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Multi-source data analysis in slow-moving landslide-affected built-up environment: a case study in Calabria Region (southern Italy)

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Abstract: The paper concerns the characterization of slow-moving landslides (in terms of both geometrical and kinematical issues) and the estimation of the vulnerability of structures (e.g., buildings) and/or infrastructure (e.g., roads) interacting with them. These goals represent key steps for quantifying the risk to facilities provided that reliable input data are available. The latter profitably include information gathered from non-invasive spaceborne remote monitoring (e.g., Differential Interferometric techniques) and virtual surveying (e.g., Google Street view imagery) to be integrated with ancillary multi-source data acquired by adopting geological, geomorphological and geotechnical criteria.
The approach proposed in this work relies on the methodological frameworks developed by the authors on the topic in the last few years within multidisciplinary joint research activities.
The approach was applied to a case study in Calabria region (southern Italy) affected by several slow-moving landslides, which caused damages to the exposed facilities (buildings and roads). The monitoring data jointly analyzed with ground-based geotechnical monitoring, the available geological-geomorphological information and the results of extensive multi-temporal damage surveys – carried out on both buildings and roads virtually and on site – allowed i) characterizing slow-moving landslides based on deterministic and/or probabilistic methods and ii) generating predictive tools for estimating the degree of loss (inherently related to the expected damage) of the exposed facilities.
The results achieved highlighted that the use of conventional and innovative multi-source monitoring/survey data, if properly integrated according to a multidisciplinary approach, can enhance the studies aimed at addressing two key steps of quantitative risk analyses (i.e., the characterization of slow-moving landslides and the estimation of vulnerability of exposed facilities). Once further validated, the proposed approach could be part of a circular procedure to allow for prioritizing building/road (extraordinary) maintenance activities and scheduling/implementing risk mitigation measures.

Keywords: slow-moving landslides, built-up environment, monitoring/surveying data, damage

Landslide susceptibility assessment: Chicken or the egg for the risk analysis?

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Abstract: This article explores the complexities of landslide risk assessment, emphasizing the qualitative nature of analysing hazards and consequences. It highlights the necessity for well-defined frameworks to evaluate these risks and the significant role of expert judgment in refining assessments due to inherent uncertainties. The text argues for the development of clear methodologies that stakeholders can understand and accept, incorporating best practices and local knowledge to mitigate legal risks associated with predictive inaccuracies. Additionally, it suggests the use of catastrophe modelling to solve the issues linked with uncertainty.

Keywords Landslide, risk, hazard, susceptibility.

Prediction of rainfall-induced landslides in a changing climate: issues and perspectives for regional-scale approaches

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Abstract: In 2022, the Emergency Event Database recorded 387 natural disasters worldwide, affecting 185 million individuals and causing 30,704 deaths, with economic losses totaled around 223.8 billion US$. Landslides do not affect wide areas as floods, megafloods, and earthquakes; however, they are numerous and they occur frequently in hilly and mountainous areas. The Global Fatal Landslide Database lists 4862 non-seismic landslides that caused 55 997 deaths worldwide in the period 2004-2016. In a European survey, 849 543 landslides were mapped in 20 national inventories. Within Europe, Italy has a long history of landslides and related damage, with 528 903 landslides mapped by the national geological survey. According to the last Polaris report by CNR-IRPI, between 1973 and 2022, landslides caused 144806 people homeless or evacuees, 1077 deaths, 10 missing and 1443 injured persons in Italy.
Landslides in Italy, as in most areas of the World, are mostly triggered by intense and/or prolonged rainfall. As a consequence, regional- and national-scale landslide early warning systems are usually based on rainfall-related prediction tools (as rainfall thresholds) and susceptibility maps.
An increase in the frequency and magnitude of intense rainfall events was observed and more changes are expected due to climate change. Given the high spatial and temporal variability of the landslides, climate (and its change) can affect them in multiple ways and at different temporal and geographical scales. The landslide response to climate change varies depending on the landslide type and size, and on the local stability or instability conditions. The response is different for first-time shallow failures and for the reactivation of large deep-seated landslides. Overall, the increase in frequency and intensity of the rainfall events results in a change in the frequency, abundance, and location of rapid and very rapid landslides, mostly shallow slides and debris flows, which are the primary cause of landslide casualties and of fatal landslide events, so deserving particular attention in the prediction chain. Nevertheless, these issues are often neglected in the operational prediction of rainfall-induced landslides.
Several investigations were carried out in Italy for the prediction of rainfall-induced landslides, for the implementation of landslide early warning systems and for the evaluation of the impact of climate and environmental changes (mostly rainfall and land use) on landslide activity, occurrence, and frequency. In this contribution, a brief overview of the defined methods, models and tools is presented. Special emphasis is placed on the definition of rainfall thresholds defining the minimum triggering conditions for the initiation of shallow landslides, given their usability in regional and national warning systems and in the evaluation of changes in the triggering conditions of the landslides. Regional-scale analyses of the ongoing and expected effects of climate change on rainfall-induced landslides are discussed. A spotlight on a region in Central Italy widely and repeatedly affected by landslides triggered by extraordinary rainfall events is also proposed.

Keywords: landslides, rainfall, climate change, Italy

Guidelines For Asset Management of a Critical Energy Facility Located on a Landslide Zone Using Geotechnical Investigations, Numerical Analysis and Monitoring

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Abstract: Asset management of critical facilities with specific reference to risks imposed by geotechnical hazards is a globally raising concern, as the loading and strength conditions for such phenomena are highly uncertain and transient; making it difficult to quantify the expected structural performance and consequences. The case study presented herein attempts to demonstrate a series of geotechnical engineering solutions with optimized initial investment and maintenance costs, undertaken to lead the decision makers for managing the overall risks. The project site, located in northwestern Türkiye resides on a paleo landslide setting and hosts a functional energy power plant establishment with main structures located along the coastline. A successive mass instability has triggered along the eastern part of the property, imposing potential risks to the serviceability of the main access road connecting the industrial facility to the state transportation network, as well as raising concerns for the suitability of this zone to be used as a future expansion area of the plant. A series of geotechnical investigations were planned and executed for characterizing the seismically active site, limit equilibrium and finite element based numerical studies in the form of back analyses were conducted for assessing the current stability of the mass based on field and laboratory testing, and a suite of alternatives were considered for taking engineering counter measures to the ensure performance requirements of the access road, the facility and connecting pipelines under scenario earthquakes were met in accordance with the allowed tolerances. A detailed monitoring program is actively run for over 7 years using an array of inclinometers and piezometers, along with visual inspections, which provides an opportunity for calibrating the numerical models and providing a benchmark of the success rate of the predictions reported prior to activation of the monitoring programme. Lessons learned from the experience gained through the monitoring phase are also discussed.

Keywords: back-analysis, geotechnical monitoring, risk management

Rock slope stability analysis of highly fractured rock mass under different flow rules

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Abstract: The rock masses that are highly fractured or soft behaving as hard soils, are considered as homogeneous and isotropic and by that way its behavior is not controlled by discontinuities. Rock slope stability analysis in such rock masses presents the failure pattern along a circular surface, similar to slope failure in soils. The most widely applied failure criterion for the rock slope stability analysis of in such rock mass is the generalized non-linear Hoek and Brown that is usually transformed to equivalent resistance parameters of the linear Mohr Coulomb criterion, being still the most widely applied for its simplicity. It is still also commonly considered the application of the associative flow rule in the failure criterion, being well known as non-conservative hypothesis for the analysis providing overestimation of the general stability evaluated by the factor of safety. The investigation is performed to analyze the influence of different flow rules on the rock slope stability analysis by the limit equilibrium method. The Hoek and Brown failure criterion is introduced in the parametric form proposed by Serrano and Olalla that permits direct implementation of the shear and normal stress relationship. This parametric form is widely used and published for different geotechnical structures in rock mechanics, such as anchors, tunneling, foundations, slope stability (infinite slopes, planar and circular failure surface). The results of this analysis of the rotational failure in rock masses are given in the form of non-dimensional charts for better illustration of the influence of dilatancy angle on rock slope stability, by that way confirming the importance of its incorporation in the analysis. The analysis performed by finite element method is also presented for its comparison to limit equilibrium method. The sensitivity analysis regarding uncertainty on the estimation of different basic input parameters of the Hoek and Brown failure criterion, i.e. uniaxial compressive strength, geological strength index and rock mass constant, is also done for the assessment of its influence on the factor of safety.

Keywords: rock slope stability, circular failure surface, failure criterion, flow rule, dilatancy

Integral approach in stability analyses for weak anisotropic rocks

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Abstract: Slope stability of cuts in weak rock masses is a practical problem where anisotropy has a high influence in the definition of geotechnical models used in stability analyses. Even in cases with extensive field investigations, some uncertainties still exist, thus it is a challenging task to compromise between the economy and reliability of the solution. Such rock masses are susceptible to local or global instabilities sometimes expressed as wedge, planar or rotational mode of failure, depending on combinations of slope elements, discontinuity orientations block-sizes in the rock mass media. Findings are based on the authors experiences gathered in phases of investigation, design and construction of deep cuts in highly weathered and fractured schists for A2 motorway from towns Kicevo-Ohrid, railway section from town Kumanovo to Bulgarian border and other infrastructural projects. An extensive data basis is collected for rock mass parameters, modes of failure and methods for rock mass stabilization for over of 80 deep cuts constructed in such rock mass media. Known limit equilibrium, kinematical and empirical methods are used in analyses, but the results are presented in a partially modified diagrams from known Q-slope and Slope Mass rating methods. In the diagrams, values from calculations of Factor of Safety and Probability of Failure are added to the zones that define stable, conditionally stable or unstable areas. An attempt is done to incorporate also some finding related from design approaches in new Eurocode 7 generation. Analyses indicates, that integral approach is necessary to combine results from stability analyses with tolerable level of risks for Consequence Classes in Eurocode 7. Some charts that define a relation between range of Reliability Index β for each class are defined. The findings leads to the conclusion, that interaction and integration of technical, economic and social aspects and involving different perpectives is necesary in process of rock slope risk management. Recommendations for further development of the methodology are also presented.

Keywords: anisotropic rocks, analytical methods, integral approach, empirical methods, slope stability

High-Precision Landslide Monitoring Using Laser Scanning Technology

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Abstract: Landslides represent complex geological phenomena that pose significant threats to human infrastructure, ecosystems, and safety. In response to the imperative need for advanced monitoring techniques, this paper undertakes an extensive examination of recent advancements in geodetic technologies, specifically focusing on the application of state-of-the-art laser scanning techniques. The paper explores both Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicles Laser Scanning (UAVLS), emphasizing their capabilities in achieving high precision and high spatial resolution data for comprehensive landslide monitoring.

Recent developments in laser scanning technologies have revolutionized the field of geodetic monitoring, enabling surveyors to capture detailed three-dimensional data with unparalleled accuracy and resolution. TLS, conducted from ground-based stations, and UAVLS provide complementary perspectives, facilitating a better understanding of landslide dynamics.

The approach employed in high-precision landslide monitoring using laser scanning techniques is multifaceted. Data acquisition involves the accurate laser scanning of object surface to capture detailed topographic information, while data processing techniques include point cloud registration, georeferencing, 3D modelling, analysis and integration with other geospatial and geological data. The paper underscores the significance of achieving millimetre-level precision and high resolution in some application associated with landslide events.

Different examples of the conduced case studies are presented to illustrate the practical application and effectiveness of high-precision laser scanning in landslide monitoring. These examples examine the technology's ability to capture complex terrain features, monitor changes over time, and provide valuable insights for understanding landslide mechanisms.

Challenges within the field, such as the complexity of data processing workflows, and comparison with other monitoring techniques, are critically examined. The paper identifies potential approach for future research, including the development of automated algorithms for real-time monitoring and the integration of laser scanning with other technologies.

The insights presented herein contribute to the ongoing efforts in geohazard management, fostering more effective risk mitigation strategies and enhancing early warning systems..

Keywords: High-Precision Landslide Monitoring, Terrestrial Laser Scanning (TLS), Unmanned Aerial Vehicles Laser Scanning (UAVLS), Geodetic Techniques, Landslide Dynamics

Landslide mapping and zonation at national, regional and local scale – Recent experiences from Republic of Macedonia

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Abstract: The paper presents an overview of a two recently performed landslide mapping and zonation projects in the Republic of Macedonia. The first case study is a national scale mapping in the frame of geohazards study for the needs of the spatial plan of the country, intended for use in period 2023-2040. Due to limitations in regards to landslide characterization and a relatively low number of landslides in the database, the rather simple arbitrary polynomial approach was adopted, at a scale of 1:200000. The casual factors for landslide development considered in the analyses were the lithology, terrain slope, land use, rainfalls, and earthquake acceleration. Two susceptibility models were performed, with different return periods for maximum expected earthquake acceleration according to Eurocode 8. The results are compared with previously performed studies and certain conclusions and recommendations for further needed activities were drawn. The study also touches the subject of overall management of the landslide problems in Macedonia. The second case study is related to the regional scale mapping of the Polog region, the most prone region for landslides in Macedonia. Several techniques for landslide susceptibility mapping were applied, such as LiDAR semi-automated susceptibility mapping, frequency ratio method, arbitrary polynomial method, InSAR hotspots detection. Depending on data availability, different datasets were used for the specific methods. Then, based on the results of the landslide susceptibility mapping and the parallel creation of a landslide database for the region, an attempt was made to access the landslide hazard and risk for a number of most critical locations. These locations were considered for design of remedial measures. In first phase, the preliminary designs were made, consisting of at least two possible solutions. These solutions were then subjected to a cost-benefit analysis, upon which the final design was performed for the most feasible solution. The adopted solutions are now in the phase of construction, with some of the examples presented in the paper.

