of the Lokavšček spring, which leads directly to the settlement of Lokavec.

In this study, we combine the use of aerial photogrammetry using a drone and satellite radar interferometry (InSAR) to determine active zones and define vertical and horizontal displacements. Due to the absence of vegetation and adequate spatial orientation, we considered the area suitable to test this methodology for potential long-term monitoring. Aerial photographs with the drone are taken in campaigns based on rainfall seasons. The pre-programmed routes take about 2 hours. Due to the relatively low flight altitude (about 75 m) and the high-performance camera, we can produce high resolution photogrammetric products with a ground sampling distance of 2 cm. The latter complements the low spatial resolution of InSAR, which is about 15-20 m for Sentinel 1 images. The determination of vertical changes in topography is much more precise with InSAR than with photogrammetry, providing an accuracy of about 1 mm/year. The accuracy of photogrammetric products is generally dependent on their spatial resolution. We also check and validate the results of horizontal movements with fast static GNSS measurements. Due to the ongoing monitoring, that began in June 2021 and will be performed until June 2023, we are only able to present preliminary results.

Validation of innovative mitigation strategy through long-term landslide and structural monitoring

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ABSTRACT: Long-term monitoring is a fundamental tool for the study of medium-to-large slow moving landslides that might be eligible for structural countermeasure works. Since in the design of geotechnical numerical models, uncertainties regarding the soil parameters are high, the possibility to rely on monitoring data to calibrate the model is a fundamental tool to check the robustness and overall value of the reference model. Sometimes, by analysing the signals between potential triggering factors and displacements on a long period, comprising also extreme meteo-climatic events, it can be possible to skip the numerical modelling step altogether by acting directly on the activating factors. In this case, a grey box model that needs to be validated on one additional dataset might be defined. In this work, we present a case study consisting of a complex shaped slope instability crossed by a stream called Rio Verde. The scarp of the slope cuts across a National Road that connects the Veneto and Friuli Venezia Giulia regions (Italy). The potential risk of road disruption with major impacts on the valley economic life is high. A dataset of continuous monitoring of several years is available for the landslide. It consists of Global Navigation Satellite System (GNSS) data, piezometer, in-place inclinometers, and a thin plate weir that continuously measure the Rio Verde's discharge. A grey box model linking the landslide displacements with the Rio Verde discharge has been proposed. Based on these results, new monitoring instruments have been installed, and a low-cost mitigation strategy consisting in the removal of the water from the stream is being implemented. Since the typology of the countermeasure work is unconventional, the protraction of the continuous monitoring is fundamental to assess and quantify the efficacy of the measure, to validate the conceptual grey box model, and to decide to proceed with an additional intervention if needed be.

Long-term monitoring of active large-scale landslides based on integrated systems in South Tyrol (SoLoMon project)

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ABSTRACT: Active large-scale landslides alternate long-lasting "ordinary" semi-steady-state slow moving periods of activity to short-lasting "non-ordinary" acceleration phases that can lead to major damaging events. As their complexity and dimensions determine serious technical difficulties in implementing cost-effective structural mitigation measures, long-term monitor is crucial for risk reduction, as it allows for a better understanding of the spatial and temporal behaviour of the phenomenon and, therefore, to focus on the most risk-significant elements of the landslide. Nowadays, a large selection of methods is available for the integrated cross-validated multi-scale multi-source monitoring of such phenomena in order to achieve a sound knowledge of slope movements on a continuous and time-lapsed basis.

The EFRE-FESR SoLoMon project aims to apply relevant remote, proximal and in-site monitoring techniques to representative case studies of large-scale landslides in South Tyrol, namely: (1) the Ganderberg Deep-seated Slope Deformation; (2) the Trafoi rock slide and (3) the Corvara earthslide-earthflow. The "ordinary" movements rate of (1) and (2) are in the order of some cm/year, while for (3) it ranges from cm/year to dm/year depending on the considered landslide section. During the last decades, "non-ordinary" acceleration phases in (1) and (2) reached one order of magnitude higher and damaged roads and threatened houses. A few centuries ago, (1) also dammed the valley when a rock slab detached from the scarp and evolved as rock-avalanche. At the same time, recent "non-ordinary" acceleration phases of (3) reached up to some m/day damaging skiing infrastructures and threatening a national road and some houses.

In the frame of SoLoMon project, the following monitoring techniques are applied in an integrated manner: (a) periodic (once per year) high-resolution (5 cm) airborne Lidar and Orthophotos surveys of the entire landslides analysed with Dem of Difference and Offset-tracking techniques (landslides 1, 2, 3); (b) Continuous Robotic Total Stations monitoring using reflectors (landslides 2, 3); Continuous in-place D-GPS (landslides 1, 2, 3). Monitoring data from these systems will be integrated in a single functional web-accessible portal together with other relevant datasets gathered during previous projects by landslides mapping, periodic D-GPS surveys, automated inclinometers and piezometers, PSI and CR interferometry. The portal will feature data analysis tools and routines that will allow the discretization of areas characterized by an homogenous cinematic by integrating machine learning algorithms such as hierarchical clustering. In addition, data will be

viewed and queried simultaneously in the graphical interface allowing the integration of all the information. Furthermore, the monitoring database will be used to activate automatic or semi-automatic self-adapted alert procedures based on previously measured displacement trends. The presentation aims to illustrate the project, the characteristics of the test sites and the preliminary results obtained.

Monitoring of rockfall prone areas in eastern Slovenia

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ABSTRACT: In recent years, about ten large rockfalls with a volume of more than 10,000 m^3 have been observed in the eastern part of Slovenia, causing damage to infrastructure, and resulting in two fatalities. However, rockfalls in size from a few cm^3 to a few m^3 occur daily and endanger residential and commercial buildings, roads, and railway lines. The most problematic are very narrow valleys with very steep slopes above and below the railway line. Because rockfalls occur suddenly and usually without visible warning signs, they are extremely difficult (or impossible) to predict and thus pose a major potential risk to people and infrastructure. Within the framework of the project Development of Research Infrastructure for International Competitiveness of Slovenian RRI Space - RI-SI-EPOS - a set of pilot areas were equipped with meteorological and geotechnical sensors (rain gauges, air temperature and humidity sensors, tilt gauges, kit for measuring rock stress and deformability, laser distance metres, crackmeters and rock temperature sensors) providing real time monitoring data. Monitoring areas were selected based on the following criteria: frequency of rockfalls, risk to the population and infrastructure, and diversity of rock composition (carbonate and igneous rocks). The research also considers that each individual rock type has different engineering properties and predisposing factors that can affect exfoliation, discontinuity formation and fractures. However, the type of rock, its mineralogical nature, anisotropy, or isotropy very often determine susceptibility to fracture formation and subsequent opening of cracks. In the framework of a new research project (ARRS J1-3024, 2021-2024), we will study the sensitivity of rock faces to climatic change and variations in freeze-thaw cycles in the selected pilot areas. To achieve this goal, we will use a multi-method approach consisting of experimental field measurements, observations, and monitoring that will allow us to determine the initial state of rock instability, the associated volume and frequency of rockfalls, and the near-surface rock temperature. This will be accompanied by numerical modelling and numerical simulations using the finite element method to estimate the accumulation of damage and the evolution of stress and temperature fields due to changes in ambient temperature and freeze-thaw cycles in the rock face. In this paper we will present the pilot areas and the first results of the eight months field monitoring.

Landslide Mapping

A landslides database model for CliRtheRoads project in Serbia

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ABSTRACT: Within the project Mainstreaming Climate Resilience in the Road Transportation Management in Serbia (CliRtheRoads), a complex software solution was developed to support Public Enterprise Roads of Serbia in climate change adaptation planning and management. The software solution comprises 1) a web portal for data entry and management for authorised users 2) publicly available web GIS part 3) mobile GIS application and 4) back-end database.

In order to store and process the data collected during field visits and surveys, the database developed in the project first phase (Valjevo test area), was modified to include new datasets and to store new datatypes (as floods), and new modules (as activity cost) for Kraljevo test area. Both test areas have been chosen due to their diversified characteristics, many climate related hazards, and the fact they suffered greatly from disasters recently. The database was upgraded to a new model to maintain legacy data from both test areas and future infrastructure resilience projects based on the same approach to enable all data to be stored and mapped in a unified manner. The data model includes 1) main concepts (entity types) for the instabilities, with detailed data comprising common and specific attributes, 2) storage of multimedia (mainly photo from field work, but possible video as well), 3) knowledge base with the cost of activities, including catalog per each entity type with job type and description, unit and total price, maintenance type (regular maintenance, rehabilitation, urgent maintenance), including recommending activities (system allow a user to add specific activities, description, and cost that is further calculated and aggregated with other data); 4) secondary data from other sources (other projects, legacy data, and external resources), or from interpreted data. The data was stored in the PostgreSQL Database, a web application was developed (using PHP) to facilitate data input, maintain a knowledge database and calculate the cost of recommended activities. There are 461 records with fully described instabilities (slides, falls, topples, flows), documented by a large number of photographs from the field. Additionally, every record is supplemented by engineering solutions to support field engineers or decision-makers for better road management in climate changing conditions.

In this paper, we will present a data model of the system and software solution for the automatization of the procedures for selecting proper intervention and investments of engineering and non-engineering measures for the road network.

Qualitative and quantitative assessments of input LiDAR data for landslide inventory mapping

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ABSTRACT: An innovative technique for detailed landslide inventory mapping is airborne laser scanning and LiDAR-derived DTMs in high resolution. LiDAR data used in this study was obtained in the framework of the "Methodology development for landslide susceptibility assessment for land use planning based on LiDAR technology (LandSlidePlan IP-2019-04-9900)" project fully supported by the Croatian Science Foundation. To select the optimal digital terrain model (DTM) for landslide delineation, quantitative and qualitative assessments were done individually for three landslides. The quantitative assessment included a comparison of minimum, maximum, mean, and standard deviation values of DTMs derived by using four interpolation methods (Kriging, IDW, Natural Neighbor, and ANUDEM) in six raster resolutions (0.15, 0.3, 0.5, 1, 2, and 5 m). Furthermore, by comparing point cloud LiDAR data and interpolated DTMs elevation values, the mean-absolute-error difference (MAE) and root-mean-square-error (RMSE) were calculated. Hillshade, roughness, and curvature morphometric maps were derived for 24 DTMs per landslide, resulting in the qualitative assessment of 216 different morphometric maps. The quantitative assessment showed minimum and negligible differences between DTMs for landslide areas; therefore, the qualitative assessment prioritised determining the optimal DTM for deriving morphometric maps needed for landslide delineation. Based on visual interpretability of landslide parts (i.e., crown, ridges, and toe) and the terrain quality (i.e., expressed details, irregularities, and blurriness) on the derived morphometric maps, the LiDAR DTM derived using the Kriging method in 0.3 m resolution was selected for landslide inventory mapping in further studies.

