General Report: Slope Stability in Engineering Practice

Rapport Général: La stabilité des talus dans la pratique de l'ingénieur

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ABSTRACT: This General Report reviews 39 papers from 25 countries or provinces that were submitted to the 19th ICSMGE Int. Conf, Seoul, 17-22 September 2017 on the topic of slope stability in engineering practice. These papers describe advances in our understanding of hazard mapping, the development and use of monitoring and early warning systems, analysis methods, and mitigation measures.

RÉSUMÉ : Le présent rapport général passe en revue les 39 publications, provenant de 25 pays et provinces, qui ont été soumises au 19ème congrès CIMSG de Seoul, 17-22 septembre 2017 pour le sujet traitant de la stabilité des talus dans la pratique de l'ingénieur. Ces documents décrivent les progrès dans notre compréhension de la cartographie des dangers, le développement et l'utilisation de systèmes de surveillance et d'alerte précoce, des méthodes d'analyse et des techniques de stabilisation.

KEYWORDS: Slope stability, landslide, debris flow

1 INTRODUCTION

The mandate of Technical Committee 208 (TC208) of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) is to improve the state of the art and state of practice relating to the classical engineering problem slope stability. Thirty eight papers have been submitted to the 19th International Conference in Soil Mechanics and Geotechnical Engineering (ICSMGE) describing advances in this area of focus. This general report summarises these contributions to draw themes from the research work being reported in this conference proceedings.

1.1 *Breakdown of research papers by country*

The origin of the research contributions is presented in Table 1 and illustrates the universal distribution of slope stability problems throughout the world, with a particular emphasis on Asia.

Table 1. Number of papers in session by country / province

Country	Papers	Country	Papers
Japan	6	Hong Kong, China	1
India	4	Iran	1
Taiwan / Chinese Taipei	2	Kazakhstan	1
Canada	2	Lebanon	1
Korea	2	Mexico	1
Morocco	2	Nigeria	1
Norway	2	Russia	1
USA	2	Singapore	1
Australia	1	South Africa	1
Austria	1	South East Asia	1
Mainland China	1	United Kingdom	1
Czech & Slovak Republic	1	Uzbekistan	1
France	1		

1.2 *Focus of papers*

The advances reported in the TC208 sessions can be summarized into advances in our understanding of hazard mapping, the development and use of monitoring and early warning systems, analysis methods, and mitigation measures (Table 2). The largest single focus of the contributions is mitigation methods, with 16 manuscripts addressing various mitigation options. This is a significant increase from the last ICSMGE in Paris in which only six contributions focused in this area (*Bowman and Fannin,* 2013).

The remainder of this general report describes an analysis of the themes that emerge from the research contributions made to each of these areas of advancing slope stability practice.

Table 2. Number of papers by approach or focus.

Approach / focus	Papers
Hazard Mapping	4
Monitoring & early warning systems	5
Analysis methods	13
Mitigation measures	16

2 ADVANCES IN HAZARD MAPPING

A total of four manuscripts included in the proceedings describe advances in hazard mapping. The first relates to the challege posed by managing geohazard of linear infrastrucure. *Derradji et al.* note that the significant expansion of the motorway network of Morocco in the past two decades has led to an increased need for hazard mapping along the nearly 1500 km added to the network since 2000. In particular, they present a useful overview of the framework used to generate risk maps for landslides in marly rock along a 104 km section of highway A2 between Fez and Taza.

Abou-Jaoude and Wartman describe the development of a comprehensive national hazard map for Lebanon using a framework based on geological maps, a high-resolution digital elevation model (DEM), earthquake peak ground acceleration (PGA) maps, rainfall data, and a preliminary landslide inventory database within a Geographic Information System (GIS).

García et al. use a neural network approach to quantify the hazard posed by rainfall-induced landslides. This manuscript uses the severe rainfall events in September 2013 in Guerrero to demonstrate the utility of the technique in the spatial quantification of the areas at risk and to simulate rainfall-induced landslide scenarios possible in the future.