Keywords: landslide, mapping, zonation, national, regional, local

Landslide Risks in the Western Balkans Under the Climate Change

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Abstract: Under the global warming impact, the Western Balkans region has experienced a mean temperature increase exceeding the global average, of about 1.4°C rise over the last 60 years. Depending on global efforts to reduce greenhouse gases emissions, further warming of the region could vary from 1.7 to 4°C. Alongside the temperature rise, the Western Balkans countries have seen change in inter-annual and intensity distribution of precipitation, as well as increase in frequency and severity of the extreme weather and climate events. Changes in climate characteristics are increasing the risks from natural disasters such as floods, droughts, wildfires, and landslides, and emphasize the need for risk assessment of such events in future periods in order to prevent catastrophic consequences and preserve lives and assets. In this study we have analyzed changes in the precipitation patterns and intensity distribution by the end of the 21st century using the results of an ensemble of eight regional climate models from the EURO-CORDEX database, under the RCP4.5 and RCP8.5 IPCC scenarios. The results showed increase in the average number of days with heavy precipitation events and in the amount of water accumulated in heavy precipitation events, especially in the mountains and hilly parts of the region. Besides, more frequent, longer and severe drought events and heatwaves, and the changes in vegetation and land use, further diminish the natural capacity to mitigate landslide risks, intensifying the overall vulnerability across the region. Projected increase landslides risks indicate the need to incorporate future climate change impacts into the risk management strategies, land-use planning and infrastructure development across the Western Balkans region.

Keywords: climate change, landslides, risk assessment, precipitation, natural disasters

Determination of the soil-water characteristic curve of the soil by physical modelling tests

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Abstract: An increasing number of published studies in the last decade show that physical model experiments are becoming an increasingly popular and available tool in the study of various problems, such as rainfall infiltration, surface runoff, hydromechanical response of soils and slopes, slope stability, effectiveness of remediation measures, hydraulic barriers, effects of vegetation, etc. The soil water characteristic curve (SWCC), which relates soil suction to soil moisture content, is one of the most important features in unsaturated soil mechanics. Together with the hydraulic conductivity function, it plays a crucial role in the transient rainfall infiltration process and thus has a major influence on the stability of slopes exposed to rainfall. However, several studies have shown that direct measurement of unsaturated hydraulic parameters using conventional methods can be challenging and time-consuming. This is especially true for fine-grained soils, where unsaturated soil property functions cover a wide range of soil suction that these soils may typically exhibit, and where measurements for the determination of the SWCC typically require the combination of different measurement techniques and equipment. On the other hand, measurements in uniformly graded coarse soils can be challenging due to the typically highly non-linear and steep shape of SWCC, where only a few kPa of soil suction can distinguish between saturated and residual soil moisture conditions. In this study, preliminary results are presented to determine the SWCC of a uniformly graded sand by a specifically designed physical model tests. A 30 cm high slope inclined at 35 degrees and instrumented with soil moisture and pore water pressure sensors was subjected to increasing and decreasing simulated rainfall intensity to obtain data on steady-state seepage conditions that can be used to hydraulically characterise the slope material. The preliminary results indicate that the presented method is not only useful for soil hydraulic characterisation, but that the data collected through the experiment could also be useful for studying hydraulic hysteresis effects on soil moisture and pore water pressure conditions.

Keywords: physical modelling, landslides, rainfall infiltration, soil-water characteristic curve, unsaturated soil

Tailing Dam Stability Evaluation using 3D Numerical Modeling

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Abstract: The disposal of tailings represents a significant engineering challenge in the mining industry, primarily due to the vast volume of material involved and the potential environmental risks. As such, the assessment of tailing dam stability is a critical component of the engineering process, alongside design considerations. Terrain topography plays a pivotal role in both design and stability assessment; flat terrains generally simplify these processes. In contrast, complex terrain conditions necessitate a design that accommodates spatial constraints, which in turn makes stability assessment more intricate and demanding. Traditionally, 2D limit equilibrium and stress-strain analyses have been the standard, offering reliability for simpler design scenarios. However, for more complex designs, these traditional methods fall short due to complex boundary conditions that significantly impact the stability of tailing dams. These complex conditions can only be accurately assessed through 3D analysis. This paper delves into a comparative study of 2D versus 3D limit equilibrium and stress-strain analyses in tailings dam design and stability assessments. Beyond the complex boundary conditions inadequately captured by 2D analysis, the distribution of pore pressure within the dam material also undergoes significant variations, which 3D methods can more accurately account for. The advantages of 3D analysis become particularly evident in the identification of risks associated with the intricate designs of tailing dams. Neglecting these complexities and resorting to oversimplified methods for stability assessments can escalate environmental risks, potentially leading to dire consequences. Thus, this paper underscores the importance of adopting advanced techniques in managing the stability risks of tailing dams in complex geological settings.

Keywords: slope stability, 2D and 3D analysis, tailing dams

Mapping, Modelling and Monitoring for the Safe and Economic Design and Management of Rock Slopes

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Abstract: Technological improvements including the routine use of aerial photogrammetry, semi-automatic rock mass characterization, three-dimensional slope stability modelling and ground-based radar monitoring (i.e. mapping, modelling and monitoring) can now be applied rapidly to develop a continuously improving digital twin in parallel to a rock slope excavation sequence for civil and mining engineering projects. This is critical for reconciling the effectiveness of geotechnical models for predicting future slope stability (or instability) by reducing uncertainty in ground condition and behavior understanding as excavations progress. This paper presents case studies to describe the application of a manual digital twin approach with multiple layers of monitoring. Monitoring systems used to manage safety risks were developed in response to uncertainties in ground characterization and limitations in slope stability analysis and design, i.e., to address known or perceived residual risks prior to excavation. Fast data collection and analysis permits comparison of the three-dimensional model with observed slope conditions as a form of reconciliation and allows for critical geological structures to be added to the geotechnical model as excavations progress.

Keywords: slope stability, 3D analysis, photogrammetry, monitoring

Interpretation challenges when detecting landslides in flysch environment: examples from visual analysis of LiDAR DTM in the City of Buzet

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Abstract: Landslide inventory maps document the extent of landslides in a territory, providing information about the spatial distribution, types, pattern, recurrence and statistics of landslides. In recent studies, inventory maps are commonly prepared by visual interpretation of innovative remote sensing imagery, e.g., LiDAR (Light Detection and Ranging) topographic datasets, by detecting the geomorphic expression of landslide features. Given that landslide inventories are essential input parameters for a variety of subsequent analyses in landslide research, the accuracy of the final inventory map is an important issue. While the geographic accuracy mainly depends on the type and resolution of the interpreted imagery, thematic accuracy may strongly depend on the interpreter's skills at identification and classification of slope failures. However, distinguishing landslides from other specific topographic forms in areas characterized by complex geological settings and multi-hazard processes may become challenging even for highly experienced interpreters. In such environments, errors in landslide mapping can result either from geomorphologic convergence between landslides and other morphological processes, or if landslide features have been strongly modified or even removed by other processes. In this study, we present several case studies of the visual interpretation of 0.3 m LiDAR DTM in the City of Buzet in Croatia, showing difficulties of unambiguous landslide detection. The research was conducted within the frame of scientific research project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (LandSlidePlan, HRZZ IP-2019-04-9900). The study area (19.96 km2) is flysch terrain in central Istria, composed of a rhythmical alternation of marls, carbonates, and thinly bedded carbonate-siliciclastic turbidite sediments. Weathering processes and high erodibility of bedrock led to the formation of numerous landslides and various erosional features. First, we present specific morphological features formed along hillslopes and sidewalls of low-order valleys, and discuss whether they actually represent landslides. Furthermore, we show the appearance of Badlands and gully head on LiDAR DTM derivatives and explain the possible morphological convergence between these phenomena and landslides. For example, they both may create similar arcuate scarp and sharp flanks, and share little apparent difference along the toes. Finally, we present examples of numerous concave scarps formed along the edges of gully channels and discuss the differences between forms representing zones of landslide depletion and erosional features.

Keywords: landslide inventory, mapping accuracy, geomorphological convergence, LiDAR, City of Buzet

Evaluating the Effectiveness of Deep Learning Algorithms in InSAR Data in Early Warning Systems for Landslide Risk Mitigation

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Abstract: Landslides are a significant natural hazard that can cause severe damage to infrastructure and impact local communities' safety and prosperity. Accurate and reliable prediction of deformation caused by landslides is crucial to implementing effective disaster management strategies that can mitigate the risk of landslides and their impact on communities and provide an accurate early warning system. This study proposes a comprehensive approach to cumulative deformation induced by landslide prediction in the Caiazzo hamlet (southern Italy), a critical area that has experienced significant landslides that have impacted settlements and infrastructure. The study uses a CNN-LSTM algorithm with Spatio-Temporal dependency to predict cumulative deformation caused by landslides, employing geological, geomorphological, and geospatial data as predisposing factors. These factors include elevation, slope, Topographic Wetness Index (TWI), Stream Power Index (SPI), geology, flow direction, curvature, Normalized Difference Vegetation Index (NDVI), and land use. The Permanent Scatterer Interferometry (PSI) technique was applied on 132 and 143 SENTINEL1-A ascending and descending tracks, respectively, to obtain cumulative deformation data as labels, providing an extensive data set that allowed for accurate and reliable prediction of landslide deformation. The proposed CNN-LSTM algorithm integrates convolutional neural networks (CNNs) and long short-term memory (LSTM) networks to learn the spatio-temporal dependencies between landslides' predisposing factors and their cumulative deformation. This approach allows the algorithm to capture the complex relationships between the predisposing factors and the occurrence of landslides, resulting in accurate and reliable understanding of landslide kinematics and providing early warning system accurately. The close match between predicted and observed cumulative deformation indicates that the CCN-LSTM model effectively captures the complex relationships between the various factors contributing to cumulative deformation prediction. Our finding illustrates more than 70% of predicted deformation with less than 2 mm error and 90% with less than 5 mm error after prediction. Overall, the proposed algorithm's superior performance in predicting cumulative deformation caused by landslides highlights the potential of deep learning algorithms to enhance landslide prediction and disaster management strategies. The proposed algorithm can support effective decision-making, provide valuable insights for disaster management, and help mitigate the impact of landslides on local communities and infrastructure.

Keywords: Landslide prediction, CNN-LSTM algorithm, Spatio-Temporal dependency, Deep learning, Early Warning System, PSI technique

Monitoring of deep-seated Liberty bridge landslide on right bank of Danube in Novi Sad

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Abstract: The Liberty bridge in Novi Sad is a 1382m long cable-stayed bridge over Danube, connecting the city of Novi Sad with town of Sremska Kamenica via national road of IB category, No. 21. On right bank of the Danube, in the surrounding area of six bridge piers is situated a deep-seated slow-moving landslide, commonly known as Danube-type landslide, which caused significant displacement of the piers in the period between 1981 and 1990. As a result, continual monitoring of ground water level in the terrain and the displacements of the landslide itself has been carried out since 1992, with various interruptions, as a part of four-part measures envisioned for remediation of the landslide. The landslide itself is retrogressing, multiple rotational type, which advances to the river itself, with varying degrees of activity in the smaller sliding bodies within the large landslide body. Activity of the landslide is assumed to have begun as early as late Pliocene. Currently the maximum depth of the detectable large active rupture surface is 36m and it reaches the riverbed itself, some 100-150m from the bank itself, with a number of smaller, shallow secondary landslides occurring in the body itself. In order to monitor ground water levels, several electrical and common, solid standpipe piezometric installations have been installed since 1992 in the terrain over the years. Construction of several boreholes with inclinometer installations has been carried out as well, which allowed for monitoring of displacements in the body itself with standard inclinometer instruments. Inclinometer measurements have been combined with geodetic monitoring of the borehole's caps over the years, which included horizontal but also vertical displacements. This paper presents the results of monitoring of the aforementioned landslide, its process, and gives an assessment and explanation of possible risks that could occur in the future in the terrain. Aside from the established monitoring methods, a combination of UAV surveillance with the present methods is suggested in the future, which would allow for precise measurements in the entire terrain, resulting in a significantly better understanding of the progression and activity of the landslide.

Keywords: landslide, detection, monitoring

Application of drone photogrammetry in hazard assessment in Međine municipality

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Abstract: After heavy rainfall at the beginning of September 2023 in the municipality of Međine, 6 km southwest of Mostar, debris flow appeared which caused minor material damage to the surrounding buildings. Immediately after the appearance of the debris flow, a wider area of 160 ha was recorded with the help of a drone to analyze the hazard, which over time contributed to the formation of the alluvial fan on which the site is located. The recording was done with the DJI Mini 2 drone, and the resulting photos were further processed with different software. Agisoft Metashape was used to generate a point cloud, a 3D terrain model, an orthophoto, and a digital terrain elevation model (DEM) based on 337 photographs. The DEM image was used in further analysis within the FlowR software to obtain a debris flow simulation. An orthophoto was used to validate the simulation. After a successful simulation, using the same settings, another simulation of the debris flow in the same area was made, but this time the DEM images that can be downloaded for free from https://www.earthdata.nasa.gov/ were used, and then comparisons of the obtained simulations were made, using digital elevation models of different resolutions.