Landslide inventory mapping based on LiDAR data: a case study from Hrvatsko Zagorje (Croatia)

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ABSTRACT: This paper presents a result of landslide inventory mapping at the Bednja Municipality and Lepoglava City study area in NW Croatia. The landslides were interpreted from the high resolution (30 cm) digital elevation model (DEM) and its derivatives (slope and contour map, hillshade). The DEM was interpolated from the point cloud obtained by laser scanning undertaken in spring 2020. The scanned area (approximately 20 km^2) is predominantly a hilly area, with bedrock geology of predominantly Miocene sediments composed of sandstones, marls, and limestones. The total number of interpreted landslides was 912, which makes the average density of 45.1 ls/km^2. The maximal interpreted landslide area was 13,779 m^2, and the minimal interpreted landslide was 3.3 m^2.

Additionally, landslide distribution was analysed related to land use, distance to roads and buildings. According to the spatial plans, most of the studied area is covered by forests, agricultural areas, pastures, and artificial areas. The highest density of landslides is also in the forest areas, while the

lowest is in the artificial areas. Furthermore, almost 64% of the mapped landslides are located within 50 m of the roads, and more than 39% of the mapped landslides are located within 100 m of the buildings and residential houses. Due to the level of detail provided and its completeness, the presented landside inventory map is an important tool for risk management at the local level because it gives detailed information necessary for risk evaluation as well as to decide about feasible options for risk mitigation, e.g., stabilisation measures vs relocation of the development to a more favourable location.

High resolution LiDAR DTM reveals new insight on landslide phenomena in the Rječina River Valley

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ABSTRACT: This paper presents the results of landslide detection and detailed landslide mapping in the Rječina River Valley (19 km^2), situated in the hinterland of the city of Rijeka, based on the visual interpretation of high resolution (1 x 1 m) airborne LiDAR (Light Detection and Ranging) Digital Terrain Model (DTM). The application of the innovative tool in landslide research resulted in the identification of a large number of landslides in the Rječina River Valley, significantly larger than expected given the previous knowledge about landslide phenomena in this area. Namely, previous researches were mainly focused on large, deep-seated recent and historical landslides which have been occurring for more than 270 years, while the number, types, and spatial distribution of relatively smaller but rather frequent landslide phenomena covered by dense forests were mostly unknown. Hence, the visual interpretation of different topographic datasets derived from the 1-m LiDAR DTM has revealed more than a thousand landslide phenomena in the study area and enabled the creation of the first geomorphological historical landslide inventory of the Rječina River Valley at a scale of 1:2,000. Given the geomorphological settings and landslide characteristics, four groups of landslide phenomena can be generally distinguished: (i) large and very large, deep-seated historical landslides located in the central part of the Rječina River Valley; (ii) large and large-moderate landslides predominantly located on slopes in the upper part of the Rječina River Valley; (iii) small to moderate-small landslides located within gullies formed in the upper and the central part of the Rječina River Valley; (iv) and very small to small landslides formed by bank erosion of the Rječina meandering watercourse. Very small and small landslides prevail in the study area, with an average landslide area of approximately 1.600 m^2. This new insight can significantly serve not only for a better understanding of geomorphological processes in the study area but also for geological hazard and risk assessment that could be applied for spatial planning, engineering, and civil protection purposes.

Influence of expert knowledge on completeness and accuracy of landslide inventory maps - Example from Istria, Croatia

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ABSTRACT: In this paper are presented possibilities for using remote sensing LiDAR data for landslide identification and mapping and the influence of expert knowledge on the results. Visual interpretation of landslides was carried out on high-resolution airborne laser scanning (ALS) LiDAR dataset. Scanning was undertaken in March 2020 for a pilot area in the City of Buzet, Croatia. Based on the characteristics of the acquired LiDAR Point Cloud, bare-earth DEM with 30 cm resolution was created. Several different topographic derivative datasets such as slope, hillshade, contour lines, and roughness maps were created in order to interpret the LiDAR data. Seven experts with different levels of expert knowledge on LiDAR interpretation were given one week to carry out visual identification and mapping of potential landslides at a large scale (1:200) to ensure detailed landslide mapping. Statistical analyses were performed based on the collected data to determine differences in the mapping accuracy and the number of recognized landslides between different experts. Results show that experts familiar with the geology of the study area and with potential landslide mechanics obtained better results than experts who mapped landslides based only on topographic and geomorphological features specific for landslide movement. Notwithstanding, the overlap of all mapped landslides did result in a substantially complete inventory map based on the landslide frequency–size distribution in the pilot area.

Slope gradient anomalies as indicators of potential slope instabilities

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ABSTRACT: From a geomorphological point of view, slope mass movements could be considered as natural mechanisms of slope equilibration. Unequilibrated hillslopes could theoretically be indicated with the areas of the ongoing slope processes which will complete with the temporary stabilisation of the hillslope. To determine the areas of potential past occurrences of the slope mass movements, we modified the GLA index which was primarily developed for the identification of river gradient anomalies caused by the recent tectonic uplift or subsidence (Žibret and Žibret, 2014; Žibret and Žibret, 2017). We present the test whether the modified GLA method named the slope gradient anomaly (SGA) method, can be applied to active slope mass movements, and present preliminary results of the application of this method to hillslopes on several known landslide areas and several random areas, where we test the wider applicability of the method. This is an initial report on how to detect active slope mass movements with the analysis of DEM with the SGA

method based on the concept of linear slopes. Preliminary results of the testing carried out on a limited number of samples indicate high potential for detecting middle to large-scale landslide events and expose the limitations regarding the precise selection of profiles and an impact of artificial constructions which may give false-positive results. Further tests and modifications are required, including the appropriate selection of correct orientation and position of the profiles, segmentation, correct mathematical slope approximations, automatization of the process etc. to develop a reliable new method for the detection of active slope mass movements. The most promising aspect of this method is in its potential for automated detection of the past landslide events which would allow fast and automatic processing of the large areas of interest and considerably expand the existing landslide databases.

Landslide Susceptibility, Hazard and Risk Modelling

LandSlidePlan - Scientific research project on landslide susceptibility assessment in large scale

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ABSTRACT: The scientific research project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (LandSlidePlan, HRZZ IP-2019-04-9900), funded by the Croatian Science Foundation, deals with new and under-investigated subjects in respect of inventory mapping of small and shallow landslides and presents innovative approaches to scientific research of landslide susceptibility assessment using cutting-edge LiDAR technology for collection of input data. The project has three main scientific goals. The first goal is to create the best optimal digital model of the bare-earth terrain that shows realistic landslide footprints and differences between disturbed and undisturbed land that may influence land use. The second goal is to create the most reliable large scale landslide susceptibility map with the best differentiation of landslide-prone and non-susceptible areas using scientific methods customised to specific engineering geological conditions of Croatian environments with sliding threats. And the third goal is to create maps depicting information about landslides tailored according to the needs of the system of physical planning in Croatia (particularly land-use planning), encompassing local and regional levels under, harmonised at the national level. Due to different natural conditions and land uses in different parts of Croatia, the methodology will be developed for pilot areas in the City of Zagreb, Hrvatsko Zagorje and Istria, selected based on characteristic geological settings and degree of urbanisation.

Shallow landslide susceptibility assessment for the Polog region (North Macedonia)

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ABSTRACT: This paper presents the results of shallow landslide susceptibility assessment over the Polog region (extending for approximately 1000 km^2) in Macedonia. The geomorphological setting of the Polog study area, the complex geology, and the specific hydro-meteorological conditions make this region one of the most landslide susceptible areas in the country. According to the available landslide inventory for the Polog region, 21% of the landslides are confirmed in the class of shallow landslides. For shallow landslide susceptibility assessment over the study area, the infinite slope stability method was used. This is a simple but very useful model for shallow sliding which assumes that landslides are infinitely long but have small landslide depth compared with their length and width. Due to the complexity of the analyzed phenomenon, the variability of influential factors, and uncertainty in parameters, as well as considering that this is regional-scale analysis, the pure mechanical modeling of the problem was very hard. In order to get a sense of the shallow landslide susceptibility, several possible scenarios were analyzed such as three water saturation states of the ground (35%, 70%, and 100%) and minimum and average values for geotechnical parameters of the lithological units. The obtained susceptibility maps indicate that the most prone zones for shallow landslide occurrence match with most landslides from the inventory. This model is limited in regards to the availability of data related to soil thickness and a relatively low number of data (and unevenly distributed in the region) for the geotechnical parameters of soils and the groundwater regimes. For more advanced analysis, detailed in situ geotechnical testing and sampling and monitoring of rainfalls, surface water regimes, and groundwater levels are recommended.

Landslide susceptibility map of Croatia based on limited data and Fuzzy logic approach

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ABSTRACT: The objective of this study is a presentation of the landslide susceptibility assessment on a national scale for the Republic of Croatia using a heuristic approach. The effects of controlling factors on landslide susceptibility were estimated using the Fuzzy logic approach based on a multiclass overlay of landslide predictor maps. The predictor set relates to topographic variables, geomorphological factors, geology factors, and land cover. The selection of relevant landslide factors and the final landslide susceptibility assessment depends on subjective factors, such as

researcher knowledge of the study area, respectively knowledge of different landslides types and processes in the study area, etc. For these reasons, it was necessary to verify the final landslide susceptibility map with data on known landslides. During the last few years, the scientists from the Faculty of Mining, Geology and Petroleum Engineering in Zagreb were systematically collected data on landslides, and the database of 2,186 landslides with the exact location of the occurrence was conducted. The Area Under the Receiver Operating Characteristic Curve (AUROC) was used to validate derived landslide susceptibility maps and select the final one for further classification into three susceptibility zones. With over 90% of mapped landslides falling in high and very high susceptibility zones, the results are considered satisfactory for national scale landslide modeling. The landslide susceptibility map of Croatia was created to give a general overview of problem areas for an entire country, and it can be used to inform national policymakers and the general public. The analysis showed that approximately 20% of the area of Croatia is potentially prone to sliding. Particularly landslide-prone areas in Croatia are lowlands and hills in the Pannonian Basin, the hills of the Istrian Peninsula, and isolated narrow valleys in the Dinarides, such as Rječina River Valley and Vinodol Valley in Primorje.