Finally, *Ejezie and Ibim Will* describe their use of the infinite slope model to provide a simple screening tool to identify areas of possible slope instability along the Nun River in the Niger Delta Region of Nigeria.

3 ADVANCES IN MONITORING AND EARLY WARNING SYSTEMS

Five manuscripts describe advances in monitoring and early warning systems. *Wang et al.* describe the development of a Micro Electro Mechanical Systems (MEMS) tilt sensor and a volumetric water content sensor as a possible component of a low-cost early warning system for rainfall-induced landslides. Field validation experiments are presented to provide guidance in the determination of the appropriate thresholds for rate of tilt that can be reliably used to warn of incipient slope failure.

Yasuda and Ishikawa hypothesize that monitoring for evidence of deformation in urban slopes (i.e. cracks in retaining walls and road pavements) can be used as a non-invasive screening tool to highlight locations which may be unstable during future earthquakes. This hypothesis is investigated in their paper using the case study of a slope in Sendai Japan, which exhibited deformation during construction, and failed during the 2011 Great East Japan Earthquake.

LiDAR and photogrammetrically-derived point clouds have provided landslide researchers with exciting new source of data to identify and analyze slope instability. *Lin et al.* present a case study of how these data sources were used to investigate the large number of deep-seated landslides and subsequent debris flows that were induced by the 2009 typhoon Morakot in southern Taiwan. In particular, the analysis enabled these researchers to estimate the landslide volume, the volume of sediment transported, and the volume of sediment remaining as a source for subsequent debris flow and sediment transportation in future typhoon events.

Zekkos et al. use satellite imagery collected shortly before and after the November 17th 2015 earthquake affecting the island of Lefkada, Greece to quantify the extent of landsliding that occurred during the Mw 6.5 event. Using Unmanned Aerial Vehicle (UAV)-based imagery, three-dimensional models of the landslides were created and were used to define the geometric characteristics of the landslides, including area, height and volume.

Finally, *Hong et al.* use 231 landslide case histories to investigate the meteorological conditions leading to rainfall-induced landslides in Korea. In particular, the researchers investigate the complex relationship between antecedent rainfall on the rainfall-intensity duration (ID) combinations that were observed to lead to failure within a Bayesian statistical framework providing useful locally-relevant meteorological warning conditions.

4 ADVANCES IN METHODS OF ANALYSIS

The second largest focus of papers submitted to the TC208 session relates to advances in methods of analysis. The papers can be subdivided into two themes: i) the analysis of landslide triggering, and ii) the fundamental behaviour of soils during landsliding.

4.1 *Analysis of landslide triggering or mobility*

Nordal et al. present the lessons learned from the 1.4 million m^3 shoreline landslide that occurred in Soerkjosen in northern Norway during the evening of 9th to 10th May 2015. The authors make particular reference to the fact that a deep, weak clay layer was missed in the original geotechnical site investigation at the site, thereby highlighting the critical importance of obtaining sufficient ground investigation data when assessing the stability of slopes in soft sensitive clay soils.

Silvestri and Abou-Samra build on recent findings on the behaviour of sensitive clays of eastern Canada to reassess the stability of a 62m square, 8m deep experimental excavation with four slopes of 18°, 27°, 34° and 45° to the horizontal conducted in Saint-Hilaire, Quebec in 1986. Their findings illustrate the effect of analysis type (total stress or effective stress) and effect of using of using peak strength envelopes from laboratory test data on the validity of the outcome of the stability calculation.

Ering and Sivakumar Babu investigate the effect of spatial variability of shear strength parameters through a probabilistic back analysis of a recent slope failure in India performed using Bayesian analysis in-conjunction with random field theory.

Bogomolov et al. investigate the stress distributions within landslides, with particular emphasis on locating and defining the shape and position of zones which have experienced plastic strains.

Abe and Nakamura investigate the impact load characteristics of different shaped and scaled rock and soil landslides using experiments conducted in a very large-scale flume and during free-fall. This dataset is then used to present relationships for the peak value of the collision loads for landslides comprised of rock or soil.