Keywords: drone, model, debris flow

Monitoring of active landslide during excavation of slopes for stilling basin of Dam Svračkovo

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Abstract: Svračkovo dam site is located in the western Serbia, on the Veliki Rzav River, 8 km upstream of Arilje town. About 26 million m³ reservoir capacity shall be formed by construction of the embankment dam with the clay core - 60 m high and with the dam crest elevation of 423.60 masl. Closer area of the dam site and of the appurtenant structures comprises the area of about 0.4 km². For the requirements of construction of the stilling basin, i.e. the outlet from the diversion tunnel on the left abutment, the bench slopes from the access roads S1 and S3 are excavated. During excavation of slopes beneath the access road S3, the contemporary scars resulting from the movement of the terrain were detected on the upper access roads and in the vicinity. In addition to investigative work, geodetic surveyors were also carried out for the purposes of observing landslides in the conditions of carrying out remedial measures.

Keywords: Svračkovo, investigation works, geodetic surveyors

Detection and monitoring of slope movement by using Point Cloud obtained from the SfM technique

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Abstract: The paper presents an example of the detection and monitoring of slope movements by using a 3D point cloud obtained from the low-cost, remote, and precise SfM (Structure from Motion) technique. SfM is a photogrammetric range imaging technique for estimating three-dimensional structures from two-dimensional image sequences that may be coupled with local motion signals. Its algorithm detects common feature points in multiple images and uses them to reconstruct the movement of those points throughout the image sequence. The analyzed area represents one part of the cut 4 at km 11+620 to km 12+244 on A2 Expressway Kriva Palanka-Stracin, section Dlabochica-Chatal (Republic of Macedonia). A major landslide on the right side that occurred at the beginning of the construction of the cut, is the case study in this paper while using Unmanned Aerial Vehicles (UAV) and SfM photogrammetry. The cut is being excavated in albite-epidote-chlorite schists. The surveying was performed with a low-altitude camera drone - Phantom 4 RTK, the Pix4D software was used for processing the SfM recordings, while the analyses were done in the CloudCompare software. Four point cloud sets were analyzed in relation to the initial (the reference) one acquired before the detected movements. Multitemporal geomorphic changes in the landslide area were identified by comparing the SfM-derived point clouds in pairs. 3D distances were estimated with the multiscale model-to-model cloud comparison for each pair of point clouds. The obtained results show that the displacements on the slope range up to 70cm. Also, the 3-month observation period shows that the landslide is not settled, actually, there are certain movements, especially in its upper part. The obtained results show that the application of SfM for the detection and monitoring of displacements seems to be a very useful technique for such purposes because of its swiftness, the high detail of prospecting, and the possibility to determine very small movements.

Keywords: SfM technique, displacement, landslide, point cloud

Characterizing the hydrogeological and kinematic behavior of the Lamosano landslide (Eastern Italian Alps) through long-term monitoring

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Abstract: In North East Italy (Chies d'Alpago, Belluno), two major landslides have been active for several years: the Tessina landslide and the Lamosano landslide. The Lamosano landslide is particularly concerning as the hamlet is built directly on a landslide of approximately 6.000.000 m³. Just about 1000 m upstream of Lamosano lays the well-known Tessina landslide, a complex phenomenon involving rotational slides that can evolve into earth flows. The Tessina landslide first activation occurred in 1960, followed by significant reactivations in the 1990s and 1998. In 1992, a particularly significant event struck when a collapse of 2 million m³ of loose colluvium posed a high-risk situation for the nearby hamlets with potential overflow into the built-up area. In response to this event, the Research Institute for Geo-Hydrological Protection (CNR-IRPI) installed the first monitoring network in the area, and following investigation campaigns were carried out both in Tessina and Lamosano in the past 30 years.
Recently four sets of new in-place inclinometers and piezometers acquiring real-time data were installed to investigate the movement of the Lamosano landslide in time. This monitoring system plays a crucial role in identifying the style of activity according with variations in groundwater level due to precipitation and snow melting, seemingly the main triggering factor inducing displacements.
A drainage project is planned for the coming years to reduce the hydraulic head in these units. The design of this project will be supported by the implementation of a hydrogeological and cinematic model. Preliminary investigations are required to ensure the effectiveness of the drainage project, including the determination of hydrogeological parameters, groundwater trends, and landslide kinematics, at least as a starting point in a semi-quantitative manner. To do so, a high-resolution 3D subsoil model was created using lithostratigraphic data to identify the trend of the main hydrogeological units. Additionally, slug tests were conducted to estimate hydraulic conductivity (K) in old piezometers.
Results from the monitoring data are particularly interesting as they show an impulsive kinematic and the simultaneous activation of all 4 sensors. This indicates that the landslide moves as a block. Moreover, there seems to be a connection between groundwater levels near the Tessina landslide and water head oscillations in the Lamosano village. This hypothesis will be re-tested once more data are accumulated, but it might indicate a mutual relationship between the two geohydrological systems, which has never been hypothesized before.

Keywords: Lamosano, landslide, characterisation, hydrogeology, slug test, inclinometers, monitoring

Engineering geological properties of sandstones and marlstones of the instable coastal flysch cliffs of Slovenia

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Abstract: On the Slovenian coast, the dominant rocks are intercalations of thin-bedded hard sandstones and soft marlstones with occasional several meters thick calciturbidite layers. Due to this heterogeneity, the erosion of the coastal cliffs occurs rapidly, and the area is prone to numerous rockfalls and other types of mass movements. All these processes are a great danger to bathers and visitors of the coastal areas. The main factors causing the erosion and disintegration of the rocks are the precipitation, abrasion by the sea and waves, freeze-thaw cycles, temperature differences, wind, and undercutting of the sandstone and calciturbidite beds. The blocks of sandstones are defined by two nearly perpendicular fracture sets (R1 and R2) and the thickness of the layers. The objective of our research was to investigate the engineering geological properties of the rocks (mostly sandstones) and their correlation with other geological, geotechnical, and mineralogical parameters of the rocks. We measured these parameters at 27 sites along the Slovenian coast. We have performed the measurements of the orientation of the R1 and R2 fractures and their spacings, the thicknesses of the sandstone, calciturbidite and underlying marlstone layers, the uniaxial compressive strength determined with the Schmidt hammer, the orientation of the beds and the slope, and the depth of undercutting beneath the sandstone/calciturbidite layer. In the laboratory, we determined the mineralogical composition of the rocks, and geomechanical tests (tensile test, uniaxial compression test, and large direct shear test). Results show a very good correlation between the depth of undercutting and the spacing of R2 fractures, as well as with the thickness of the sandstone/calciturbidite layers. As expected, the correlations between layer thickness and fracture spacing are also good for both fracture sets. Somewhat unexpected is the good correlation between the depth of undercutting and the spacing of the R2 fracture set, but not with the spacing of the R1 fracture set. This could be influenced by the shoreline orientation and the inclusion of this factor is still a work in progress. Uniaxial compression test determined with the Schmidt hammer ranges greatly, from 12 to 179 MPa for sandstones (median value of 51 MPa) and from 38 to 91 MPa for calciturbidites (median value of 82 MPa). Mineralogical composition shows a good correlation of undercut depth with quartz content in the sandstones (which can be explained by higher cementation) and a correlation of undercut depth with clinochlore content. Based on calculations using the RocScience Dips program, the possibility of planar and wedge-shaped slip is minimal. Numerical modeling of stability shows that tensile strength plays the decisive role for the stability of the cliffs. The authors acknowledge that project J1-2477 "Erosional processes on coastal flysch cliffs and their risk assessment" was financially supported by the Slovenian Research Agency.

Advanced geospatial solutions for monitoring, modeling and understanding of landslides

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Abstract: Landslide represents a geological event in which there is a sliding or shifting of soil, usually resulting from factors such as rainfall, earthquakes, erosion, changes in water levels, climate change, and/or human activities. Especially with the prevalent challenges of climate change, the risk of landslides becomes exceptionally high, emphasizing the need for response and preventive action in terms of crisis management. Humans strives for understanding, prediction, and preventive action to minimize potential hazards and damages from such risks. This paper demonstrates the description of advanced technologies, namely the integration of various technologies into unified automated systems, for effective monitoring, modeling, and understanding of landslides. By integrating these technologies, precise monitoring of geological changes, quick identification of potential hazards, and detailed modeling of relevant factors are enabled. An overview of the general approach to the architecture of monitoring systems will be provided, including the basic components of integrated geodetic and terrestrial radar sensors, as well as a practical example where such an approach has had necessary application.

Keywords: monitoring, geodetic technologies, terrestrial radar, landslides.

Landslide susceptibility assessment of the Teslić municipality, in the Republic of Srpska, B&H

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Abstract: This paper presents the landslide susceptibility assessment of the Teslić municipality. Paper also presents information on engineering geological properties and landslides on this area, based on field data collection and input into the digital GIS cadastre of landslides.
Landslides are a very common phenomenon in this area, but they are poorly treated in the spatial planning documentation. Geological setting are very complex, but diabase - chert formation and Oligo-Miocene complex of conglomerate, marl and clay, have the largest share in the percentage of registered landslides.
Landslides are mostly shallow, with a depth of up to 2 m, and they are most often activated in areas of intense human activity, in areas of roads and by the river courses.
Landslide susceptibility assessment was performed, after the field registration and the establishment of a digital cadastre of landslides, in polygonal form. All influential factors were taken into account, such as: lithology, slope, precipitation, distance to watercourses, land use, aspect and curvature. Modeling was performed using the multi-criteria AHP method in a scale of 25x25 m.

Keywords: landslide, database, susceptibility, Teslić

Influence of the landslide inventory sampling on the accuracy of the susceptibility modelling using Random Forests: A case study from the NW Croatia

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Abstract: The quality of landslide susceptibility maps depends on the quality of the input data, i.e. the spatial resolution and accuracy of the landslide conditioning factor maps and the completeness and accuracy of the landslide inventory map. For the pilot areas (40 km²) in NW Croatia, a detailed landslide mapping was done based on visual interpretation of high-resolution LiDAR DTM. This study aims to test the relevance of landslide inventory completeness and sampling on the landslide susceptibility model (LSM). Moreover, by analysing different scenarios, i.e. different ratios of landslides for model training and validation and sampling of landslide location and morphological conditions, we aim to provide new insight into the need for detailed landslide mapping for large-scale susceptibility modelling, as well as the impact on the final landslide susceptibility map. Landslide susceptibility modelling was performed based on 5m pixel-based analysis and Random Forests machine learning method. The landslide susceptibility analysis consists of nine scenarios that were defined considering the percentage of landslide polygons in the inventory for model training (S1 = 90%, S2 = 80 %, S3 = 70%, etc.), while the rest of the landslides were used for model validation (S1 = 10%, S2 = 20 %, S3 = 30%, etc.).Furthermore, three more scenarios were defined based on sampling strategy, i.e. original terrain inside landslide polygon, smooth terrain inside landslide polygon and original buffer around landslide boundary. Landslide susceptibility model training and validation performance were measured with the Area Under the ROC Curve (AUC) metric. The results are part of the scientific research project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (LandSlidePlan, HRZZ IP-2019-04-9900). The purpose of comparing landslide susceptibility models is to define the most suitable methodology for application in the Croatian spatial planning system at the local level.

Keywords: landslide susceptibility modelling, sampling strategy, landslide inventory, large-scale, random forests

Large-scale landslide susceptibility models: Examples and conclusions from the modelling of small and shallow landslides in the continental part of Croatia

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Abstract: The main motivation to research the large-scale landslide susceptibility modelling for application in land use planning and civil protection arises from the national landslide risk assessment (BERNAT GAZIBARA et al., 2019), which recognised landslides as a second natural risk in Croatia (CNPDRR, 2019). Furthermore, the preliminary regional landslide susceptibility analysis showed that approx. 20% of the Republic of Croatia area is potentially prone to sliding. Therefore, large-scale landslide susceptibility modelling was carried out in the frame of two scientific projects: *Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology* (LandSlidePlan, HRZZ IP-2019-04-9900) and project *Applied landslide research for the development of risk mitigation and prevention measures* (PRI-MJER, KK.05.1.1.02.0020).
Large-scale landslide susceptibility modelling was carried out on three pilot areas in the City of Zagreb, Hrvatsko Zagorje and Karlovac City using different mapping units and statistical methods (e.g. Information Value method, Weights of Evidence method, Logistic Regression and Discriminant Analysis, and machine learning methods, including Support Vector Machine, Artificial Neural Network and Random Forest). Moreover, landslide susceptibility models were computed using different scenarios of high-resolution input data, i.e. geometrical types of LiDAR-based inventory and variations of causal factors. Finally, all landslide susceptibility models were evaluated based on model fitting performance, model prediction performance, and model uncertainty. The purpose of comparing landslide susceptibility models is to define the most suitable methodology for application in spatial planning system at a local level. The research was based on innovative technologies, limitations related to the availability of spatial data in Croatia (limited amount of geological data), and urgent needs for efficient solutions applicable in the Croatian spatial planning system in line with European and global requirements related to sustainable development, human and environmental protection.