MASPREM – Slovenian landslide forecasting and warning system

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ABSTRACT: The morphology of the slope, unfavorable geological and tectonic conditions, and climatic diversity contribute to the high susceptibility to landslides in Slovenia. Previous studies have shown that one-third of Slovenia is highly susceptible to landslides. Recently, landslides have been quite frequent and have caused significant damage to infrastructure, buildings, and agricultural land. According to the latest data from the Ministry of the Environment and Spatial Planning, landslides have caused damage of about 350 million euros in the last ten years. The most common phenomenon in Slovenia is shallow landslides, caused mainly by intense short- or long-lasting rain events.

The fact that Slovenia is highly exposed to landslides underlines the need for preventive measures to reduce the hazard associated with landslides in the future. Therefore, in 2011, the Geological Survey of Slovenia (GeoZS) started developing the MASPREM system to predict landslides hazards due to increased rainfall in Slovenia. Today the system is fully automated and based on open-source software (PostgreSQL, PostGIS, Java, MapServer, OpenLayers). The system runs every 12 hours and reaches the forecast 24 hours in advance.

The calculation of the forecast model is based on the following input data: national landslide susceptibility map, threshold values for each engineering-geological unit, and rainfall forecast models ALADIN/SI and INCA (obtained by Slovenian Environmental Agency). The results of the calculated landslide prediction models are displayed in the form of maps with a five-level scale on the web application control panel. In case of a calculated hazard, the system automatically sends an e-warning to registered users. MASPREM is also used by the GeoZS emergency service, which provides early warning in the case of increased hazard of landslides and by the Administration of

the Republic of Slovenia for Civil Protection and Disaster Relief. In addition, the Slovenian landslide forecasting and warning system, aimed at better understanding and reducing landslide disaster risk, was also written down in the latest Kyoto2020 Commitment for Global Promotion of Understanding and Reducing Landslide Disaster Risk (KS2020), a long-term and global framework for the landslide community to develop ISDR-ICL Sendai Partnerships 2015–2025.

In 2021, the system MASPREM received the Bronze Award for Regional Innovation from the Chamber of Commerce and Industry of Slovenia.

Harmonized approach for mapping the earthquake-induced landslide hazard at the cross-border region between North Macedonia, Greece and Albania

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ABSTRACT: For landslide hazard assessment in cross-border regions, a harmonized approach for susceptibility and hazard mapping is essential, applicable in all countries. This paper presents the harmonized approach for landslide susceptibility and hazard assessment at the cross-border region between North Macedonia, Albania, and Greece. The adopted methodology is based on a thorough review of both the current national perspective in terms of available data and research for landslide hazard assessment in the three countries and of the available European projects dealing with landslides hazard assessment. Indeed, the European ELsusv2 initiative is selected as a harmonized approach for regional landslide susceptibility mapping for the cross-border region under investigation. The earthquake as a triggering effect is considered to produce landslide hazard maps in terms of permanent displacements caused by different earthquake scenarios. The peak ground acceleration value within the slide mass required to cause the safety factor to drop to 1.0 is denoted by the critical or yield acceleration ac. This acceleration is commonly determined based on pseudo-static slope stability analyses and/or empirically based on slope behavior observations during past earthquakes. Critical acceleration ac values are assigned to each category of landslide susceptibility from the Elsusv2 maps for the cross-border region. The suggested ac values based on engineering judgment align with the ones proposed in Hazus methodology for landslide hazard evaluation.

Further on, an analytical relationship is used to assess the permanent slope displacement for the different earthquake scenarios. The final product of the landslide hazard zonation is presented by GIS maps of expected permanent displacements for the pre-defined earthquake scenarios for mean return periods equal to 475 and 975 years, respectively. The presented approach for the cross-border region is a simple tool used to recognize the hazardous areas, where only limited available

geotechnical and seismological datasets exist. It should be pointed out that this approach can be a good starting point for further alternate approaches-new directions, which are progressively developing into the communities dealing with landslide hazards. It is essential to emphasize the necessity in creating a national strategy for landslide hazard and risk management by different triggering events (rainfall, earthquakes) for future better mitigation plans and urban development of the cities. The presented research was performed in the framework of the CRISIS Project (101004830 - CRISIS - UCPM-2020-PP-AG) supported by the Union Civil Protection Mechanism. The landslide hazard maps will contribute to the definition of the risk of the infrastructure due to landslide triggering in the different Working Packages of the project. The project CRISIS and the landslide hazard zonation provided for the cross-border region will contribute towards better long-term mitigation strategies in each of the countries involved in the study.

A proposal for the landslide damage questionnaire in suburban areas

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ABSTRACT: In this paper, we propose a landslide damage questionnaire that can be used for landslide damage characterization and determination of landslide hazard and risk in suburban areas. Landslides are one of the most often and most expensive natural disasters. Landslide losses are significantly different and they depend on a variety of different criteria such as the size and type of landslide, lithological setting of terrain, the terrain slope gradient, the quality of materials used for construction, and the construction typology. Buildings and a variety of other structures can be damaged or even permanently destroyed (roads and other infrastructure). Damage from landslides is usually characterized as either direct or indirect and in most questionnaires only data about the direct damage is collected. We have selected the Umka landslide near Belgrade as a case study. The Umka landslide is the most systematically investigated and one of the biggest populated landslides in Serbia. Landslide is still very active, with known mechanisms and sliding intensity for the last 50 years. Landslide is active at least for several decades, and its genesis is tightly related to the evolution of Sava meanders and its level fluctuation. Although the landslide is known and occasionally mentioned in public and mass media, certain migration of population is still evident. Besides permanent displacement from the landslide – some new housing objects with permanent residents are still occurring, even within the most active and most affected part of the landslide, which is probably caused by significantly lower prices of households in this area. The Highway Institute from Belgrade performed the last inventorying and damage classification on objects during 1989–1990, when a map and brief report of the damaged objects was created (with the type of foundation, walls, and category of object). During that investigation the local water system was mapped and population was evaluated using the most recent census data. Since the last

inventorying was performed 25 years ago, and a landslide is still not stabilized and despite the fact that project documentation for stabilization exists from that time, the vulnerability of the population is still present, while in some areas it is even more intense, as a result of unplanned and illegal construction works during after the 2005, when all construction works are officially banned for the most active parts of the landslide. Previous inventorying didn't include the info about households and population working and life habits which is necessary data for the risk estimation. Given the foregoing, there was a requirement for an updated inventory of all objects that are in risk area. The base for the creating new inventorying sheet was abovementioned questionnaire from 1989-1990. Our proposal of questionnaire contains 11 groups of questions that include all necessary fields for gathering the data which is essential for landslide hazard and risk estimation. It can be used as a basis for inventorying landslide damage in suburban housings which usually occupy larger land plots.

Slopes of higher protection priority rating using modified Colorado Rockfall Hazard Rating System - Case study

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ABSTRACT: Rockfall is the fastest and the most frequent type of landslide affecting the Croatian coastal area, and as such represents the threat to infrastructure positioned under rock slopes. On the large-scale roadcut sections, it is necessary to determine zones that pose a greater risk to the infrastructure, i.e. higher protection priority zones. The studied road section is located on the south-eastern coast of Istrian Penninsula, connecting villages Brsec on the south-west and Moscenicka Draga on the north-east. The existing road is approximately 8,0 km in length, executed mostly by cutting into the existing terrain, with the sub-vertical slopes up to 16,0 m high. Rock mass of the roadcuts is built out of sedimentary carbonate rocks - limestones and dolomites. The wide area belongs to the Ucka-Cicarija Onlay, a tectonically very active area in geological history, causing many discontinuity systems and fault zones resulting in different structural problems within roadcuts. To determine the zones of higher protection priority, a modified Colorado Rockfall Hazard Rating System (CRHRS) was used. CRHRS recognizes several different factors that contribute to rockfall: slope profile factor (slope height, segment length, slope inclination, and slope continuity), geological factor (state of discontinuities/erosion rates of material, block size, or volume of material expected to fail), climate and presence of water on the slope (amount of precipitation, occurrence of freeze and thaw periods, and the duration that water is present on the slope), rockfall history (frequency of rockfall occurrence) and a number of traffic accidents attributed to rockfall. Within the project, 66 zones of the studied road section were distinguished. According to the recommended priority levels, different slope protection measures were carried out.

Analysis of land surface and air temperatures in Slovenia for rock weathering and rockfall activity assessment

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ABSTRACT: Rockfalls are frequent mass movement events, caused by different factors and triggered by earthquakes, storms, strong winds, rainfall, etc., or human activities. Rockfalls are more frequent in areas with the high energy potential of terrain (steep slopes, rock faces), further enhanced by the in-situ weathering of rocks. For physical weathering, hydrometeorological factors are important, such as air humidity, air temperatures, wind direction, wind intensity, precipitation types and amounts. The weathering rate also depends on the rock type and the discontinuities present. In order to study rock weathering and potential rockfall activity in Slovenia, an analysis of land surface temperatures and air temperatures was performed. For the former, the ERA5-Land reanalysis data provided by the Copernicus, and for the latter, the measured data in the precipitation monitoring network of Slovenia (Slovenian Environment Agency-ARSO) was applied. The grid for LST was 9x9 km, and the number of meteorological stations in Slovenia used was more than 150, the period under analysis was 2015-2020. We used hourly data to better assess frost weathering potential. Station-based air temperatures were compared to land surface temperatures and their diurnal, monthly, and seasonal differences were discussed. Furthermore, local data from the nine geological laboratories in Slovenia operated by the Geological Survey of Slovenia were used (air temperature, rock cliff temperatures). Using satellite land and air temperature data, analysis of the number of daily freeze-thaw events per year was conducted and a corresponding Rock frost-weathering susceptibility map of Slovenia was prepared. The developed susceptibility map was compared with the Informative Rockfall Susceptibility map of Slovenia (from 2011) and with data from the rockfall inventory of Slovenia, handled by the Geological Survey of Slovenia. A comparison with the Rockfall stability map of Slovenije with a grid 242 x 242 m produced in 1996 was done. The Rock frost-weathering susceptibility map of Slovenia with a resolution of 9x9 km was then using solar insolation data, slope inclination data, rainfall data, and rock-type susceptibility to rock-falling upgraded to an improved Rockfall susceptibility map. Rock-type susceptibility to gravity mass wasting was prepared on the basis of lithological types, which are classified in Slovenia into 28 engineering-geological units. All engineering-geologic units were divided into 6 classes of rockfall susceptibility, with 1 indicating very low rockfall susceptibility and 6 indicating very high rockfall susceptibility.