4.2 *Advances in our understanding of the fundamental soil behaviour related to landslides*

Siva Subramanian et al. investigate the soil behaviour pertinent to the triggering of landslides in cold regions. Including the effect of climate on the unsaturated soil behaviour of the slope, the authors conduct a series of parametric numerical simulation studies for an embankment slope failure case example to investigate the effect of snowmelt water infiltration and freeze-thaw action on the hydrological conditions required to result in failure.

Green et al. investigate the phenomena of static liquefaction of loose granular deposits along the Atlantic coast of Gabon. The paper summarises a significant site investigation program conducted following the 1971 major landslide event at Cape Lopez including cone penetration tests (CPTu) data, pressuremeter tests, geophysical surveys, in situ density measurements, and sampling complimented with repeated topographic and bathymetric surveys to characterise the problem.

Won and Cotton present the results of an advanced laboratory testing program aimed at characterising the effects of stress changes associated with the construction of a deep open cut excavation of 24-29 m on the deformation and shear strength of the overconsolidated clay slopes of a potential river diversion channel in Louisiana, USA. The authors note that the soil shear strengths observed from the stress path testing program were significantly different from the conventional Ko -consolidated triaxial tests.

Zhakulin et al. discuss the unique challenges posed by landslides in highly collapsible loess soils through the numerical modelling of a case study of a landslide affecting a highway in the Almaty region.

Matziaris et al. investigate the role of fines in centrifuge physical model experiments of sand slopes subject to rainfall infiltration. Their results indicate that a 10% addition of silt to a pure sand slope made it more susceptible to rainfall-induced failure than the pure sand baseline experiment.

Zheng et al. investigate the influence of grain hydrophobicity on the behaviour of soil slopes subjected to rainfall. As noted by the authors, fire induced soil water hydrophobicity is a major contributor of post-wildfire debris flow, through a significant change to the infiltration and runoff rates of the soil. Physical model tests are reported to investigate the role of hydrophobicity on erodibilty for two different sands.

Khasanov et al. describe the results of an experimental program studying the shear strength of sand in flat shear, triaxial stress state, and under passive and active loadings. The authors propose an alternative theory of the strength of the soil, which is different from the well-known Mohr-Coulomb theory of strength

5 ADVANCES IN MITIGATION MEASURES

With 16 manuscripts submitted, the single largest focus of papers submitted to the TC208 session relates to advances with regard to mitigation measures. These papers can be further subdivided into two themes: i) structural mitigation measures, and ii) infiltration / drainage mitigation measures. Of these two themes, the majority of the contributions focus on the use of soil nails / rock anchors, illustrating the significiant adoption of this mitigation strategy in engineering practice.

5.1 *Structural mitigation measures*

Yang et al. investigate the optimal position of piles placed as part of a landslide remediation scheme using numerical analyses based on the strength reduction method. Their findings indicate the optimal location of the piles is not constant for all landslides; however, is instead a function of the landslide mechanism which dictates the distribution of stresses and deformations.

Hazarika et al. report the results of an experimental program aimed at defining the contribution of 1/10th scale small diameter steel piles within a 1g physical model. An extensive experimental parametric study is then used to illustrate the effect of the installation angle of piles, connecting the head of piles, and combination of vertical and slanted piles (coupled piles) on the magnitude of reinforcement.

The work of *Saha* focuses on identifying the optimal spacing of stone columns to increase the stability of soil slopes. This analysis uses the concept of a unit cell within a limit equilibrium framework to mathematically derive the optimum area-replacement of the stabilised slope required for the most cost effective implementation of this mitigation measure.

Qin and Chian investigate the seismic stability of pile stabilised slopes using a kinematic analysis (i.e. upper bound theorem of limit analysis theory). The resulting analytical solution is used to conduct a thorough parametric analysis to illustrate the effect of soil strength parameters, slope geometry, and magnitude of seismic loading.

Schweiger et al. discuss the issue of including of 3D structural reinforcement into the classical 2D finite element representation of soil slopes. In particular, the authors discuss and evaluate the effectiveness of a strategy in which structural elements at a certain spacing can be introduced in 2D by means of a special element formulation to take advantage of the computationally less demanding nature of these calculations over full 3D analyses.