Keywords: landslide susceptibility modelling, large-scale, spatial planning system

Landslide susceptibility assessment using Frequency Ratio model for the Polog region, North Macedonia

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Abstract: The aim of this study is to assess the landslide susceptibility in the Polog region, which is considered as one of the most landslide prone-areas in North Macedonia due to the combination of complex geological setting, an articulate morphology and specific climate conditions. Geographic Information Systems (GIS) and Frequency Ratio (FR) model were implemented in this study to assess the contribution of conditioning factors to landslides, and to produce a landslide susceptibility map of the Polog region. The landslide inventory map for the study area was prepared by applying three approaches: (1) collecting archive landslide data, (2) detecting landslides by visual analysis of a digital terrain model (DTM) obtained by LiDAR (Light Detection And Ranging) terrain scanning, and (3) analysis of DInSAR (Differential Interferometric Synthetic Aperture Radar) indicated zones with registered displacements. Twelve landslide conditioning factors were generated for landslide susceptibility modeling, which include slope, elevation, aspect, plane curvature, profile curvature, roughness, distance to roads, lithology, distance to faults, rainfalls, distance to rivers and land use/land cover. The relationship between landslides and conditioning factors was statistically calculated with FR analysis. FR values were used to produce the Landslide Susceptibility Index (LSI), based on which the study area was divided into five zones of relative landslide susceptibility, being very low, low, medium, high and very high. The results of the analysis have been validated by estimating the relative density of landslides, that is, calculation of the so-called R-index. The statistical results show that the R-index value increases as the landslide susceptibility level increases from very low to very high, which indicates a high-quality landslide susceptibility map obtained by using the FR model. The results also showed that the FR is simple method for landslide susceptibility assessment since the input, output, and calculation process are readily understood.

Keywords: landslide, susceptibility, frequency ratio (FR), inventory, validation, Geographic Information System (GIS)

Žirovac landslide: a case study of the local scale landslide investigation for engineering purposes with its assessment on a regional scale

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Abstract: A detailed analysis of the "Žirovac" landslide on Croatia's state road section in the village of Žirovac is given in this case study. The landslide was triggered by the Petrinja earthquake in December 2020 and was subject to fast-paced processes of investigation and mitigation. The engineering geological and geotechnical survey including boreholes and geophysical investigations were performed on a large local scale.
The earthquake-induced rotational landslide was observed on the road embankment section, which was reported to be an old landslide, continuously covered by new layers of gravel material. Despite the localized, earthquake-induced landslide, the wider slope area showed significant signs of terrain sliding and/or creeping which could be observed on the existing damaged buildings and shallow constructions.
Performed investigation results indicated the presence of two landsliding mechanisms: (1) The local, rotational landslide of the road embankment induced by the Petrinja earthquake combined with the unfavourable load of the continuously added embankment layers and the underlying material degradation due to groundwater flow; (2) The global, translational creeping landslide of the wider slope area caused by occasional but significant groundwater flow and consequential degradation of the deeper-seated bedrock. The local landslide, as a primary subject of the investigation works performed, was limited to the road embankment section and embankment material. Although 225 m wide, the length of the moving material was only 20 m, with a sliding surface depth of 2.5 m. The global landslide was reported as an old creeping landslide, causing occasional but continuous damage to the surrounding buildings and infrastructure. According to the investigation works performed, the global landslide was defined as a translational landslide, approximately 300 m wide and 300 m long with its sliding surface formed at the depth of 5 – 8 m, just above the underlying impermeable cretaceous clays.
Although the investigated local landslide was induced by the Petrinja earthquake, the effect of the global landslide on the local sliding was taken into consideration in the engineering geological report for landslide mitigation purposes. The continuously reported local landslides, prior to the Petrinja earthquake, were probably induced by the continuous creep of the global landslide.
This case study also observes the imperfections of the fast-paced, local scale investigations for quick mitigation purposes regarding the landslide characteristics determination on a regional scale.

Keywords: landslide, earthquake, local scale, engineering

Application of Landslide Susceptibility Maps in Spatial Planning at Local Level

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Abstract: Landslides, as one of the most common and worldwide present natural hazard phenomena would expectedly, due to climate change, become an increasing threat. The severe socioeconomic and environmental damage and losses, as well loss of human life caused by landslides, involved a considerable variety of techniques and practices to mitigate the potential losses arising from landslide occurrence. The approach to completely avoid landslide-prone areas end exclude human activities from them is rarely feasible, and it is neither possible nor desirable to limit development in all landslide-prone areas. Solution lies in determination and selecting of effective various mitigation approaches through the space management included in spatial planning. The landslide hazards mitigation strategies include the major mitigation approaches that are: restricting development in landslide-prone areas; enforcing codes for excavation, construction, and grading; engineering for slope stability; deploying monitoring and warning systems; and providing landslide insurance. To enable enforcement of landslide hazards mitigation approaches, a necessary condition is providing of landslide inventory and landslide susceptibility maps in landslide-prone regions. These maps must be made based on standards and guidelines for landslide hazard maps and assessments sufficiently detailed to support mitigation action at the local level. In this paper we will present landslide hazard mitigation approach included through the municipality spatial plan of the Jelenje Municipality, near the City of Rijeka, Croatia. The central part of Jelenje Municipality is in the Rječina River valley known for numerous landslides in the past. Determination and selecting of effective mitigation approaches based on previously created landslide inventory and landslide susceptibility maps using high-resolution LiDAR morphometric derivative maps. The landslide susceptibility assessment on a scale 1:5000 was performed using univariate statistical analysis and geofactors relevant to landslide occurrence. The landslide inventory and landslide susceptibility maps are including in municipality spatial plan as professional backgrounds to enable officials and spatial planners to reduce landslide hazard through implementation of local regulations in conditions of use, construction and protection of the environment. The presented results are part of the scientific research project "Methodology development for landslide susceptibility assessment for land-use planning based on LiDAR technology" (LandSlidePlan, HRZZ IP-2019-04-9900).

Keywords: landslide, inventory, susceptibility, spatial planning, landslide hazard mitigation

Investigating the factors governing the damage occurrence on buildings exposed to slow-moving landslide risk

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Abstract: The interaction between slow-moving landslides and human settlements is a remarkable issue for both scientific and technical communities involved in identifying the most suitable strategies for land-use planning and urban management. In the last years, the interest on the topic is increased by the evidence that several urban areas are affected by active landslides involving complex geological formations and moving along shear zones where fine-grained soils prevail. Although the representative velocities of those landslides usually range from extremely slow to slow classes, exposed buildings can suffer damages whose severity increases over time as cumulative displacements increase with high socio-economic impacts.
To address this issue, empirical procedures implementing data collected by way of in-situ/laboratory tests and monitoring techniques can help in generating tools able to predict the onset and the development of the slow-moving landslide damage to the exposed buildings. However, to obtain reliable results, a preliminary effort is required in terms of knowledge on the factors governing – in different way – the response of the above buildings to displacement patterns at foundation level such as: i) the landslide mechanism, which includes information about the so-called Intensity Measure (e.g. a representative velocity or differential displacements cumulated in a reference time period), ii) the characteristics of the involved soils, iii) the position of a given building with respect to the landslide-affected area (i.e. at the head, body or toe), iv) the characteristics of the building (structural and foundation typology, geometry, state of maintenance).
Following this line of thought, this study analyzes different well-documented case studies in southern Italy wherein a rich sample of slow-moving landslide-induced damage to buildings was collected. Provided that similar geological and geomorphological features as well as landslide types and urban fabric are considered, the analysis of the multi-source information gathered from in-situ damage surveys and both conventional (ground-based) and innovative (remote sensing) monitoring techniques allowed investigating the role played by each of the above governing factors. These results could turn out to be helpful in generating damage forecasting tools, which can facilitate the decision makers in activities aimed at mitigating the slow-moving landslide risk to buildings by way of structural and/or non-structural measures whose design calls for the adoption of numerical procedures.

Keywords: slow-moving landslides, building damage, forecasting tools.

Harmonized approach for earthquake - induced landslide susceptibility assessment in Vodno urban area

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Abstract: In the last 20-25 years Skopje, and more specifically Vodno mountain has been exposed to intense urbanization, population growth, followed with intense anthropogenic processes such as application of structural loads, vegetation cuts and excavations, which have significantly changed the initial conditions of the terrain. As a result, during the last decade, this reflected with numerous instabilities on the terrain, which raised great interest among the media and scientific community which work in the area of landslide hazard assessment. Thus, in this research paper we will provide a harmonized approach for earthquake induced landslide susceptibility in this urban area. For the analysis we are going to use several datasets such as geomorphological (DEM raster file), land use, detailed plan of the buildings and loads, detailed geological and finally seismological datasets would be used.

In the first phase, the following research paper would present two methodologies for landslide susceptibility, implemented in QGIS open-source geographic information system. The susceptibility zoning is going to be estimated with SZ plugin, which provides the estimations through a several classifiers. In the paper we are going to apply the weight of evidence, logistic regression, and decision tree methodologies. Through the SZ plugin we will use different mapping units to fit the model and to visualize the relative receiving operating characteristic (ROC) curves. In the second phase, the European ELSUS v2 initiative for landslide susceptibility mapping for the given area study is going to be used. The results from both approaches will be compared accordingly. In the second phase, based on the obtained data, the stability of the slope of mountain Vodno is going to be evaluated by application of the most important datasets and aspects, through the infinite slope limit equilibrium method. In addition, an analytical relationship is going to be applied to estimate the total slope displacements, according to the theory of Newmark. Finally, the landslide hazard zonation will be presented by QGIS maps, showing the expected permanent displacements for pre-defined earthquake scenarios.

The given analysis would provide important aspects about the stability of the analysed slope and should be taken into consideration at decision making process for urbanization of the Vodno mountain in Skopje. This approach would prove reduction of the vulnerability of the people in the aforementioned area, though the process of the future spatial planning in synergy with science. Furthermore, if necessary, designers can use them for identification and proposition of structural and/or non-structural measures, that would be used for reducing the risk of earthquake induced landslide hazards.

Keywords: earthquake - induced landslides, susceptibility, SZ plugin

Assessing the use of voice classification methodology for landslide forecasting

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Abstract: Nowadays regional scale landslide warning systems typically depend on statistical or empirical approaches aimed at identifying rainfall condition capable of landslide triggering. These approaches are often easy to implement but of a relevant degree of uncertainty. In recent years, artificial intelligence has entered the field of landslide hazard assessment, demonstrating its potential in reducing uncertainties. Currently, it is primarily used for landslide hazard assessments, mapping, and detection, but its application for temporal landslide forecasting remains limited. This study explores the use of voice classification methods to identify the "rainfall signature" associated with the initiation of rainfall-induced landslides, examining its potential for landslide forecasting. Hourly rainfall time series serve as input data for the model, labeled based on their association with the presence or absence of landslide events. A long short-term model (LSTM) is employed to recognize the pattern of rainfall time series and associate them with landslide occurrences. Since this is one of the first attempts of its kind, multiple association rules between rain gauges and landslides and various model configurations have been tested to identify the best-performing setting without overfitting issues. The model is tested in Emilia-Romagna region (Italy), an area where previous studies on rainfall conditions associated with landslide initiation exist, providing a benchmark to assess the results' quality. Over 1000 rainfall-induced landslides over 10 years, along with an equal number of rain events without landslides, were used to train the model. The data were divided into training, validation, and test sets, randomly shuffled multiple times to assess the model's robustness. Results indicate that the model's accuracy is highly dependent on its initial setup, varying from 60% to over 90%, with a positive prediction power of the best model configuration equal to 82%. Computational time for applying the learning model was evaluated on a standard desktop PC and found suitable for its implementation in a landslide warning system. While this is a preliminary attempt with certain aspects needing further refinement, the early results suggest that the predictive capabilities of the model are significantly higher than those of statistical or empirical approaches.

Keywords: Landslide, Forecasting, Rainfall, Artificial Intelligence, LSTM

Preliminary landslide hazard map of Serbia

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Abstract: In this work a preliminary landslide hazard map of Serbia is presented as an output of a work group assignment in 2018. Simple multi-criteria approach based on experts' opinion is implemented over a set of data which are mostly publicly available. Input data included: Digital Terrain Model (and its derivatives) at 30 m resolution; Engineering geological map of Serbia at 1:300 000 scale (and its derivatives); Hydrometeorological dataset (and its derivatives); depth to bedrock model at 250 m resolution. There were seven conditioning factors which were derived from these input raster datasets. In addition, available landslide inventory on the national level was used to validate the model. The methodology first involved creating a questionnaire for domestic practitioners in the field of engineering geological mapping, to determine the sub-setting of conditioning factors into classes and individual weights of each conditioning factor in accordance with their influence on landslides. The weights were normalized in 0-100% range and then used as raster multiplicators for each reclassified conditioning factor. After their multiplication and addition in GIS environment a landslide hazard model was created. Result suggests that very high and high hazard class occupy about 12% and 28% of the territory, respectively. Administratively and spatially, the SW and W Serbia are the most affected. Validation suggests that very high and high hazard classes were confirmed in 46% of the inventory, moderate class has 31.5%, whereas remaining 22.5% can be considered as false negatives, leaving room for further improvements of this preliminary map version of the map.