Regional rockfall exposure assessment, experience from Serbia

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ABSTRACT: Rockfalls are common in hilly and mountainous areas, especially along roads with engineered slopes and cuts. Such is the case for most of the road routes in Central, Eastern, Western and Southern Serbia, especially on low-category state and local roads. Rockfalls can induce hazards of high magnitude and frequency, causing temporary or long-term effects. They impose constant problems to the road management enterprises, requiring frequent maintenance or mitigative activities. Therefore, strategies that are including rockfall hazard assessment are increasingly important in road management, but also in planning, engineering design, and research, and such practice is in its beginnings in Serbia. In this article, experience from a case study in Central Serbia, covering a pilot road network of 276 km within an area of roughly 1700 km^2 will be presented. The sampled road network transects hilly to the mountainous area of complex geological features, strongly tectonized and intensively weathered, which meets conditions for a rockfall-prone environment. Assessing wider areas for rockfall occurrences needs to be conducted from a large to site-specific scale, which from the implementation point of view translates to implementing GIS spatial tools and local 2D-3D numerical stability models, respectively. In the present work, the former, i.e., the regional scale of assessment, using GIS tools was in focus. The primary input was the Digital Terrain Model, obtained from open data ALOS mission at 12.5 m resolution. The first step was to delineate areas that can host unstable blocks, which was done by inspecting planar sliding kinematic condition against available data on slope angle and azimuth, discontinuities strike and dip, as well as the internal friction angle, which was all estimated or interpolated across the present lithological domains by various raster operations in a GIS environment. In total, there were nearly 5000 potential detachments delineated in the entire area. The further step was to run the rockfall simulation by using delineated detachment zones as input source points in a simple kinetic model CONEFALL, available as a GIS-based standalone tool. The output model simulated several thousands of rockfalls throughout the area, differing in runout distance (from a couple of tens of meters to 650 m), velocity (up to 42 m/s), and energy (up to 1040 kJ). When overlapped with the road network sample, the resulting model reveals the network exposure to rockfall, highlighting locations with runouts that reached the road lines, which makes about 6.7% of the total network length. Therein, zones of estimated velocities and energies lower than the manageable threshold occupy 95%, while the remaining 5% cannot be coped with standard measures (mesh, concrete or elastic barriers, etc.). This is an excellent quantification tool for supporting decisions on road maintenance, planning, prioritizing, and budgeting.

An upgrade to the erosion risk assessment method of active flysch cliffs along the Slovenian coast

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ABSTRACT: Many coasts are subjected to high erosion and can pose a threat to residents and visitors to the coastal areas. Problematic are steep slopes in unstable rocks or sediments, which are undercut by erosive forces of sea, wind, and precipitation, along with other geologically destructive factors such as physical and chemical weathering, freeze-thaw cycles, etc. Eocene flysch, occurring on the Slovenian coast, represents an alternation of mostly thin-bedded marlstones and thin- to thick-bedded sandstones, with rare intercalations of carbonate megabeds. Due to its heterogeneity, flysch is very problematic and susceptible to erosion and to all of the above-mentioned influencing factors. In the beginning of 2021, the parish house close to the main church in the city of Piran on the edge of the cliff needed to be supported by civil engineering measures due to the undercutting of its foundations. Small landslides (rockfalls and falling stones/rocks) and subsidence of the area at the top of the cliffs also appear in the more exposed areas. To quantify the erosion risk of the Slovenian coastal areas, we propose an upgrade of the erosion risk assessment method of active coastal cliffs, presented by Rio & Gracia (2009, Geomorphology 112). These authors presented a practical GIS-oriented approach for the determination of three indices: 1. Hazard Index (HI), representing several physical variables (lithology, slope, exposure to water storm fronts, sea-level changes, etc.), 2. Impact Index (II), represents the socioeconomic variables (land use type, presence of nature reserves, population density, change, etc.), and 3. the final Risk Index, which is weighted and combined from the HI and II. All indices are quantified into classes from 1 to 4 and can be presented on the map, showing the areas of each risk level. Coastal flysch cliffs of Slovenia were divided into 30 sections, and the mentioned factors and indices were calculated for each section. Preliminary results show quite different values of indices among the sections, with differences attributable to their different exposure to the sea waves, wind, different lithological composition of the flysch, populated areas, etc. Our upgrade consists of several modifications of the original method; firstly, the modification of the lithological factor, as all analyzed rocks are in the flysch, and their thickness varies a lot. Secondly, the introduction of the influencing factor of the wind, as very strong winds from various directions are present in the area, and they contribute to both direct and indirect erosion, by moving the tree roots. Additionally, some of the originally proposed factors like Rocky shore platform, Tidal range, Difference between the storm and modal wave height, Relative sea-level trend, and Rainfall have all the same values in our area due to relatively small extent, so we are proposing modifications of these as well, to emphasize the differences among the studied sections. We are still upgrading and testing our method to include all the necessary factors and are comparing the GIS-obtained results with direct mapping of erosion-related relief changes with Unmanned Aerial Vehicles (drones) and Terrestrial laser scanning (TLS) of the selected flysch sections.

Laboratory Testing, Physical and Numerical Modelling of Landslides

Numerical simulations of landslide physical model results

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ABSTRACT: Physical models are widely used in landslide research. They allow direct and accurate measurement of the main driving forces and features of the fundamental processes regulating a landslide. Physical modelling is principally used to: i) investigate specific or general landslide mechanisms, ii) validate mathematical formulations or numerical codes, iii) infer how a real in-situ slope and landslide scenario may evolve. This paper will provide some remarks on the first two issues. The FEM (Finite Element Method) and MPM (Material Point Method) analyses of a reduced-scale slope model that is gradually saturated by water table raising, is used as a benchmark. In this case, the experiment shows that the slope fails by shear and then liquefaction occurs, and numerical simulations can capture such slope instability sequence. On the other hand, flume tests of saturated granular flows are simulated via SPH (Smooth Particle Hydrodynamics) to interpret the spatio-temporal evolution of the pore water pressure within the rapid flow. An example of test regarding Landslide-Structure-Interaction is also proposed. The paper discusses the extent to which physical models and numerical simulations are complementary. The limitations of both types of approaches are also highlighted, such as scale-effects or computational costs.

Physical modelling investigation and integrated analysis of landslides for defining risk scenarios

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ABSTRACT: Predicting natural processes, such as rainfall-induced landslides, is a problem of great importance. Every year, meteorological events trigger both superficial and deep landslides on many slopes, causing damage and victims. The study presented here focuses on the hydraulic and hydrologic issues that take place in an unstable slope under the rainfall infiltration. The mentioned studies are dealt through a physical modelling, a numerical simulation techniques, and through in situ experimental measurements. Our research is based on an integrated approach which, starting from the observation of the real phenomenon, reproduces the observed phenomenon in the laboratory and models it using an appropriate mathematical scheme. The in situ data refer to a

monitoring station installed near the site where a large mudflow occurred. The physical model consists of 2 connected, independently tilting flume branches (respectively designed to study landslide triggering and propagation), each 1m wide and 3m long. The flume is equipped with tensiometers for measuring soil water potential inside the slope, a Time Domain Reflectometry (TDR) system and probes for measuring soil volumetric water content, and laser transducers for measuring soil surface displacements in the direction orthogonal to the sliding plane. The analysed landslide-prone area is located in Campania (southern Italy), where disastrous mudflows occurred in May 1998, with many human casualties. The applications allow a better understanding of the role of the rainfall infiltration and pore water pressure changes in the triggering mechanism, and suggests how the porosity of the soils involved can affect the kinematic behaviour. The author believes that these changes must be carefully considered when assessing hazard levels, planning mitigation interventions regarding slope stability and designing future mitigation strategies for risk reduction.

Role of stratigraphy for rainfall-induced shallow instabilities in volcanic soils: a case study

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ABSTRACT: A large area close to the Somma-Vesuvio volcanic complex (Campania region, Italy) is covered by thin layered pyroclastic soils produced by successive explosive eruptions of the volcano, wind transportation and air-fall deposition. These soil layers can be found on very inclined slopes, their stability being ensured by the soils' unsaturated conditions and related matrix suction (Cascini et al., 2014). Therefore, it is not surprising that the most superficial layers are often affected by rainfall-induced slope instabilities that later originate high mobility debris flows or debris avalanches. Numerical modelling of the triggering phase of these phenomena is particularly complex due to the mechanical and hydraulic characteristics of the materials involved (Cascini et al., 2013). This study examines the transient groundwater regime and the associated stability conditions within a relatively small but very steep slope (height difference 24 m, average slope angle 38°) for which the stratigraphical and geotechnical characteristics of the soils are well characterized. The slope was affected by a debris flow that initiated in the topmost 2 m of soil at the end of a 4-day long rainfall event. Rainfall data recorded at a nearby rain gauge were used to impose the transient hydraulic boundary conditions at the ground surface, for a period of 1 month prior to the instability. Given the role played by the partial saturation conditions of the soil layers, a series of coupled hydro-mechanical finite element analyses has been conducted, considering different schematizations of the stratigraphical settings in the topmost portion of the slope, to assess the role played by the soil water characteristic curves and the permeability functions adopted in the model for the different soil layers. The time-dependent stability conditions in the slope were assessed adopting the c-phi strength reduction technique, considering daily steps of the transient model. The results of the analyses provide indications on the level of stratigraphic detail needed to properly model the observed instability in the considered slope, as well as on the hydraulic properties that must be considered for the most superficial soil layers to effectively simulate the response of the slope to the rainfall conditions applied at the ground surface.

Small-scale physical landslide models under 1g infiltration conditions and the role of hydrological monitoring

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ABSTRACT: Despite the considerable progress made in recent decades, there is still a need for a deeper understanding of the physical processes, mechanisms and crucial factors that lead to rainfall-induced landslides. With ongoing climate change affecting the frequency and intensity of meteorological extremes, and the imperatives of continuous urban expansion undoubtedly influencing the frequency and magnitude of landslides, it is no coincidence that the issue of rainfall-induced landslides has received increasing attention from both the scientific community and landslide practitioners in recent decades. Close observation of the hydromechanical response of slopes exposed to different rainfall loads plays a crucial role in understanding the driving mechanisms and factors affecting rainfall-induced landslides. In combination with appropriate monitoring techniques, small-scale physical landslide models can provide accurate insight into the relevant variables under precisely controlled initial and boundary conditions. This paper presents a model platform for physical modelling of scaled slopes under 1g rainfall infiltration conditions, developed at the Faculty of Civil Engineering, University of Rijeka, Croatia, within the four-year research project "Physical modelling of landslide remediation constructions' behaviour under static and seismic actions". Some of the main features of the model platform and the materials used for testing are described. Special attention is given to the sensor network that allows precise monitoring of soil moisture and pore water pressure in a scaled slope during rainfall simulation. Finally, two interesting examples of monitoring data are singled out and analysed with working frameworks relevant to the study of scaled slope models exposed to rainfall.