Keywords: landslide hazard, Serbia, multi-criteria analysis

Assessment of risk scenarios to support landslide studies

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Abstract: The definition of risk scenarios that are as reliable and detailed as possible is a primary objective to increase the effectiveness of civil protection actions in the alert phases, together with adequate self-protection actions. In the workflow that characterizes integrated emergency management systems, risk scenarios are an essential element for connecting the information coming from the early warning systems and the actions at responding to the need of safeguard human life. Nowadays, the availability of high-resolution terrain data allows access to an almost precise knowledge of the territory, forgetting purely topographical approaches whose application over a vast domain has proven impractical or misleading. This translates into new potential in the definition of event scenarios and risk scenarios.
In reality, alongside highly advanced pre-announcement and monitoring systems, there are often barely outlined event scenarios and mostly qualitative risk scenarios, and therefore lacking the effectiveness they should and could have. To achieve a level of detail that effectively supports the activities in the intervention phase, it is necessary to aim, even more decisively, towards a quantitative analysis of the risk deriving from hydrogeological phenomena. Event scenarios, as is known, describe the phenomena that can occur, quantitatively define their magnitude, locate the vulnerable areas, i.e. those that can be affected by the event. Landslide phenomena, for example, are distinguished by kinematics, the type and size of the material involved, the speed of movement, the impact energy.
The risk scenarios, therefore, describe the foreseeable effects of the events identified and described by the event scenarios on the exposed elements. In general, in risk analysis, vulnerability is considered invariant or, in any case, is only assessed quickly, whereas it is almost always decisive in defining the level of risk to which a vulnerable area is subject.
In this work we propose a simplified vulnerability assessment method for people exposed to fast moving landslides. The procedure is very flexible because it can be developed at different levels of detail and at different spatial scales depending on the size of the objects involved.
The proposed approach has some similarities with other methods used in the vulnerability assessment to other natural risks, as earthquake and floods and, therefore, it can be adopted for multi-risk analyses. Referring to a case study, it shows the advantages and potential of the approach for a high-resolution landscape mapping at reach scale to support landslides studies.

Keywords: risk assessment, vulnerability index, integrated approach, non-structural measures

Regional landslide susceptibility assessment: case studies from Greece

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Abstract: In the present study, regional-scale landslide susceptibility mapping for two well-known landslide prone Regions in Greece was carried out using qualitative both quantitative methods. Geological settings and especially the variety of geological units, was the key difference between these areas. For this analysis, the Analytic Hierarchy Process (AHP) and the Frequency Ratio (FR) methods were conducted in both cases for six common-used predisposing factors (lithology, slope, land use, distance from faults, distance from hydrographic network and road density). The study made use of the National Database of Landsides, while moreover an abundance of field surveys was carried out in these areas, with a view to ensuring both the accuracy of landslide spatial distribution as well as their special features. Due to the variety of information and the abundance of data provided, some interesting outcomes were reached, concerning the characteristics of the landslides, after applying simple statistical analysis. Landslide susceptibility index (LSI) was used for mapping landslide susceptibility level. ROC curves were performed to validate the results. Thus, the output maps generated by this procedure were verified by comparison with known landslides not used for training the models (prediction rates) or known landslides with an equal number random set of points free of landslides (success rates). One of the main aims of this work, was to evaluate the importance of the conditioning factors in predicting landslide occurrences using the mentioned models. According to the results, in both areas the importance of different predisposing factors seems to vary in shaping the landslide susceptibility level. This research recognizes the critical role played by scale for landslide susceptibility modelling. Therefore, part of the aim of this work is to discuss the minimum, yet sufficient data required to develop more versatile, generalized regional susceptibility models (medium scale), that can then be used as indicators for national scale (small scale) analysis and in the exploitation of research results by local stakeholders and Civil Protection authorities.

Keywords: landslide inventory, susceptibility assessment, Greece, LSI, ROC curves

Review of the Publicly Available Digital Landslide Inventories in the Republic of Serbia

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Abstract: Landslides are recognized as major global geohazards, possessing the potential to inflict significant socio-economic damage. With the ongoing challenges of rapid population growth, urbanization, and current climate changes worldwide, the anticipation is that landslide risks will intensify in the future. In this context, the quality of landslide susceptibility, hazard, and risk analyses must be enhanced. Landslide inventories, serving as crucial data sources for quantitative landslide zoning, stand out as essential tools for conducting these analyses. While many countries around the world either have established or are in the process of developing national or regional landslide databases, there remains limited insight into their contents, data formats, completeness, structure, and accessibility. The same holds for the Republic of Serbia, a developing country with a national landslide database in the establishment phase. Consequently, this paper presents a brief review of the existing digital landslide inventories in the Republic of Serbia, that are publicly available (online). Three digital landslide databases – "BeoSlide", "BEWARE" and "Disaster Risk Register of Serbia" have been analyzed and compared in terms of their structure and scope, variety, and quality of the provided data. The concluding remarks of this review focus on recommendations for enhancing digital landslide databases in Serbia, which could also greatly benefit the development of the national database.

Keywords: geohazard, database, BeoSlide, Beware, GeoSrbija

Landslide events in Slovenia 2023: causes and consequences

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Abstract: Between August 3 and 6, 2023, Slovenia was hit by a natural disaster of national scale. Extreme rainfall with a return period of up to 250 years led to flooding and triggered several thousand landslides. Most landslides were recorded in the area north of Kamnik, in the area of Zgornja Savinjska dolina and in the wider Koroška region between Črna na Koroškem and Dravograd, as well as in the area of Poljanska dolina. At the Geological Survey of Slovenia (GeoZS), field data on landslides and related phenomena were mainly collected during intervention visits, which we carried out in coordination with the civil protection headquarters. During the intervention visits, we determined the type of slope mass movements, the extent of the events and the causes of creep, as well as assessing the potential for further movements and planning possible temporary intervention measures. We estimate that around 10,000 slope mass movements were triggered during the event, with extremely high densities in some areas. Due to the large amounts of water, the landslides mostly turned into mud or debris flows, with material deposited on the foothills some 10, 50, 100, sometimes even more than 100 meters away from their original location. As a result, facilities and infrastructure have also been affected and threatened, sometimes far away from the original areas of origin of the phenomena. In most cases, the rock surface is covered by clastic sediments of varying thickness. In Koroška, weathering of metamorphic and magmatic rock can also be observed. Less frequent were wedge-shaped rockslides, where material slide along deep structural discontinuities in the slope. In some exceptional cases, landslides occurred for very unusual geological grounds, where they would not otherwise be expected. This paper examines the rainfall conditions during the event, the nature of the slope mass movements and the intervention activity.

Keywords: landslides, slope mass movements, extreme rainfall event, 2023

Rainfall-triggered slope instabilities under projected Precipitation Extremes: A Comparative Study Using Physical and Numerical modeling

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Abstract: The main contribution of this paper is seen in the assessment of the impact of infiltrated water on moisture, suction, and evapotranspiration which, as it was seen, have a significant impact on the slope stability exposed to heavy rainfall. Intense rainfalls, as a result of an atmospheric impact, climate variations, and changes, are often seen as a cause for instability, landslides, or significant erosion of natural and engineering slopes. Through the infiltration of atmospheric water, the natural moisture of the material is affected, which reduces the initial suction and finally reduces the unsaturated soil shear strength. Hence, it is recommended that it is necessary to include the impact of precipitation in the slope stability analysis. In the literature, this phenomenon is described as soil-atmosphere interaction. Therefore, this dissertation will present an advanced concept for slope stability analysis that takes into account the time-dependent mechanical, hydraulic, and thermal behavior of soils as a multiphase system.

The main goal of the study is to contribute to the understanding of the hydromechanical behavior of unsaturated sandy soils and their impact on rainfall-induced slope instability through a holistic approach that combines theoretical, laboratory, experimental, and numerical results.

The paper presents an analysis of an ideal slope example subjected to intense rainfall, for which both physical and numerical models were employed. The aim was to assess the impact of infiltrated water on moisture and suction as the main factors that lead to instability. The comparison shows a very good agreement between the measured and calculated state variables such as the development of deformations, pore pressure, suction, and moisture content over time. In general, the results confirm the hypothesis that the role of precipitation can have a significant impact on the destabilization of the surface layers at slopes where initial erosion occurs, leading to local instability which eventually ends in global fracture and landslides. It can also be concluded that the duration of precipitation and the initial degree of saturation have a significant impact, so if they change and lead to complete saturation of the surface layers of the slope, they will cause runoff water down the slope and formation of local gullies, as it was observed on the dam after heavy rainfall in the past. The results indicate that the global degree of slope safety after a critical event defined by the relevant intensity and duration of precipitation can lead to a reduction of 10% to 30% depending on the geometry and the material of the slope. In conclusion, certain recommendations aim to raise the level of design of engineering slopes in the future, which will generally contribute to more stable and safer infrastructure slopes.

Keywords: rainfall, slope, unsaturated soil, stability, erosion

Preliminary results of rock thermal regime due to solar irradiation in urban environment in Ljubljana, Slovenia (IPL-262)

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Abstract: Near-surface temperature measurements in small rock samples are being undertaken in urban environment to help better understand freeze-thaw cycles under natural environment for a study on sensitivity of rock faces to climate change. Measurements are under way since 2022 in a small plot-scale pilot observatory on the top of the roof of the main building of the Faculty of Civil and Geodetic Engineering, University of Ljubljana, close to the city center. Four gray limestone (type Repen, very hard) rock specimen (sizes: 10 x 10 x 20 cm) from a quarry in Karst region of Slovenia were put into a cube using insulated material (XPS- Extruded Polystyrene) around each specimen so that only the polished face area 10 x 10 cm is exposed to light and air. We installed these four cubes separately in such a position that rock surface in each of it is exposed to one of the four main direction of the sky – the rock area is placed vertically to catch solar irradiation. The cubes are not throwing shadows to each other. A nearby weather station (also on the roof top) is measuring the most relevant hydrometeorological parameters (solar irradiation, air temperature and humidity, solar wind velocity and direction, rainfall rates). The temperature at 1-cm and 20-cm depth inside rock specimen are monitored with frequency and precision using temperature sensors. All measured data are stored and sent to a web cloud for presentation and nearly real-time monitoring (see: https://www.unesco-floods.eu/links/field-equipment/). The measurements are a small part of the ARIS (Slovenian Research and Innovation Agency) project J1-3024 that runs from October 2021 till September 2024, that was acknowledged in 2022 as the project IPL-262 Deciphering the sensitivity of rock faces to climatic changes and freeze-thaw cycles in permafrost-free regions (https://www.landslides.org/projects/ipl-projects/). The obtained measurements will be used together with other measurements in pilot monitoring observatories in Slovenia performed by Geological Survey of Slovenia (https://glvn.geo-zs.si/en/) for validation of a 1D numerical model of heat flow into the rock mass from its surface caused by direct and diffuse sun insolation and from surrounding air masses. Knowing rock thermal regime is essential to better understand crack initiation and propagation as a part of dynamics of frost weathering and as a triggering factor for rock falls.

Keywords: free-thaw cycles, frost weathering, plot-scale pilot monitoring, solar irradiation, thermal regime

Landslide impact on road infrastructure in the Western Balkans

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Abstract: Landslides stand among the most common road-related disruptions throughout the Western Balkans Region, especially in the last couple of decades that have been witnessing severe weather anomalies, likely related to climate change. It is therefore inferred that landslides will become even more prominent in near future. Their assessment is, therefore, crucial for all further road planning, design, and management entailed. By fitting into EU : the Western Balkan countries are lately taking actions to pinpoint landslide and otherwise hotspot areas along the road networks and prioritize future investments accordingly. Herein, an example of landslide assessment along the road network and its impact is presented, with an adjusted methodology for large-scale frameworks, such as Western Bakan. The results show that roads are significantly affected by landslides in the Region to a level that it is difficult to discern areas of higher priority, thereby highlighting the need for developing sophisticated methodologies for their impact assessment. Landslides are confirmed as one of the topmost natural hazard types that cause road network disruption. When it comes to climate change, anticipated for the near and far future, it has been indicated that there are zones where the landslide hazard and their impact are expected to increase locally, but also zones where it will stagnate or drop. It has been demonstrated that such large-scale assessment can be very useful for public enterprises and governmental entities in their further decision-making and financing the road network maintenance, reconstruction, and extension.

Keywords: landslide hazard, road network, climate change, the Western Balkans

Rapid 3D rockfall susceptibility assessment of Orašac rock slope, Croatia

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Abstract: This paper presents a rockfall susceptibility assessment on a detailed (cliff) scale, by using the data from the high-resolution 3D point cloud obtained by unmanned aerial vehicle (UAV) digital photogrammetry. The studied limestone rock slope is located in Dubrovnik-Neretva County, south Croatia. Discontinuity orientations, required for 3D rockfall susceptibility assessment, were manually mapped, using the structural geology toolbox Compass, integrated within CloudCompare v2.12, providing information about the number and orientation of individual discontinuity planes, the number of discontinuity sets and weighted density concentrations associated with certain discontinuity set. Based on the acquired input data, a 3D rockfall susceptibility assessment was done for planar failure, wedge failure, and flexural toppling failure. Rockfall susceptibility assessment consisted of performing spatial kinematic analysis for normal and overhanging slopes based on the Markland test and highlighting points in the 3D point cloud susceptible to certain types of failure. Based on discontinuity orientations and orientations of the points in the point cloud, the Kinematic Hazard Index was calculated for every point in the 3D point cloud, and potential rockfall source areas were highlighted. The Kinematic Hazard Index was calculated by in-house MATLAB code which enables rapid 3D rockfall susceptibility assessment considering complex slope topology in both normal and overhanging areas of the studied rock slope.