Digital image correlation and the use of high-speed cameras for 3D displacement monitoring in 1g small-scale landslide models

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ABSTRACT: Small-scale physical models of landslides triggered by rainfall and seismic conditions provide a good insight into the initiation and progression of full-scale landslides in nature. In order to track and document the displacements on the surface of the small-scale model, a digital image correlation-based optical measuring system with high-speed cameras is used here. Each model is prepared for the optical measurements by adding specially chosen marker points (pins) that are monitored by a pair of high-speed cameras during each experiment. An additional set of non-high-speed cameras with higher resolution is used to monitor the deformation field on a selected smaller part of the model. This enables to obtain the 3D displacements and velocities of each marker point in order to detect any movement or crack opening on the surface both visually and accurately from the optical measurement results. The described system and established measurement procedure

are advantageous as they provide the 3D displacement and velocity data for a large number of points on the surface with less equipment than conventional contact measurement methods. The collected data, in combination with other monitoring sensors, allow the observation of landslide initiation and the analysis of landslide evolution in all parts of the model slope during the sliding process. In this paper we present the measurement procedure and the results obtained optically in selected small-scale experiments.

Mechanism of rainfall induced landslides in small-scale models built of different materials

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ABSTRACT: Physical modelling of landslides by analysing the behaviour of small-scale landslide models subjected to artificial rainfall can be divided into modelling under 1g conditions and under increased acceleration (n times gravity) in a centrifuge. In this paper, the landslide initiation, progression, and deposition caused by artificial rainfall in three small-scale models built with sand or sand-kaolin mixtures at the same slope angle will be described. The evolution of landslides is monitored by observation of volumetric water content, matric suction, and pore water pressure, as well as by monitoring slope deformations and failure development. Analysis of the factors affecting the landslide initiation, propagation and their relationship to the slope material, the infiltration process, and the overall resistance of the soil in a slope in terms of soil strength, effective pressure and the contribution of matric suction in the unsaturated part of the slope will be discussed. The main observations from the results of the tests carried out in relation to the initiation and development of the observed instabilities of sandy and clayey slopes are given.

Impact of gravity retaining wall on the stability of a sandy slope in small-scale physical model

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ABSTRACT: Physical modelling of landslides by analysing the behaviour of small-scale landslide models subjected to artificial rainfall can be divided into modelling under 1g conditions and under increased acceleration (n times gravity) in a centrifuge. Physical modelling of landslide initiation began in Japan in the 1970s on scaled natural slope models. After initial experiences with field and laboratory researches, small-scale landslide modelling has found wide application around the world in various aspects of landslide investigations, analysing different types of landslides, different types of slope materials and landslide movements. The main task of landslide physical modelling has been to study the initiation, motion and accumulation of fast flow-like slides caused by infiltration of surface water. Studies that have included landslide mitigation measures in the small-scale physical model are rare and have not established correlations with the behaviour of on-site mitigation

structures. This paper discusses the behaviour of a small-scale sandy slope supported by a gravity retaining wall in the foot of the slope, during artificial rainfall in 1g loading conditions. Two models of sandy slopes, with and without retaining wall applied, were exposed to identical intensities of artificial rainfall. The results of the simulations indicated that the slope supported by the gravity retaining wall at the toe remained stable under the same conditions under which the sandy slope collapsed. The supported slope also remained stable under much longer rainfall. At the end of the simulation, the supported slope was subjected to much higher rainfall intensities, well above the infiltration capacity of the sandy material, and surface runout was affected. The combination of surface erosion and saturation of the superficial layer of the slope led to the initiation of a debris flow, while the complete saturation of the slope at the moment when the ground water level reached the surface of the slope caused the soil strength to be exceeded and the formation of a surface of rupture and consequently movements of the formed landslide body. Although the landslide movement caused displacement and longitudinal deformation of the gravity wall at the slope foot after local shear failure in front of the wall foundation, in general the gravity wall significantly improved the stability of the slope. The results of the measurements carried out with the installed geodetic and geotechnical monitoring system allowed a comprehensive understanding of the whole process of infiltration of precipitation and reduction of soil strength until the development of the fracture surface in the slope, as well as the process of incremental load development on the retaining structure until the limit resistance of the structure.

Preliminary results on the undrained cyclic behavior of uniform sand at low confining stress

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ABSTRACT: Earthquakes are one of the main landslide triggering factors. Earthquake-induced cyclic shear strain and stress generate the rise in pore water pressure and a soil strength degradation, which tends toward soil failure. Slopes where shallow landslides can be formed due to geological conditions are most susceptible to this type of loading, mainly because of the low confining stresses of the soil. The effective confining stress has a significant role in the soil response during static and cyclic loading. Tests performed on soil samples under monotonic shear indicate that shear strength properties increase with decreasing effective stress due to dilatancy. This paper presents the preliminary results of an undrained cyclic triaxial tests on sand material used for modelling small scale shallow landslides under 1g conditions. Based on the scaling rules for 1g conditions, the frequencies of strain amplitudes for undrained strain-controlled cyclic triaxial tests were defined. Undrained cyclic triaxial tests were performed on the sand type used in a small-scale landslide model. Samples were consolidated at low confining stress, which corresponds to an assumption of a shallow landslide used as a prototype. All tests were conducted in the Laboratory for geotechnics at the Faculty of Civil Engineering in Rijeka, Croatia. The influence of loading frequency and low confining stress was investigated and a simple pore pressure build-up model was proposed, which can be used to estimate the increase in pore water pressure due to cyclic loading at low confining stress for loading frequencies of less than 1 Hz.

Laboratory rheology measurements of natural debris material

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ABSTRACT: Debris flows are fast-moving masses of debris material that often occur in mountainous regions. Due to high velocity, they endanger the local population. To predict the time of arrival and the extent of hazard zones, the rheological properties of debris flow material, among others, are needed. This study presents the rheological investigation of debris flow materials in Slovenia. The rheological parameters were measured at different sediment concentrations using two shear-rate controlled coaxial cylinder rheometers (Brookfield DV3T HB and ConTec Viscometer 5) and standard tests for determining the workability and flowability of construction materials (e.g., funnels, V-funnel, flow channel, flow table, L-box). The measured data were evaluated by using the Bingham rheological model. The study was conducted in two separate stages. Firstly, the rheological parameters were measured only on fines (0-0.063 mm). These tests were used to determine the correctness of the rheological parameters measured in the rheometer by predicting their behaviour in standard tests. Afterwards, an attempt to predict rheological properties from these tests was made. In the second stage of this study, debris materials up to 16 mm were tested. A comparison of the rheological parameters obtained from the two coaxial cylinder rheometers was made. The study shows that the rheological parameters measured with the coaxial cylinder rheometers give reasonably good predictions of standard tests results, while the vice versa, i.e., from these standard tests estimation of rheological parameters is not possible. Although fines predominate the behaviour of a debris flow, the rheological properties are not only defined by fines, and thus should be tested in large rheometers with a wide grain-size distribution.

A use of similarity laws in landslide physical modelling: preliminary considerations

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ABSTRACT: Physical modelling of landslides has started in the 1970s in Japan on natural slopes exposed to artificial rain. Subsequently, small-scale laboratory models' development began in the 1980s with the aim of studying landslide behaviour such as triggering, movement, and accumulation. The research presented here is part of the Project funded by the Croatian Science Foundation entitled "Physical modelling of landslide remediation constructions' behaviour under static and seismic actions". When remediation constructions become part of a small-scale model, the determination of a scale ratio and the need to establish, at least partially, similarity laws with regard to a real slope is inevitable. Although many studies use a small-scale model to investigate the landslide behaviour of a real slope, there are only a few studies that consider the scale ratio and similarity laws. In this paper, a summary of some of these studies is given, along with an overview of all the similarity laws and the properties they account for in the context of landslides. Since the most important problem with small-scale 1g models is the low values of overburden stresses in a model, laboratory tests are performed in an attempt to determine the relationship between the constitutive behaviour of the material in a small-scale model and a real slope. An example of

geometric similarity is given here using the grain-size distribution curve and its influence on other similarities and their properties such as infiltration rate, soil weight and strength, etc. Some preliminary results of laboratory tests are presented together with a discussion of possibilities and limitations in achieving better similarity of small-scale models with real slopes.

Earthquake effects in assessment of an earth dam slope

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ABSTRACT: Major earthquakes trigger landslides mainly due to seismic accelerations affecting the excess of frictional strength of the underlying soils. It is expected that the total displacement of landslides triggered by an earthquake depends on the magnitude and frequency of the earthquake, so the numerical simulation needs to consider more input accelerations. This study considers different in magnitude and frequency earthquake scenarios which affect a slope susceptible to landslide. Effective and efficient modelling of soil media is of great importance, especially when the pore pressure in the soil medium changes. As for the formulation of the coupled approach, a soil element is represented as a mixture of three constituents - soil grains, water and air in the pores. For the mathematical description of the coupled approach, the mixture theory with the concept of volume fractions is considered. In the application of the model, the behaviour of a soil slope is simulated numerically. The simulation is performed starting from a specified initial degree of water saturation in the soil body due to rainfall. The simulation considers a non-linear behaviour in terms of the water retention curves and material model for the solid state and analysis is carried out using PLAXIS and ANSYS. It is assumed that the pore air pressure remains equal to the atmospheric pressure during the calculation and the matric suction is equal to a negative value of the hydrostatic water pressure. The coupled model allows to take into account the deformations of the soil skeleton and at the same time considers the change of the pore water pressure during the earthquake excitation. The boundaries are considered as absorbing elements in order to impede the outward propagating waves. The seismic behaviour of the slope provides interesting results that take into account both the deformation and the evolution of the pore water pressure.

Landslide Case Studies

The Krvavec bottom cabin lift station protection against torrential hazards by a new slit check dam and a series of flexible net barriers

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ABSTRACT: In May 2018, several small landslides were triggered during local intensive rainfall event, which turned into a hyperconcentrated granular flow. The mass flow destroyed the existing torrent control structures and damaged the bottom station of the Krvavec ski resort. Approximately 20,000 m^3 of debris was deposited during the event. After first intervention and cleaning of the deposits, the Slovenian Water Agency decided to prepare a technical documentation for the restoration of the area and the protection of the village of Cerklje na Gorenjskem. Firstly, a geological survey with geological mapping and identification of potential erosion zones and a conceptual design with mitigation measures was prepared, which is divided into three parts: torrent control measures on the Reka torrent (downstream from the Lukenjski and Brezovški graben confluence), a new large reinforced concrete check dam, and a series of flexible net barriers on the Brezovški and Lukenjski graben to stop intensive erosion processes in the source area. On the Reka torrent classic torrential measures were carried out until late 2020. Existing concrete weirs were renewed or completely reconstructed. Rip-rap was used for bank protection. All measures were designed for the discharge with a 100-year return period.

Large reinforced-concrete check dam with 14,000 m3 sediment retention capacity is foreseen on the confluence of the Brezovški and Lukenjski graben, and it is designed to withstand the dynamic impact of a new potential mass flow determined by mathematical modeling of mass flows. This check dam is quite easily accessible and sediments will be regularly removed and the full capacity of the dam will be restored after each event. A building permit for the check dam is being gathered.

The Brezovški and the Lukenjski graben are both torrents with steep gradients and are both prone to erosion. Their sediment source areas are mainly gravel and sand, and their torrent bed is not stable. Both torrents are not accessible, so classic torrent structures are not a feasible option. Therefore, flexible net barriers are planned to be constructed in both torrents. Eight such structures are planned on the Brezovški graben and four on the Lukenjski graben. Their dimensions vary, their height is between 3 and 6 meters, the span of the top of the barrier is between 9 and 25 meters. With these barriers, when filled with debris, their longitudinal gradient will be lowered and erosion processes on their banks will be limited. The removal of the debris is not planned for these structures, since their only function is gradient stabilization, lowering flow velocity and reducing intensity of erosion processes. A few barriers will be equipped with Geobrugg Guards® to monitor the dynamic response of the nets to filling by inflowing debris, supported by video monitoring. Also, in-situ concrete abrasion monitoring on plates are foreseen to be installed in the area to study concrete resistance in torrents. These net structures and monitoring will be constructed in 2022.

The presented case study is a good example of the holistic approach how to control erosion processes that results in small landslides and granular/hyperconcentrated flows.

Design of rockfall protection at the Špičunak location, Gorski kotar, Croatia

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ABSTRACT: The Špičunak location at the state road D3, near the Lokve settlement in the Gorski kotar region, Croatia, is well – known by numeous traffic interruptions caused by landslide and rockfall occurrences. Rockfalls at the Špičunak location are mostly predisponed to uccur due to geological setting and heavy, jointed rock mass in the road cut, which is approximately 180.0 m long and 23.0 m high. Structural and kinematic analysis of possible future rockfalls were carried out using modern approaches and recent techniques in rockfall hazard analysis. These approaches include application of remote-sensing techniques enabled to ensure digital terrain models (DTM) from three-dimensional high-resolution point cloud (3D HRPC) of the rock cut surface; engineering geological mapping using combination of remote-sensing techniques and field mapping. The three-dimensional, high-resolution point cloud (3D HRPC) were established based on terrestrial laser scanning (TLS) and photogrammetry survey with an unmanned aerial vehicle (UAV) using Structure form Motion (SfM) technique. Based on established 3D models, the cut was analyzed to identify the main characteristics of the rock mass structure as well as to detect and map the discontinuities and discontinuity sets, orientation and dip of discontinuities, spacing of discontinuities, persistence of discontinuities and roughness of discontinues. Traditional geotechnical survey was conducted to determine the characteristics of the main discontinuity sets at the cliff, as well as to carry out a rock mass classification using Geomechanical classification and Geological Strength Index (GSI). Detailed analyses of field survey and remote sensing data pointed to three different zones, based on their properties and rock block standings according to the general orientation and dip of the cut face. To identify possibility of failures associated with the present joint sets and their orientations, the kinematic analyses of plane, wedge and toppling failure mechanisms were carried out based on joint sets discontinuity features data collected by both traditional geological and geotechnical field survey and remote sensing survey and data analysis. Based on the kinematic analyses results, adequate protection measures were selected and designed to prevent further block detachments and rockfalls. In this paper we will describe field investigation, establishing of the rock cut model based on remote sensing and traditional geotechnical investigations, stability analysis, as well as design element necessary for ensuring of stability of the rock mass in the cut and the safety of traffic along the road.

The Ladiser Landslide mitigation project with a flexible high tensile steel mesh protection system

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ABSTRACT: Slope stabilization systems with meshes made of high-tensile steel wire have been in use for 20 years and have proven to be reliable systems on loose rock and soil slopes. Design can be carried out for any specific geotechnical setting of a slope using a freely available software called RUVOLUM®. The flexible, high tensile steel mesh can also be used to stabilise landslide areas in combination with a previously dimensioned anchor grid using global stability analysis software.

This paper presents a landslide case study in Austria where TECCO®, flexible, high tensile steel wire meshes for slope stabilization were successfully applied while previously installed concrete rib works failed. Several rockfalls and slides led to road closures in Tyrol during the winter of 2018. Focus will be on an event in the Oberinn Valley, southwest of Innsbruck. The Ladiserroad (L286), a state road in Tyrol, was affected twice within a short period of time. The cause of the rockfall and the landslide is most certainly due to the particularly unfavourable combination of weather conditions at the time, with heavy rain, heavy snowfall, thaw, and then freeze-thaw cycles. Part of the slope, from the Bündnerschiefer formation, was previously secured with concrete ribs that were carried away. A larger section of the slope than previously identified failed and subsequent protection measures were planned and executed in the summer of 2018. The chosen solution became an anchored solution using TECCO®, a high tensile flexible steel mesh cover. Approximately 10,000 m^2 were stabilised with an optimised nail grid of 2.5x 2.5 m, while the nail length ranged from 3 to 15 m. The landslide and its mitigation, design and installation will be presented in detail, as well as the state of the project four years later.

Highway construction in fossil landslides zones – Lessons learned from the Grdelica Gorge, Serbia

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ABSTRACT: During the Highway E75 construction in the Grdelica gorge in Serbia (Corridor X), complex fossil landslides were reactivated on two cuts. Extended geotechnical investigations were performed in several phases from 2000 to 2019. However, remediation measures were developed after additional geotechnical monitoring and re-design during the final stage of highway construction.

Initial reactivation of both fossil landslides started in 2014 after wide excavation for highway construction and was followed by additional geotechnical investigations in 2015. Design solutions were completed in 2016, but after implementation of remediation measures displacement were escalated on both cuts in 2017-2018. More geotechnical investigations were performed again – including geotechnical monitoring using inclinometers and piezometers. After many phases of additional investigation and monitoring results, and re-design in several iterations, implementation of the final design solutions began in 2018.

Both landslides were formed in a complex geological setting, i.e. extremely anisotropic albite-chlorite-muscovite schists from early Palaeozoic. The engineering geological conditions were determined by mineralogical composition, presence of highly weathered and tectonized zones, as well as presence of local torrential streams and surface erosion. Therefore, the physical and mechanical properties of the landslide bodies and sliding surfaces, as well as ground water conditions, were also complex. Mechanism of landslides were differenced, from typical landslide with several sliding surfaces and displacements vectors, to a combination of sliding and debris flow mechanism within the same landslide body. The depth of sliding surfaces and the geometry of the landslides were also impressive, ranging from 22 m to 43 m.

In this paper, two case studies of fossil landslides reactivated during highway construction under complex geological conditions and lessons learned after several phases of investigation and design will be presented.

Remediation measures of landslides on state roads in the Republic of Croatia – Presentation of case studies

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ABSTRACT: Landslides are common on state roads, which directly affect the flow of the traffic and the connection and functioning of the population in surrounding area. Therefore, it is necessary to investigate them in the shortest possible time and determine and carry out the remediation solution as soon as possible. Since these are state roads whose functionality is immensely important, it is necessary to ensure that traffic is maintained during these activities. Therefore, design solutions and execution technology should be adapted to these requirements. Landslides often occur on road embankments and cover materials above the bedrock because the soil strength parameters are exceeded as a result of groundwater flow.

The paper presents experiences from practice on landslides remediation in the Republic of Croatia: landslide Laz 18 on state road D29 in chainage 38+254, landslide Dedin on state road DC3, section 015 in chainage 2+060, landslide Vranja on state road DC500, section 001 in chainage 2+400, landslide Dubravci on state road DC3, section 012 in chainage 4+400.

The cause and mechanism of landslides, design solution for remediation measures and experience during the execution of works are presented. Landslide remediation measures mainly consisted of a pile wall with a cap beam or retaining wall and geotechnical anchors or rockbolts where required. In addition, reconstruction of the stormwater drainage system was carried out in the impact area of each landslide. During the remediation works, construction sites were organized so that at least one traffic lane was available for the needs of traffic and road functioning. After the completion of remediation works, monitoring equipment was installed to monitor the geotechnical structure and verify the design solution.

Deep landslide in the jointed flysch sediments on the Bar-Boljare Highway, Montenegro

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ABSTRACT: The subject of the paper is a case study of a deep landslide that formed in the jointed flysch sediments on the Bar-Boljare highway, Smokovac-Mateševo section, Montenegro. The landslide has affected 140 m of the left highway lane in the cut and has endangered the Uvač 4.1

bridge abutment. The landslide displacement first occurred in May 2019 and continued to intensify in early June of the same year. The cause of the instability occurrence is in the unsecured temporary subvertical cut (approximately 15 m high) constructed between left and right lane of the highway. The landslide was formed in the flysch formation, which consists of an alternation of sandstones and siltstones with a developed joints system. The landslide was initiated in the northern part of the site, where a wedge failure occurred (average block size 4 – 6 m), resulting in the formation of a 50 m wide unstable zone. The instability further propagated along the slope towards the southern part of the site, where a second sliding body was formed, the movement of which caused the displacement of the retaining wall and the bridge abutment. The total length of the landslide along the slope is about 80 m. This was further confirmed by a simple kinematic analysis. One of the unfavourable circumstances is the presence of a 2 to 3 m wide fault zone, so that the landslide zone partially propagated through this weakened zone. The whole mechanism of the process caused appearance of a clearly visible frontal scarp in the rock mass about 110 m long and a transverse crack separating two unstable masses (northern and southern) about 70 m long. Assessment based on the geotechnical investigation and inclinometer data suggests that the deepest points of sliding zone vary are between 17 and 22 m. Slope stability analysis was performed on typical cross-sections to confirm the assumed sliding mechanism and to obtain numerical parameters for design of remediation measures. The analysis was performed using Slide and RS2, Rocscience software.

Based on the results of the geotechnical investigation, inclinometer data and numerical analysis it was concluded that the unfavourable position of discontinuities in the rock mass was a predisposing factor for the landslide occurrence. This refers primarily to the joint sets, since the orientation of stratification is relatively favourable from the aspect of slope stability, which is atypical for this zone and is rarely the case for unstable flysch slopes. One of the characteristics of the landslide is also a high-quality rock mass composed mainly of sandstones and also affected by sliding.