Keywords: rockfall susceptibility assessment, 3D point cloud, discontinuity mapping, UAV

Fines content influence on the dynamic slope behavior in small-scale physical models

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Abstract: Small-scale physical models have already been used for some time in an attempt to simulate the natural slope behavior subjected to static and dynamic loading.
For the purpose of this research, small-scale physical slope models with a 40° slope inclination were made using pure sand specimens and two artificial mixtures of sand and kaolinite powder with different mass ratios. Physical models were saturated and subjected to dynamic loading in order to simulate the behavior of slopes that can form shallow landslides. The shaking table was used to apply the dynamic loading, using a loading frequency of 5.5 Hz and a horizontal displacement amplitude of 0.2 cm. Using two high-speed cameras, the model's surface displacements were measured. Accelerometers were placed inside the slope body to measure the acceleration response during dynamic loading. Additional theta probes and mini tensiometers monitored the slope's hydraulic response before and after dynamic loading.
For the three different soil materials used in physical models, the shear stress, shear strain, strength degradation and the equivalent viscous damping were calculated using the acceleration measurements. Both acceleration and surface displacement measurements were used to calculate the soil densification during and after the dynamic loading, providing us with insight into post-cyclic compaction. A change in volumetric water content and matric suction at the end of the dynamic loading was measured with theta probes and tensiometers.
Performed simulations showed the significance of fines content on the dynamic slope behavior. Unlike the models made with pure sand specimens which showed soil densification prior to slope failure, slopes with mixtures of sand and kaolinite powder showed a small densification followed by hardening without any amplification recorded during cyclic loading. The crown and the foot of the slope have proven to be the most critical parts in small-scale models. Higher material permeability increases the tendency to accumulate water and saturates the material at the slope's lower parts during dynamic loading. Similarly, cracks on the slope's surface formed during the dynamic loading can infiltrate additional water, ensuring locally higher slope saturation resulting in soil softening and additional strength degradation.

Keywords: landslide, small-scale model, dynamic soil behavior, sand-clay mixtures

Influence of rainfall and soil conditions on the Krbavčići landslide reactivation (Istria Peninsula, Croatia)

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Abstract: The Krbavčići landslide occurred at the end of January 1979 near the City of Buzet, Croatia, after prolonged heavy rainfall. The landslide damaged the local road and the retaining wall at the landslide foot, and a new stable landslide position was taken after major sliding. The Krbavčići landslide is located in an area built of flysch rock mass, which is susceptible to sliding and where many different types of mass movements have been recorded in the past. The determined dimensions of the landslide are 370 m in length, 30 m in width in the upper part and 150 m in the lower part, with an estimated landslide volume of 3×10^5 m^3. The field investigation indicated that the sliding surface is located within the weathered bedrock zone at the contact between the weathered and fresh flysch rock mass at the depth of 15 m. Weathering of the flysch rock mass changes the geotechnical properties and shear strength, and potentially unstable deposits are formed.

The paper describes the available information about the Krbavčići landslide occurrence, precipitation analysis for landslide reactivation, and laboratory testing of flysch deposit samples from the landslide body. Among the basic laboratory tests, ring shear test on the undisturbed samples on the newly development sample cutter will be performed to determine the residual shear strength. Due to the specific shape of soil samples, the ring shear apparatus is commonly used to test remolded soil samples. Therefore, a newly developed sample cutter is developed to enable sampling, installation, and testing of the undisturbed soil samples. The precipitation and soil conditions that lead to the reactivation of the Krbavčići landslide are analyzed and discussed.

Keywords: ring shear test, landslide reactivation, flysch rock mass, rainfall, undisturbed samples

Debris-flow Susceptibility Assessment in Flow-R: Ribnica River Case Study

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Abstract: Debris flows are among the most dangerous erosional geohazards due to the fast rate of movement and long runout zones. Even though the initiation can be triggered in mountainous areas, inhabited and with steep slopes, their propagation and deposition can endanger not only buildings and infrastructure in the urbanized areas, but also threaten human lives. As these initiation areas usually represent unattainable terrains with rapid vegetation cover development, field observations and aerial photo analysis become high-demanding tasks. Consequently, medium-to-regional scale susceptibility assessments are increasing in interest. They allow for efficient and effective identification of the most endangered zones and can be used to propose where further detailed studies should take place. In those terms, since it can be challenging to obtain enough data for larger regions, empirical models with low data requirements represent an adequate solution to the susceptibility modelling problem. In this paper, a medium-scale debris flow susceptibility assessment has been carried out along the Ribnica River in western Serbia. Both the source areas and the propagation extent have been identified with the Flow-R empirical model based on simple probabilistic and energy calculations. The key input data used to investigate debris flow susceptibility in the study area was 10 m resolution DEM. The combination of DEM, its associated morphological derivates, landuse and lithology datasets, with Holmgren's modified propagation algorithm and the angle of reach, allowed for the 1:25000 susceptibility assessment. The results are reasonable and can be of great use for determining the areas that need to be prioritized for further detailed studies.

Keywords: debris flow, Flow-R, susceptibility assessment, empirical model

Optimization of pipeline design solutions for slope stability in Sakhalin region, Russia

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Abstract The article discusses the optimization of design solutions for stabilizing landslide prone slopes on the main pipeline route on the Sakhalin Island, Russia. The calculations of slope stability for various areas located in difficult engineering and geological conditions reveal the possibility of significantly reducing the length of bored piles.

Keywords: pipelines on landslide prone slopes, safety factor, sensitivity analysis, retaining wall, landslide protection measures.

Effect of K0-consolidation on undrained behaviour of natural sand

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Abstract: Often the primary cause of landslides, slope failures or earthquake-induced/static liquefaction is the instability of a loose to medium dense granular soil within the larger soil medium, in which the rapid pore water pressure generation can cause instability during an undrained static or dynamic loading. The term instability is used as deviatoric strain-softening characterized by instability line, IL. Multiple studies have shown that the behaviour of soils is influenced by the history of Ko-consolidation, and the Ko has a significant effect on the triggering instability, however, only a few studies in the literature have discussed the effect of anisotropic consolidation on undrained monotonic behaviour of sands and a consensus is yet to be reached. Therefore, the effect of consolidation history on the instability of natural soil is investigated in this study using natural sand borrowed from river terraces consisting mainly of silica oxides (around 78%) with particles of subangular shape and uniform grain size distribution. The sand has about 2% fines content with a mean grain size of d50 = 0.26mm and a uniformity coefficient Cu = 1.8. Program for undrained triaxial testing was developed as this type of test was chosen as the method most commonly applied in laboratory tests for studying this phenomenon. The investigated sand was prepared using the moist tamping method in layers because it was thought to be the most suitable for achieving high range of initial relative densities. A vast number of experimental studies have already been performed using this "Skopje sand" and this sand already has a significant database of triaxial experiment results but until now there haven't been performed test using Ko consolidation. We believe that this study will be a significant addition to the database and hopefully will inspire further research and even some large-scale laboratory experiments or on-filed landslide studies.

Keywords: landslides, Ko consolidation, triaxial monotonic undried test

Seismic Methods for Near Surface Characterization

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Abstract: Near-surface characterization i.e., determination of the physical-mechanical characteristics of the soil and rock mass that constitute the terrain are of great importance in avoiding catastrophic consequences during seismic and geotechnical hazards. To this end, in recent decades, technology has advanced quite rapidly and a number of methods for near-surface imaging have been developed. What has been alluded to in recent years is getting a more realistic picture of the terrain structure, and this is made possible through the development and application of more sophisticated software tools for both processing and post-processing as well as imaging. Surface seismic geophysical methods have been applied in IZIIS for a long period. Geophysical surveys using the combined seismic methods approach were performed in Strumica, North Macedonia, at the location of Orta Mosque. The main and primary reason for this study has been the appearance of cracks in the building of the Orta mosque which have expanded over time. The main objective has been definition of the seismo-geological and tectonic characteristics of the terrain, potential anomalies, local tectonic deformations, and discontinuities in the terrain structure, resulting from potential inner dynamic processes. The seismic methods of refraction and reflection were applied for the survey. They represent non-invasive, cost and time effective, widely accepted geophysical methods for near-surface characterization. In situ measurements using the seismic methods were performed at the survey location in a very practical and effective way. The same seismic equipment and, in most of the cases, the same acquisition parameters were used, providing time and cost-effective survey for subsurface characterization. The seismic models resulting from the seismic refraction survey indicate layers composed of unconsolidated deposits recorded at maximum depth of over 20m. The seismic reflection sections are shown in a 3D display to get a more realistic picture of the local deformations and discontinuities as well as the slope of the bedrock. The seismic sections point to deformations and local disturbances not only in the surface layers, but also in the deeper layers. Disturbances in the terrain structure indicate inner dynamic processes that are assumed to be the cause of appearance of cracks in the building.

Keywords: geophysical survey, seismic methods, site characterization

Physically-Based Approach for Municipality-Scale 3D Slope Stability Analysis

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Abstract: The 2021 Report on Hydrogeological Instability in Italy highlighted a substantial vulnerability, with 93.9% of municipalities facing threats such as landslides, floods, and coastal erosion. The Daunia Apennines, situated in the Apulia Region, southern Italy, emerge as particularly susceptible to diverse geo-hydrological hazards, including a pronounced concentration of recurrent landsliding in the north-western region. To address this problem, collaborative initiatives have recently been undertaken by CNR-IRPI in conjunction with the Department of Civil Protection of the Puglia region, including GEO_PUGLIA and Seismic Microzonation projects designed to provide essential tools and information for in-depth investigations into the complexities of geo-hydrological hazard processes. This research contributes to addressing the critical need for effective assessment and management strategies in high-risk areas, focusing specifically on the urban/peri-urban areas of the Daunia Apennines. The municipality of Carlantino (FG) serves as a case study within the broader Seismic Microzonation project, encompassing many municipalities affected by damaging landslides. The methodological approach adopted involves the development of a three-dimensional geotechnical model covering an area of 2.5 km². Subsequently, a 3D limit equilibrium analysis, following the principles proposed by Cheng & Yip (2007), is employed to generate a safety factor (FS) map. This approach considers force and moment components simultaneously in both the slip and transverse directions, providing a better understanding of the stability conditions.
Exploration of three distinct scenarios, each related to the depth of the water table concerning the ground level, unveils critical insights. The identification of the most unstable portions of the area, particularly those adjacent to the urban center of the town of Carlantino, demonstrates the methodology's capacity to pinpoint high-risk zones. This research sets the stage for future developments including the incorporation of seismic forcing to assess susceptibility to triggering new or reactivation of existing landslides, especially in areas with documented seismic activity. By bridging scientific inquiry with practical applications, this study contributes to the ongoing efforts aimed at enhancing our understanding of and resilience to geo-hydrological hazards on both regional and municipal scales.

Keywords: geo-hydrological hazards, municipality risk assessment, three-dimensional modeling

Seismic behavior of ancient landslides in the Daunia Apennines: numerical analyses for Seismic Microzonation studies

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Abstract: Landslides and earthquakes represent major geological hazards in Italy, particularly along the Apennine Chain, known for its seismic activity. Daunia Mountains are one of the areas of main concern within the peri-Adriatic Apulia region, southern Italy, due to a substantial number of existing landslides and recurrent slope failures. Over 30 percent of this area is affected by instabilities, primarily comprising ancient and large landslides. Recent failures are smaller and tend to impact limited areas.

The historical records document frequent occurrences of moderate-large magnitude earthquakes in this region, primarily originating in the Southern Apennines. Additional seismic activity originates in the foredeep-foreland zone of northern. In few cases occurred centuries ago, the seismic events had disastrous consequences with hundreds to thousands of victims and destruction of parts of historic centers.

Effective earthquake risk reduction strategies hinge upon the creation and application of Seismic Microzonation maps, also known as seismic hazard maps that offer detailed insights into expected ground motions.

In Italy, such maps are currently being produced for hundreds of cities and towns at the 1:5000 scale, to properly account for the influence of local geological-geomorphological conditions (site effects) on the ground shaking intensity, as well as for the presence of local-scale seismically-induced ground failures (e.g., landslides, liquefaction). The ultimate goal is to obtain Seismic Microzonation maps that are valid and uniform throughout the country, without losing the degree of detail that cannot be neglected in such approaches.

A real case of a large peri-urban landslide is presented here as an example to evaluate the different types of numerical analyses useful for estimating earthquake-induced displacements, increasing the degree of complexity from the Newmark analysis to advanced tenso-deformation analyses. Limits and advantages of each approach are examined, showing how they can help infer the origin of such landslides and current stability conditions.

Keywords: landslides, microzonation studies, earthquakes, numerical Modelling

Slope stability calculations for design solutions optimization of pipeline piles

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Abstract: The article discusses the optimization of design solutions for stabilizing dangerous landslide processes on the route of a main pipeline on the Russian Far East. The possibility of significant reducing the driving pile length based on slope stability calculations for various sections located in complex engineering-geological conditions is shown.

The purpose of research was to develop recommendations for adjusting typical project solutions for the landslide protection construction to optimize the overall project cost. The research area is characterized by slope heights from 15 to 25 meters and average slopes from 25 to 35°. The geological structure of the considered sections includes: technogenic deposits, modern eluvial and colluvial-diluvial deposits, represented by clay, gravel and pebbles of semi-solid to solid consistency and Cretaceous deposits, represented by weakly fissured argillites. Groundwater is widespread in fissured argillites of Cretaceous age and has an occurrence depth from 5 to 20 meters. The main factors determining the slope stability and landslide processes development are seismic activity and active erosion. The seismicity of the area according to Russian regulatory and technical documents reaches up to 9 points.

In order to prevent the landslide development and the disruption in the operation of the main pipeline a preliminary project for the deep-seated retaining wall placement has been developed. The piles in the single-row pile grillage are planned to have a diameter of 630 mm, a length of 17.5 m, and a spacing of 1.6 m along the axis. The limit equilibrium methods were used in the calculations (represented by the Morgenstern-Price, the simplified Bishop and the generalized Janbu method). Calculations for the selected profiles were carried out for two scenarios: the main combination of loads and a special combination of loads (considering seismic effects).