The landslide was remediated in 2021 through a combination of several types of remediation measures that included construction of bored piles with a diameter of 150 cm and a depth of 20 m with a cap beam, prestressed geotechnical anchors up to 30 m long connected with a reinforced concrete grid, 6 m long bolts, and surface and underground terrain drainage.

Lateral spreading caused by 2020 Petrinja Earthquake 6.4 M_W

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ABSTRACT: Spreading is type of landslides is defined as an extension of cohesive soil or rock mas combined with a general subsidence of the fractured cohesive material into softer underlying material. The surface of rupture is not a surface of intense shear. Liquefaction spreading are the most common ground failure type during an earthquake and occur at gentle slopes between 0.5 to

3 degrees with a lateral movement that can reach several meters. This type of landslides form in sediments of sensitive cays, silt and sand that have lost strength with disturbances that damaged their structure due to sudden increasing of pore water pressure and liquefying of this underlying material. Movements during lateral spreading are translational and often retrogressive, starting at a river bank or a shoreline and spreading away of it. Lateral spreading would be triggered by an earthquake with a magnitude which shaking can cause liquefaction, commonly higher than M_w>6.0 and ground acceleration higher than PGA>0.1g. The 2020 Petrinja Earthquake 6.4 MW (6.2 ML) hit Central Croatia at 12.19 PM on 29 December 2020 with an epicentre located approximately 3 km west-southwest of the City of Petrinja. The maximum felt intensity was estimated at VIII (Heavily damaging) to IX (Destructive) on the European macroseismic scale and maximum values of the horizontal PGA=0.25g. The earthquake shaking caused significant damage at houses, roads and infrastructure in three the biggest cities in Sisačko-Moslavačka County: Petrinja, Sisak and Glina and surrounding villages. The earthquake triggered numerous surface postearthquake effects such are liquefaction, sinkholes and landslides in the area of approximately 3500 km2. Based on rapid field investigation, all these phenomena were identified and mapped. It was found that liquefaction occurred at 53 locations and covered the area of 1410 ha while the lateral spreading was identified at 27 locations. The liquefaction occurred in sandy sediments in alluviums of the Kupa, Sava, Glina and Maja rivers while the lateral spreading evidences are visible to several hundred meters away from river banks. The greatest damage was identified in the Palanjak, Palanjački Bok and Galdovo (part of the City of Sisak) villages along the Sava River, Letovanić and Stara Drenčina villages along the Kupa River, as well as in the City of Glina along the Maja River old channel. In this manuscript we will present a review of lateral spreading evidences occurred as postearthquake phenomenon of the 2020 Petrinja Earthquake, their spatial distribution, description of typical mechanisms, as well as examples of location with damage caused by lateral spreading. Geological setting of the locations effected by liquefaction and lateral spreading will described and description of liquefied material presented.

Preliminary results of surface changes monitoring on an ephemerally active alluvial fan (Planica Valley, NW Slovenia)

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ABSTRACT: Alluvial fans are sedimentary bodies formed by a variety of different fluvial and sedimentary gravity flow processes. These processes are usually dependant on ephemeral and potentially catastrophic flood events triggered by intense rainfall, rapid snowmelt, or the release of impounded water. These events result in the deposition of heterogeneous sedimentary deposits such as debris-flow deposits, debris-flood deposits, sheetflood deposits, and confined and unconfined torrential channel deposits. This study investigates episodic activity of an alluvial fan in the Planica Valley (NW Slovenia). The valley is a post-glacial alpine valley bounded by steep carbonate slopes. Its floor and lower slopes are covered by several gravel-rich Holocene alluvial fans, on which sediment is actively deposited during sporadic intense precipitation events in subannual cycles. A permanent meteorological station is located near the valley. The aims of this study are (i) to detect erosional and depositional surface changes induced by intense precipitation events, (ii) to calculate the volume of deposited and eroded sediment, and (iii) to link surface changes to triggering

meteorological events. The surface changes on the alluvial fan were monitored by aerial surveying using Small Unmanned Aircraft and photogrammetric modelling of the surface. A network of seventeen permanent ground control points was installed to ensure centimetre-level accuracy of photogrammetric modelling and monitoring of surface changes. The photogrammetric modelling resulted in Digital Elevation Models of five-centimetre resolution. Surface changes and volumetric analysis of eroded and deposited sediment were determined based on Difference of DEM (DoD) using QGIS programme. Detected surface changes were temporally correlated with precipitation events from the meteorological records. Nine repeated surveys were conducted between December 2019 and November 2021, from which eight DoD models were created. Surface changes are categorised into severe, moderate, and minor changes. Two rainfall events resulted in severe changes characterised by erosion of more than 800 m^3 of sediment and deposition of more than 2100 m^3 of material, indicating an additional input of 1200 m^3 of sediment from the fan catchment. These changes occurred after 24-hour rainfall events with 63.4 and 66.9 mm of rainfall. Three events resulted in moderate changes with less than 300 m^3 of sediment deposited and less than 180 m^3 eroded. Surface changes occurred after 24- or 48-hour events of up to 68 mm of rainfall. These events predominantly just redeposited the existing sediment on the surface of the alluvial fan, with only minor inflow of additional sediment from the catchment. After 24-hour precipitation events with 40 to 50 mm of precipitation, three minor surface changes occurred. Less than 40 m^3 of sediment was deposited or eroded during these events. Triggering precipitation events generating surface changes are common rainfall events for the study site. The study shows that under the prevailing regular meteorological conditions, the transport and deposition dynamics on a typical alpine alluvial fan are quite intense and frequent.

Symposium Program

23—26 March 2022

///// 23 March 2022 // Workshop

Faculty of Civil Engineering, Radmile Matejčić 3, Room G207

	WORKSHOP PRESENTATIONS
13.00 – 13.30	**Josip Peranić** *Small-scale physical landslide models under 1g infiltration conditions and the role of hydrological monitoring*
13.30 – 14.00	**Nina Čeh** *Digital image correlation and the use of high-speed cameras for 3D displacement monitoring in 1g small-scale physical models of landslides*
14.00 – 14.30	**Giovanna Capparelli** *Physical modelling investigation and integrated analysis of landslides for defining risk scenarios*
14.30 – 15.00	**Sabatino Cuomo** *Numerical simulations of landslide physical model experimental results*
15.00 – 15.30	Coffee Break

Faculty of Civil Engineering, Radmile Matejčić 3, Laboratory of Geotechnics

15.30 – 17.30	Physical Model Laboratory Test

///// 23 March 2022 // Welcome

Faculty of Civil Engineering, Radmile Matejčić 3, The Aula

18.00 – 22.00	Welcome Party

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///// 23 March 2022 // Exhibition

Faculty of Civil Engineering, Radmile Matejčić 3, The Aula

19.00	Opening of the Photo Exhibition *Take a look at the landslide*

///// 24 March 2022 // Registration

Faculty of Civil Engineering, Radmile Matejčić 3, The Aula

8.00 – 9.00	Participant registration

///// 24 March 2022 // Symposium

Faculty of Civil Engineering, Radmile Matejčić 3, Room G004

9.00 – 10.00	Symposium Opening Ceremony
10.00 – 10.30	Coffee Break
	INVITED LECTURES Conveners: Snježana Mihalić Arbanas, Matjaž Mikoš
10.30 – 11.00	**Nicola Casagli** *The International Consortium on Landslides for disaster risk reduction and sustainable development*
11.00 – 11.30	**Michel Jaboyedoff** *Failure hazard of rockfall sources: some aspects of the hazard quantification*

SYMPOSIUM PRESENTATIONS
Conveners: Biljana Abolmasov, Martin Krkač

/ Landslide Monitoring /

11.30 – 11.45	**Matteo Del Soldato**, Camilla Medici, Pierluigi Confuorto, Silvia Bianchini *Statistical literature analysis of combined GNSS-InSAR landslide investigation*
11.45 – 12.00	**Pierluigi Confuorto**, Silvia Bianchini, Matteo Del Soldato, Davide Festa, Federico Raspini, Nicola Casagli *Ground deformation monitoring service of Veneto region (NE Italy) by means of Sentinel-1 data*
12.00 – 12.15	**Galena Jordanova**, Marko Vrabec, Krištof Oštir, Timotej Verbovšek *Monitoring the Slano blato mudflow using InSAR and UAV photogrammetry (preliminary results)*
12.15 – 12.30	**Giulia Bossi**, Gianluca Marcato, Filippo Tommaso Catelan *Validation of innovative mitigation strategy through long-term landslide and structural monitoring*
12.30 – 12.45	**Giulia Bossi**, Alessandro Corsini, Giuseppe Ciccarese, Gianluca Marcato, Marco Mulas, Luca Schenato, David Tonidandel, Volkmar Mair *Long-term monitoring of active large-scale landslides based on integrated systems in South Tyrol (SoLoMon project)*
12.45 – 13.00	**Mateja Jemec Auflič**, Ela Šegina, Tina Peternel, Matija Zupan, Jernej Jež, Manja Žebre, Polona Kralj, Marjana Zajc, Matjaž Mikoš, Nejc Bezak, Milan Kobal *Monitoring of rockfall prone areas in eastern Slovenia*
13.00 – 15.00	Lunch Break

INVITED LECTURE
Conveners: Miloš Marjanović, Timotej Verbovšek

15.00 – 15.30	**Snježana Mihalić Arbanas** *Landslide evidence and spatial prediction: Application of data and information from landslide maps*

SYMPOSIUM PRESENTATIONS
Conveners: Miloš Marjanović, Timotej Verbovšek

/ Landslide Mapping /

15.30 – 15.45 **Martin Krkač**, Sanja Bernat Gazibara, Marko Sinčić, Hrvoje Lukačić, Snježana Mihalić Arbanas
Landslide inventory mapping based on LiDAR data: Case study from Hrvatsko Zagorje (Croatia)

15.45 – 16.00 **Ela Šegina**, Gorazd Žibret
Slope gradient anomalies as indicators of potential slope instabilities

/ Landslide Susceptibility /

16.00 – 16.15 Sanja Bernat Gazibara, Snježana Mihalić Arbanas, **Marko Sinčić**, Martin Krkač, hrvoje Lukačić, Petra Jagodnik, Željko Arbanas
LandSlidePlan – Scientific research project on landslide susceptibility assessment in large scale

16.15 – 16.30 **Natasha Nedelkovska**, Igor Peshevski, Milorad Jovanovski, Jovan Papić, Ivan Radevski, Svemir Gorin
Shallow landslide susceptibility assessment for the Polog region (R.N. Macedonia)