After calculating the slope stability with the design solutions, stability calculations were carried out, considering the different length of the piles, starting from 2.5 m to the design length of 17.5 m. Dependence of the safety factor on the piles length was plotted and the analysis of plots allowed to conclude that on the considered sections of the main pipeline route the design length of the piles can be reduced to 9 m. Embedding the piles into the Cretaceous argillites by 2 meters is sufficient for the safe operation of the pipeline. The calculations justify the safety of the engineering protection structures with the reduced piles length, which will significantly reduce the overall estimated cost of the work.

Keywords: landslide hazard for pipelines, pile foundations in the landslide hazardous conditions, seismic impact in the slope stability assessment

Slope stability assessment of roadway recesses in Permian sediments on the territory of the Volga upland (Russia)

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Abstract: the article discusses the problem of landslide processes activation during the construction of highways on the Volga upland territory in the central part of the East European platform. Currently, this territory is actively developing and requires the construction of a significant number of highways, including high-speed ones. At the same time, the roads geometry requires excavating deep roadway recesses in the existing terrain. This has provoked landslides activation in some areas, the scale of some of them can be classified as catastrophic. Only in the period from April to October 2022, 5 landslides of various volumes occurred on the slopes of the road recess excavated in relatively strong rock soils for no apparent reason. The largest of them is characterized by a length of up to 100 m with a thickness of deposits in the landslide body up to 30.0 m. The geological structure of the territory is dominated by the bedrock of the Urzhum tier of the middle section of the Permian system, overlain by a loose cover of Quaternary sediments. Marls, dolomites, mudstone-like clays, siltstones and sandstones represent the deposits of the Urzhum tier. Some areas of the territory are located within the local uplifts of the crystalline basement, which led to the occurrence of tectonic deformations in the overlying sedimentary rocks. This provided cracks in the sediments, which significantly reduce their strength. The authors found that the main causes of landslides in the rocks of the Urzhum tier are: 1) increased stresses in the ground mass within the wings of folds in sedimentary rocks; 2) separation of blocks from the main massif due to extended tectonic cracks; 3) the presence of thin (up to 5.0 cm) clay layers enriched with organic matter in rock soil, which with increasing humidity can reduce friction; 4) the presence of aquiferous sandstones in the upper part of the section, from which groundwater penetrates into the cracks of the separation of the landslide body. None of the existing methods for calculating landslide hazards is able to consider all these factors at the same time. To find the optimal calculation method the authors created a calculation model based on the geometric parameters of the roadway recesses, the geological structure considering weakened layers, physical and mechanical properties, orientation and size of cracks, and the position of the groundwater level. The calculation results confirmed that the safety factor is less than required in the studied area. Based on the research carried out, the authors have developed a special methodology for assessing landslide risk in such geological conditions, considering the simultaneous impact of the four above-mentioned factors. This will help to avoid mistakes in the design of highways in the future and avoid landslides on the slopes of road recesses.

Keywords: landslide hazard assessment, East European platform, Permian deposits, numerical stability calculation

Temperature and rate effects on the residual shear strength of clay soils: a state of the art

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Abstract: The temperature within a landslide's shear zone can undergo changes due to internal processes like frictional heating and chemical reactions, the magnitude of which can be particularly relevant during fast runout phases in large landslides. Alterations in boundary conditions, including heat transfer from the bedrock or ground surface, but also groundwater flows and changes in vegetation cover also can contribute to these temperature variations, over timeframes especially relevant to slow-moving landslides. The hydro-mechanical properties of soils, particularly those rich in clay minerals, exhibit dependency on temperature. Studies indicate that the residual shear strength, a crucial parameter in reactivated landslides, can vary significantly within typical temperature ranges in landslide shear zones in temperate climates. Literature also highlights the influence of the rate of shearing on the shear strength parameters of soils, including the residual shear strength, with the soil's mineral composition controlling rate strengthening and weakening behaviors in slow to rapid landslides. This contribution delves into the current state of knowledge and presents recent findings from ring-shear experiments indicating the coupled nature of temperature- and rate-dependence of the residual shear strength, which may play a substantial role especially in shallow clay landslides. This influence is particularly noteworthy in the context of climate change, emphasizing the need for explicit consideration in modeling efforts.

Keywords: residual shear strength, rate effect, temperature effect, thermo-mechanical coupling, clay, landslide

Landslide information for land management and planning: examples from Italy and Croatia

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Abstract: Landslide information and derived mapping products are relevant tools to support local authorities in land use management and planning. Landslide inventory maps are the basis to determine landslide susceptibility, hazard, and risk at different scales. Accurate landslide mapping and geotechnical characterization can be of paramount importance for the comprehension and the set-up of landslide forecast models. In addition, information on landslide spatial occurrence (i.e., susceptibility) is fundamental to evaluate the instability of the territory when is hit by a triggering event and can be a relevant component of early warning systems, which focuses on the forecast of multiple or populations of landslides over large areas based on the monitoring of a potential landslide trigger (e.g., rainfall).
In Italy, there are several examples of inventory maps prepared at different scales using diverse mapping techniques. At the National level, the IFFI catalogue compiled by the Italian Institute for Environmental Protection and Research, represents the most detailed inventory available for the entire Italian territory. In addition, a mosaic of landslide hazard maps, originally prepared by the regional administrations following national criteria, show areas classified in five levels. As an example of the use of landslide maps, the prototype SANF system (Sistema per l'Allertamento Nazionale da Frana) developed by CNR IRPI for the Italian Civil Protection Department, integrated two different landslide susceptibility zonation derived with statistically based methods. The first, at municipality level, was polygon-based and used the AVI landslide archive and morphology, land use, geo-lithology, and climatic information as explanatory variables. The second was carried at a pixel level with a resolution of 25 m, successively down-sampled at 1000m with similar explanatory information.
In Croatia, there are several recent examples of inventory maps prepared at large scale (1:2 000) using visual interpretation of LiDAR DTM (Digital Terrain Model) morphometric derivatives. The large-scale inventory maps for different study areas were compiled in the framework of the EU-funded project PRI-MJER aimed at the development of the most detailed inventory required at municipal level. In the same period, large scale landslide susceptibility zonations were derived using statistically based methods, in the framework of the scientific research project LandSlidePlan (HRZZ IP-2019-04-9900), funded by the Croatian Scientific Foundation. To ensure a rational approach to landslide mapping in the entire Croatian territory, a prototype of landslide susceptibility map was produced at a medium scale (1:25 000) with areas classified into three levels. The prototype map, in the form of a mosaic, covers three Croatian counties (total area approx. 8 000 km^2) and it is intended for regional administration to recommend cities and municipalities to the preparation of large-scale maps in zones of high and medium susceptibility. It is pixel-based map with a 25-m resolution and it is based on a heuristic approach because of the lack of national landslide inventory. Despite the small number of explanatory variables used for modelling (morphology and geo-lithology), the spatial information about zones for more detailed landslide mapping is satisfactory.

Keywords: landslide mapping, susceptibility, planning, early warning system

Instability phenomena along Liburnian coast (Rijeka Bay, NE Adriatic Sea)

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Abstract: The relief of the coastal zone length of 6.5 km between ferry port Brestova and Brseč settlement is very different concerning the other part of the Liburnian coast (Rijeka Bay, channel part of Northeastern Adriatic Sea). Very steep or vertical scarps higher than 100 m prevail in this coastal zone. Coastal slopes were mostly formed in a carbonate type of sedimentary rock mass. All coastal zone was surveyed using an Uncrewed Aerial Vehicle (UAV), and the UAV-derived data was used as a 3D point cloud and orthophoto for analysis. The submarine zone was surveyed using scuba equipment and Remotely Operated Vehicles (ROV). Interesting parts of the underwater slopes were surveyed using a multibeam echosounder and side-scan sonar. Based on the analysis, several different types of instability phenomena have been identified: Relict rock compound slides and active rock and debris fall. Rock compound slides or collapse structures are an interesting and unique phenomenon in the Kvarner area, and probably rare in the Croatian coastal area. The main scarps are situated 100 m above, and toes are 50 m below m.s.l. Some of the sliding bodies reach five million m^3. Uplift of eastern slopes of Učka Mt. and subsidence of Rijeka Bay respectively during neotectonics activity in wide Adriatic area have been main causes of the described instability phenomena formation.

Keywords: Northeastern Adriatic, coastal instability, Uncrewed Aerial Vehicle, Remotely Operated Vehicles, rock compound slides

Geological - Geotechnical Documentation for the Repair of a Landslide Section at the Old Cemetery in Smederevo

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Abstract: The study area occupies the boundary section between South Banat plains and the Smederevo district hills. The land has been shaped under the predominant influence of the Danube river in combination with present exogenic mass movements in the form of landslide. The right bank of the Danube river, almost along the river's entire flow through Serbia, is characterised by occurrence of many landslides. The river channel displacements southward are the primary cause of the landslide occurrence.
The slope where the Old Cemetery in Smederevo is situated has been shaped by landslide processes. These are most likely deep but dormant landslides with the failure surface of over 20 m. Active landslides occur in shallow, near surface areas, with the failure surface of about 2 m. In addition to present exogenic processes, human activities such as cutting, filling, land development etc. also impact the landscape.The study microlocation occupies the slope section in the Old Cemetery northern boundary area from Karađorđeva Street to Koče Kapetana Street. The slope gradient in this section is about 45°. The slope stretches to the Danube river alluvial plain, with elevations ranging from 74 to 74,5 m, whereas the elevations in the slope section under consideration range from 77 to 90 m. Overall stability of the slope is ensured by an RC retaining system – a concrete diaphragm wall built at the slope toe, whereas traces of active landslide and failures with their effects are clearly visible in higher sections of the slope.The study area is made up of the sediments of various compositions and ages. The bedrocks represented by the Neogene sediments are overlain by the Quaternary diluvial sediments. The proposed solution involves construction of the retaining system comprised of Ø800 mm piles with a capping beam. The piles will be 10 m long, with the pile base elevation at 72,0 m. The capping beam elevation will be at 83,0 m. The spacing between the piles depends on the static calculation, with an assumption that Ø800 mm piles with the spacing of 2,0 m can provide stability. The gap between the piles (from the surface of the ground to the capping beam) will be protected by horizontal sheet piling. Drains that will allow water drainage should be provided for at the sheet piles. The pile retaining wall length is 54 m.
Terramesh gabion wall filled with sand will be constructed after the pile retaining wall has been completed. The gabion walls will be supported by the pile capping beam and installed by stepping back by 0,5 m. In case the gabions have cross section of 1,0 x 1,0 m, the retaining wall face will have a gradient of 2:1. The elevation of the top the Terramesh gabion retaining wall will range from 86,0 to 89,0 m, depending on the elevation of the slope in the back (appendix 2 – the engineering-geological map). Stability of the existing RC diaphragm wall may not be compromised during construction works. This particularly applies to pile driving machine moves on the site. In addition, the use of bored pile walls is proposed because the method of drilling bored piles produces the least vibration. The back of the gabion wall (the section between the the gabion and the existing slope) will be filled with sand. The sand should be compacted in layers of up to 30 cm by manual vibro compactors (tamping rammer). Sand layers compaction should be minimum Evd = 15 MPa. The surface layer of the sand fill should be covered with topsoil and grassed.

Keywords: The Old Cemetery, Smederevo, landslide, piles

Causes and Consequences of Landslides at the locality “Bare” Busovača with the proposal of geological-geomechanical investigations

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Abstract: Busovača lies in a valley at a significant intersection of the Lašvanska and Lepenička valley roads. It is characterized by gentle hills around the city that gently cross into high mountains overgrown with dense forests. The area of the Municipality of Busovača from the aspect of morphology can be classified into three high-altitude areas: mountainous, mountainous, which is both the most common and lowland. Through the territory of the municipality of Busovača pass the main road communications to Sarajevo (capital of Bosnia and Herzegovina) and Kiseljak on one side, Zenica and further towards Doboj on the other, and Travnik and further towards Jajce, Bihac ... from the third party. In the municipality of Busovača there are many landslides that are mostly unsanitary and active, where there is a danger to human lives and material goods. One of the mentioned landslides is a separate landslide of the locality "Bare" whose foot mostly swims across the transverse route of the gas pipeline. Within the boundaries of landslides there are deformed residential areas. From the aspect of risk to human lives and material goods, I paid special attention from the aspect of the profession to the landslide in question, in order to repair and reduce the risk to human lives as soon as possible. Unfortunately, even to date, the landslide in question has not been repaired.

Keywords: area of Busovača municipality, landslide, scope of research, proposal for landslide rehabilitation "Bare"

Erosion resistance enhancement on the polymer-treated soil slope

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Abstract: The consequences of climate change are becoming more visible and impossible to ignore. Climate change, such as more frequent and intense rain events, is the main influencing factor causing instabilities, landslides, and slope erosion. Thus, it is vital to comprehend the process of rainfall erosion on the slope surfaces, the water infiltration, and shallow instabilities (locally) which over time can cause global slope instability. Nowadays, the usage of environmentally friendly materials for soil improvement become more popular because of increased environmental awareness. In the paper, the results of the research on a natural polymer solution used for soil treatment and improvement will be presented. The polymer solution is a binding viscous agent that is obtained by processing a biodegradable substance in laboratory conditions, and it has no negative impact on the environment and people. The research methodology is organized in two phases, laboratory and experimental testing. In the first phase, the basic, strength-deformable properties and water-permeable parameters of the natural (untreated) and improved (treated) soil with polymer solution are defined. Hence, through comparison, the effect and degree of improvement with polymer treatment of soil material is defined. In the second phase, experimental tests were performed on a natural and polymer-improved slope with a slope of 1:1.5, on which rainfall of 10 liters per hour was applied for a duration of 180 minutes. Through them, the efficiency of biopolymer solutions in increasing the resistance against erosion is demonstrated. As an additional measure for slope stabilization from erosion, tests were done on polymer-improved slopes with vegetation. Basically, the natural polymer solution improves the mechanical and hydrological parameters of the soil, forming a viscous gel matrix with a reinforcing bond between the soil grains that fills the pores. In dry conditions, the treated soil forms a solid surface crust that prevents evapotranspiration, and when it rains, it becomes hydrophobic and allows the free flow of water without significant soil erodibility. All the results of the conducted research confirm the efficiency of the polymer solution as a method for improving and stabilizing the soil from atmospheric influences.