16.30 - 17.30 Coffee Break

SYMPOSIUM PRESENTATIONS
Conveners: Uroš Đurić, Sanja Bernat Gazibara

/ Landslide Susceptibility /

17.30 - 17.45 **Tina Peternel**, Jasna Šinigoj, Mateja Jemec Auflič, Špela Kumelj, Matija Krivic
MASPREM – Slovenian landslide forecasting and warning system

17.45 - 18.00 **Julijana Bojadjieva**, Vlatko Sheshov, Kemal Edip, Radmila Shalic, Marta Stojmanovska, Roberta Apostolska, Stavroula Fotopoulou, Dimitris Pitilakis, Neritan Shkodrani, Markel Babaleku, Francesca Bozzoni, Antonella di Meo
Harmonized approach for mapping the earthquake-induced landslide hazard at the cross-border region between North Macedonia, Greece and Albania

18.00 - 18.15 **Matjaž Mikoš**, Mateja Jemec Auflič, Jernej Jež, Nejc Bezak
Rock frost weathering and rockfall activity assessment in Slovenia

18.15 - 18.30 **Miloš Marjanović**, Biljana Abolmasov, Uroš Đurić, Jelka Krušić, Snežana Bogdanović
Regional rockfall exposure assessment, experience from Serbia

///// 24 March 2022 // Posters

Faculty of Civil Engineering, Radmile Matejčić 3, The Aula - 3rd Floor

16.30 - 17.30 POSTER SESSION
Conveners: Sanja Bernat Gazibara, Tina Peternel, Kemal Edip

T. Peternel, J. Jež, M. Janža, E. Šegina, M. Zupan, A. Markelj, A. Novak, M. Jemec Auflič, J. Logar, M. Maček, N. Bezak, J. Sodnik, M. Mikoš
Mountain slopes above Koroška Bela (NW Slovenia) – A landslide prone area

R. Stanković, N. Vulović, B. Ablomasov, M. Marjanović, U. Đurić
A landslides database model for CliRtheRoads project in Serbia

M. Sinčić, S. Bernat Gazibara, H. Lukačić, M. Krkač, S. Mihalić Arbanas
Qualitative and quantitative assessments of input LiDAR data for landslide inventory mapping

P. Jagodnik, Ž. Arbanas, S. Bernat Gazibara, S. Mihalić Arbanas
High resolution LiDAR DTM reveals new insight on landslide phenomena in the Rječina River Valley

H. Lukačić, S. Bernat Gazibara, M. Sinčić, M. Krkač, Ž. Arbanas, P. Jagodnik, V. Damjanović, S. Mihalić Arbanas
Influence of expert knowledge on completeness and accuracy of landslide inventory maps - Example from Istria, Croatia

///// 25 March 2022 // Symposium

Faculty of Civil Engineering, Radmile Matejčić 3, Room G004

	INVITED LECTURES Conveners: Željko Arbanas, Julijana Bojadjieva
9.00 - 9.30	**Binod Tiwari** *Physical Modeling of Landslides and Slopes - Advancements and Challenges*
9.30 - 10.00	**Nejc Bezak**, Matjaž Mikoš, Mateja Jemec Auflič *Rainfall-induced landslides and debris flows under the influence of climate change: review of recent Slovenian studies*
	SYMPOSIUM PRESENTATIONS Conveners: Josip Peranić, Michele Calvello
	/ Laboratory Testing, Physical and Numerical Modelling of Landslides /
10.00 - 10.15	**Sabatino Cuomo** *Numerical simulations of landslide physical model experimental results*
10.15 - 10.30	**Giovanna Capparelli**, Gennaro Spolverino, Irasema Alcántara-Ayala, Noemi Sharon Ruiz-Cortés *Physical modelling investigation and integrated analysis of landslides for defining risk scenarios*
10.30 - 10.45	Luca Crescenzo, **Michele Calvello** *Role of stratigraphy for rainfall-induced shallow instabilities in volcanic soils: a case study*
10.45 - 11.00	**Timotej Jurček**, Matjaž Mikoš, Matej Maček *Laboratory rheology measurements of natural debris material*
11.00 – 11.30	Coffee Break

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SYMPOSIUM PRESENTATIONS
Conveners: Vedran Jagodnik, Vlatko Sheshov

/ Laboratory Testing, Physical and Numerical Modelling of Landslides /

11.30 – 11.45	**Josip Peranić**, Vedran Jagodnik, Nina Čeh, Martina Vivoda Prodan, Sara Pajalić, Željko Arbanas *Small-scale physical landslide models under 1g infiltration conditions and the role of hydrological monitoring*
11.45 – 12.00	**Nina Čeh**, Josip Peranić, Vedran Jagodnik, Sara Pajalić, Martina Vivoda Prodan and Željko Arbanas *Digital image correlation and the use of high-speed cameras for 3D displacement monitoring in 1g small-scale physical models of landslides*
12.00 – 12.15	**Martina Vivoda Prodan**, Josip Peranić, Sara Pajalić, Vedran Jagodnik, Nina Čeh, Željko Arbanas *Mechanism of rainfall induced landslides in small-scale models built of different materials*
12.15 – 12.30	**Željko Arbanas**; Josip Peranić; Vedran Jagodnik; Martina Vivoda Prodan; Nina Čeh, Sara Pajalić; Davor Plazonić *Impact of gravity retaining wall on the stability of a sandy slope in small-scale physical model*
12.30 – 12.45	**Vedran Jagodnik**, Martina Turković, Željko Arbanas *Preliminary results on cyclic behaviour of uniform sand under undrain condition at low confining stress*
12.45 – 14.45	Lunch Break

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SYMPOSIUM PRESENTATIONS
Conveners: Jošt Sodnik, Martina Vivioda Prodan

/ Landslide Case Studies /

14.45 – 15.00 **Jošt Sodnik**, Matjaž Mikoš
The Krvavec bottom cabin lift station protection against torrential hazards by a new slit check dam and a series of flexible net barriers

15.00 – 15.15 **Biljana Abolmasov**, Marinos Skempas, Svetozar Milenković, Janko Radovanović, Miloš Marjanović
Highway construction in fossil landslides zones – lessons learned from the Grdelica Gorge, Serbia

15.15 – 15.30 Mirko Grošić, **Ivan Volf**, Ivana Blagdan
Remediation Measures of Landslides on State Roads in the Republic of Croatia – Presentation of Case Studies

/ Landslide Investigation /

15.30 – 15.45 Giuseppe Ciccarese, **Marco Mulas**, Francesco Ronchetti, Marco Aleotti, Alessandro Corsini
Recent large-scale gravitational collapses in the Madonna di Puianello mud-volcanoes field calderas (Northern Apennines, Modena, Italy)

15.45 – 16.00 **Giuseppe Ciccarese**, Marco Mulas, Francesco Ronchetti, Marco Aleotti, Alessandro Corsini
Paroxysmal reactivation of a large-scale earth flow documented by multitemporal UAV photo surveys and Robotic Total Station

16.00 – 16.15 **Nemanja Babović**, Aleksandar Miladinović, Dajana Biorac
Field Investigation of the Landslide that Occurred During the Construction of the Dam "Svračkovo"

16.15 – 16.30 **Vincenzo Critelli**, Alessandro Corsini, Matteo Berti, Anna Rita Bernardi, Matteo Bernardi, Giuseppe Caputo, Giuseppe Ciccarese, Gianluigi Di Paola, Marco Mulas, Francesco Ronchetti
Probabilistic modelling of HVSR results for 3D mapping of rock-slides

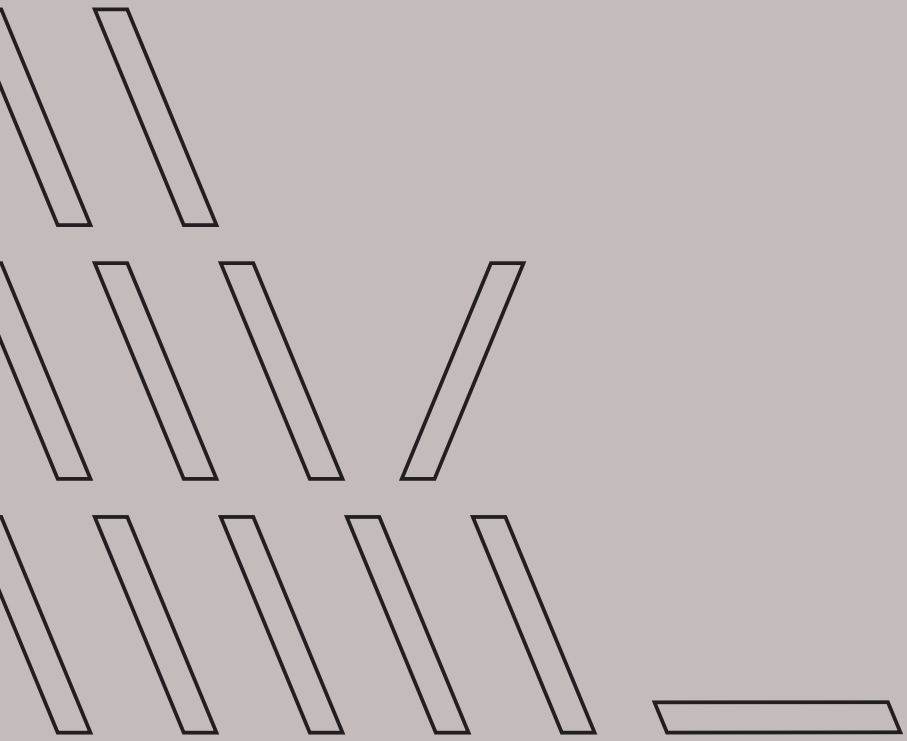
///// 25 March 2022 // Round table

Faculty of Civil Engineering, Radmile Matejčić 3, Room G207

	ROUND TABLE DISCUSSION Moderators: Paola Reichenbach, Snježana Mihalić Arbanas
10.00 – 10.10	Opening – Introducing the participants
10.10 – 10.25	**Mauro Rossi**, CNR-IRPI, Italy *Introductory speech „A review of statistical landslide susceptibility modelling"*
10.25 – 10.40	**Sanja Bernat Gazibara**, UNIZG-RGNF, Croatia *Introductory speech „Geo-environmental information for landslide susceptibility modelling – Availability of data in Croatia"*
10.40 – 11.55	**Igor Peshevski**, Ss. Cyril and Methodius University in Skopje, North Macedonia *Introductory speech „Experiences on regional landslide modeling in N. Macedonia"*
11.55 – 12.45	Discussion of all participants

///// 26 March 2022 // Field trip

9.00 – 13.00	Field Trip
13.00 – 14.30	Lunch
14.30 – 16.00	Transfer to University



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