Keywords: Erosion resistance, surface stability of slopes, soil improvement, polymer viscous solution.

Slope stability back analysis and a proposition for rehabilitation of landslide on the road section Gornji Milanovac – Klatičevo

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Abstract: During the construction on the section of the designed road Gornji Milanovac - Klatičevo (Gornji Milanovac Bypass), in the period from November 2022 to April 2023, there was an occurrence of slope instability on the right side of road cut from km 0+910 to km 0+950 i.e., terrain sliding in the form of soil creep. A landslide occurred on the part of the constructed cut slope, which extends over a total length of approximately 125 m. The surface layer of soil affected by sliding (colluvium) is made of silty-sandy clay, soft to medium hard consistency and increased water content. This material was originally created by the decomposition of the basic rock mass (bedrock) and the deposition of material from the higher parts of the slope by planar erosion (diluvium). Bedrock under the diluvium layer consists of the Neogene (Miocene) complex of red sandstones. For the purposes of defining the natural conditions in the terrain under which the terrain sliding process was activated, a slope stability back analysis was performed for the Mohr–Coulomb Failure Criterion and the state of effective stresses. Defining the cause of the soil failure is imposed as the primary goal of paper, considering the fact that during the engineering geological mapping of the terrain in the design phase, no phenomena were observed that would indicate soil instability. In addition, before the activation of the landslide, slope stability analysis with the influence of groundwater in design phase was performed in order to simulate extreme conditions during exploitation and a satisfactory safety factor was obtained. In order to define the construction of the terrain in more detail and the geotechnical conditions for the rehabilitation of the unstable slope, additional geotechnical investigations and tests were performed in August 2023, namely: exploratory drilling and engineering geological mapping of the exploratory borehole core, installation of a piezometer construction, observation of groundwater level in boreholes, as well as laboratory geomechanical testing of soil samples. After defining the cause of landslide activation, the paper proposed the use of several remedial measures as well as their mutual combination in order to completely rehabilitate the landslide.

Keywords: landslide, slope stability back analysis, rehabilitation of landslide

Drained shear strength parameters of landslide Beška

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Abstract: Exploration shafts are one of the most direct methods used to explore landslide geometrical and material characteristics. In 2009, five shafts were excavated during an extensive field investigation campaign that took place at the right Danube's bank, close to the town of Beska. During excavation, it was possible to observe several rupture surfaces along the vertical profile and several undisturbed samples were taken for laboratory testing. Laboratory tests indicated a significant difference between the peak and residual shear strength parameters of the tested clay. Residual strength was measured on the samples taken directly from the slip surface. The main goal of this paper is to compare shear strength parameters obtained using back-calculation techniques and laboratory tests.

Keywords: residual shear strength, exploration shafts, back-calculation

Addressing Rockfall Challenges in Flysch Enviroment: A Case Study in Valaora, Greece

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Abstract: Rockfalls rank among the most significant geological hazards, especially in mountainous areas where human development intersects with natural landscapes. These hazards become more complex in flysch environments, characterized by unique failure mechanisms and geomorphological conditions. Addressing these complexities, our research combines traditional engineering geological methods with advanced digital technologies, including Terrestrial Laser Scanning (LiDAR) and Unmanned Aerial Vehicle (UAV) photogrammetry. This integration aims to enhance risk assessment and develop more effective mitigation strategies. The presented case of Valaora, situated near Greece's Kremaston artificial lake, exemplifies the challenges addressed in our study. This region is characterized by its difficult terrain and a high incidence of rockfalls, especially along the slopes adjacent to provincial roads. The geological composition of this area is primarily Gavrovo-Tripolis flysch formations, which feature alternating layers of sandstone and mudstone, each offering distinct stability challenges. In this region, rockfall typically initiates with the erosion of the mudstone layer, weakening the overlying sandstone. The detachment of the sandstone leads to rockfalls, which in turn further erode the mudstone. This cycle is intensified by factors such as structural irregularities, variable shear strengths, and freeze-thaw effects, especially around the roads. Our methodology includes extensive use of LiDAR and UAV photogrammetry to collect essential engineering geological data. UAV flights with the DJI Phantom 4 Pro RTK generated dense point clouds and high-resolution Digital Surface Models (DSM), crucial for improving engineering-geological mapping. These models helped identify overhanging blocks along the slopes and categorize various geological units. To conduct kinematic analyses in structurally controlled formations, TLS LiDAR scanning was employed to gather orientation measurements and geometric characteristics (spacing, persistence) of discontinuity surfaces. We applied Principal Component Analysis (PCA) on the XYZ space of 3D points to extract joint surfaces, followed by density-based spatial clustering to create individual clusters. Depth maps were also developed to identify potential failure zones related to overhanging blocks. A critical aspect of our research was developing a rockfall event database through two-year aerial photogrammetry monitoring. Using the M3C2 (Multiscale Model to Model Cloud Comparison) algorithm, we detected changes in surface geometry between sequential point clouds. This database provides an in-depth view of the frequency, magnitude, and volume of rockfall events, essential for effective risk mitigation. It includes comprehensive details on the location, volume, shape, and distribution of rockfalls, and the location of fallen blocks on slopes and roads. Additionally, 3D representations (mesh models), obtain from SfM photogrammetry, were used for numerical rockfall simulations, accurately depicting surface geometry, and enabling precise trajectory and impact energy calculations for dislodged rock fragments. In conclusion, merging traditional engineering geological practices with advanced digital technologies in our study has greatly improved the approach to rockfall risk mitigation, allowing for a more detailed and quantitatively controlled method in developing integrated technical solutions.

Keywords: Flysch Environment, LiDAR Mapping, UAV Photogrammetry, Rockfall Monitoring, Rockfall Database, Slope Stability, Rockfall Hazard Management

Geotechnical Conditions, Stability Analysis and Remedial Measures of Visnjicka 74 Landslide in Belgrade

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Abstract: This paper presents the geotechnical conditions, stability analysis and urgent remedial measures of the landslide at Visnjicka 74 in Belgrade. The plot is at the foot of an old fossil landslide. The landslide was activated due to an excavation of the foundation pit in June 2023. Due to large displacements of the retaining structures and the surrounding objects, the urgent remedial measures were proposed. Following these measures, the further sliding was prevented and additional geotechnical investigations were performed (geophysics, inclinometer measurements, boreholes, soil sampling, laboratory tests, piezometers), in order to obtain more comprehensive insight into the processes responsible for sliding. Residual shear parameters were determined by laboratory tests, and also back-calculated using numerical analysis and inclinometer readings. Very complex geotechnical conditions were determined on site and also presented. The geotechnical conditions for future construction works are presented.

Keywords: Landslide, foundation pit, inclinometer, back analysis, stability analysis

Landslide mapping for the regional gas pipeline construction near Priboj (Serbia)

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Abstract: The on-going gas pipeline design in Serbia is currently reaching its apex, and therein, extensive investigation and planning had to be undertaken to ensure its safe execution and long-term exploitation. Therein, engineering-geological conditions play important role and at the stage of preliminary design directly imply the alinement of the future pipeline route. This paper is focused on Zlatibor-Prijepolje pipeline branch in SW Serbia, which is further split into Priboj and Prijepolje sections. The former, Priboj section, is the subject of this work. The mapping methodology included: preparation of the base maps, field mapping, and data interpretation. Preparation stage was extensive and included acquisition of earlier investigations and maps at larger scale, primarily Engineering-geological map of Prijepolje at 1:300,000 scale, which was digitized in GIS environment, and converted into mobile GIS formats for field work. The entire route was scanned using airborne LiDAR, which resulted in a dense point cloud and Digital Terrain Model of 25 cm resolution. It was used for delineating landslides, proluvial fans, riverbeds, gullies, and other relevant morphological phenomena that indicate poor stability. This interpretation was also digitized in the GIS environment and prepared for mobile GIS application. After compiling all engineering-geological data, mobile base maps were created for field work, where additional forms were digitized on-spot. General characteristics of the area can be deducted as follows. The ophiolitic mélange is dominant and hosts most instabilities, due to its high weathering grade and unfavourable hydrological conditions. All landslides are predominantly deep-seated, and mostly of earth slide type. In total, 37 landslides are identified in the area, 12 of which along the current route. Based on their spatial extents further recommendations are given regarding particular locations and segments of the Priboj section in order to optimize its rout. It has been demonstrated how integrative approach is essential to gather relevant data and characterize the terrain appropriately, for further, more detailed design stages.

Keywords: landslides, LiDAR, DTM, pipeline, Priboj

Failure estimation of the Majdanpek open pit east face based on inverse velocity model

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Abstract: The Majdanpek open pit mine south district is currently active mining prospect of copper ore exploitation in eastern Serbia. Its depth is approaching the termination depth and occurrences of large-scale instabilities and global instability of the final pit slope is possible. These can generate catastrophic mass movement inside an area that encloses a regional road route and the Pek River bed which is channelled along the outer contour of the pit. The displacements that were noted in early 2023, in the eastern face of the pit draw further concern and required a detailed monitoring campaign to be undertaken quickly. It included several approaches, but in this work focus was on surveying on 5 static benchmarks through the period January-July 2023. Due to the unknown status of the displacement acceleration or deceleration on its progressive failure path, the inverse velocity calculation of the entire series was undertaken. The series involved surveying of benchmarks using the absolute coordinates measured manually by a total station every 4-5 days. Displacements trends indicated constant cumulative increment with different rates at different benchmarks with periods of acceleration and deceleration. Long-term trend suggests that steep part of the progressive failure curve is not reached. However, inverse velocity trend in most benchmarks suggests slight decrease, indicating possible global progressive failure. Other monitoring approaches confirmed only local failures, while limit equilibrium stability models suggest both, presence of local failures and marginally stable slopes with safety approaching one. Inverse velocities estimated failure by the end of 2023. Extensive precaution measures were undertaken to avoid such scenario, including constant early warning evacuation system, as well as immediate remediation measures on reshaping the slope.

Keywords: displacement, survey, inverse velocity, open pit

Geotechnical conditions of cut 5 on the highway A1, section Gornje Polje-Caričina Dolina

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Abstract: This study focuses on the Serbian Crystalline Core, a region characterized by shale formations susceptible to erosion. Recognized as a priority area for erosion control by state authorities, the region has undergone substantial soil conservation efforts. The research investigates slope 5 on highway A1, section Grdelica-Vladičin Han, impacted by landslides triggered not only by construction activities but also by erosive rainfall affecting the vulnerable shale formations. The slope's instability prompted state intervention, leading to three sets of structural reinforcements, each consisting of two rows of piles. Post-mitigation monitoring, including inclinometer readings, indicates no further movement. The study provides a comprehensive analysis of the geological and geotechnical aspects, rainfall-induced erosion, and the effectiveness of mitigation measures.

Keywords: slope stability, landslide, Serbian Crystalline Core

Second phase of Landslide stabilisation on Cut 3, LOT 1, Motorway E75, section Gornje Polje – Caričina dolina

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Abstract: Landslide stabilization works in the zone of Cut 3 were divided into 3 phases. The scope of this paper is to provide detailed information on the Phase 2 of the designed stabilization measures. These works consisted of constructing the Reinforced Soil Embankment (RSE), up to 12.5 m height in the zone of the toe of the landslide. The embankment contributed to the stabilization of the slope as a ballast, as well as redistribution of the mass after the excavation necessary for the road deviation. The design envisaged the use of flexible geogrid which had to be manufactured from high-modulus polyester (PET) yarns with low creep by knitting production technique. The construction of the piles over which rockfill and concrete have been placed up to a height of 5.8 served as stabile foundation for the RSE. After the execution, Reinforced Soil Embankment increased safety factor against sliding of the Cut 3 and, due to its flexible type of construction, complex geometry that fits very well into natural suroundings has been achived. The paper also gives a short overview on related literature and explains the beneficial effect of a high alignment capacity of reinforcement products on the performance of the composite material "reinforced soil".

Keywords: landslide, slope stabilisation, flexible geogrids, interaction flexibility, geosynthetics

On the Performance and Related Design Considerations of Geosynthetic Reinforced Soil Structures under Seismic Conditions

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Abstract: This paper focuses on the methodology of geosynthetic reinforced soil (GRS) used in the construction of retaining structures in seismically active regions. The use of GRS in the construction of steep slopes, retaining walls and bridge abutments is well established with many successful examples around the world. These structures show favourable performance under complex boundary conditions such as extremely dynamic loads. Compared to conventional retaining walls, GRS resist seismic loads with less deformation and less risk of failure due to their flexible and ductile nature. Seismic shake table tests on a block wall reinforced with woven geogrids were carried out by Ling et al. (2003). The test setup, program and main results of this study are summarised. The second part is devoted to the seismic geotechnical design of GRS. Established design approaches are presented and the normative requirements of Eurocode 7, Eurocode 8 and some national annexes are outlined. The paper concludes with two case studies in seismically active regions.

Keywords: geosynthetic reinforced soil, earthquake, block wall, geogrid