Kumar Jha et al. report the results of a limit equilibrium parametric analysis aimed at optimising the length of geosynthetics used as slope reinforcement to obtain a desired minimum factor of safety for steep slopes.

Ye et al. propose new technology to improve the pull-out resistance of soil nails. The technique combines compaction grouting with the conventional nailing method, and the factors defining its effectiveness is assessed through an extensive program of physical and numerical modelling.

Sahoo et al. investigate the seismic performance of soil nailed slopes using physical and numerical modelling. Shaking table tests were conducted on a reinforced and unreinforced steep (75 degree) slope to characterize the displacement and acceleration responses of the slopes and the nail forces along the length of nails for comparison to the finite element models of the slopes.

The study of *Wendeler et al.* investigates the interaction of soil nails and a typical flexible facing (high-tensile steel wire mesh) through a large scale tilt test of a 10 m x 12 m area of facing. The results indicate that the inclination required to trigger failure of the surficial layer behind the flexible facing is a strong function of the type of facing used.

Chao et al. describe an advance in ground anchor inspection in which a database of anchor behaviour is used to collect information of slope inspections, maintenance activities, and anchor testing data (e.g. head appearance, head component, endoscopic visual inspection, and lift-off test). Data of anchor behaviour collected using this framework in Taiwan is then mined to identify trends in inspection outcomes.

Mahouti and Katebi report the results of a field study aimed to evaluate the load carrying capacity of tension type grouted anchors implemented in Tabriz marl. Pull out tests performed on 11 cm diameter anchors were used to assess the ultimate bond friction, and readings of anchor loads were performed to quantify the degree of relaxation over a six month period of time.

The work of *Harmse and Jacobsz* is also focussed on the long-term loading of soil nails. Based on sudden unexpected increases in soil nail load observed at a site along the Gautrain Rapid Rail Link in Pretoria, South Africa, the authors further investigated the effects of water ingress on the axial load measurements within a geotechnical physical model. The reproduction of the mechanism of increased loads due to infiltration, illustrate that the capacity of drainage systems behind soil nail walls should be actively designed to exceed the rate at which water can infiltrate behind the wall.

The aim of the work presented by *Tistel et al.* is to provide guidance regarding the prediction of the capacity of rock anchors to cyclic loads. The authors present results from an extensive laboratory program to quantify cyclic loaded rock anchors and provide initial interpretations and preliminary conclusions from their ongoing research.

Kopecký and Frankovská describe a case study in which mitigation measures were used to stabilise a portion of a newly constructed road network near Svidník, Slovakia, including structural measures such as an anchored pile wall and drainage measures such as the construction of drainage ribs.

5.2 *Infiltration / drainage mitigation measures*

Hamasaki et al. present the development of an interesting new reinforcement technology that functions as both a mechanism to reduce pore water pressures and act as a structural inclusion reinforcing the slope. The effectiveness of this technology, called Spiral-bladed Drain Pipe Reinforcement (SDPR) by the Authors, is evaluated through field pullout tests and an analysis of the hydrological response of the slope to rainfall.

Fan and Yeh describe the results of a field-scale experiment in Taiwan to investigate whether the degree to which erosion control blankets affect rainfall infiltration. Two 30° slopes were instrumented, one with an erosion control blanket, and a bare slope to act as a baseline of comparison. The observations from field moisture content sensors installed at these two slopes indicate that the erosion control blanket significantly delayed the arrival of the wetting front.

6 SUMMARY REMARKS

The papers summarized here show how the balance of focus of technical reporting has changed from presentation and analysis of case studies (as seen in at the ICSMGE Paris) to mitigation of slope instability. This is an encouraging development, indicating that both the State of Art and State of Practice have matured beyond characterisation in a significant number of regions for particular ground conditions and landslide types. On the other hand, for a large number of scenarios, considerable research is clearly still necessarily ongoing on fundamental soil behaviour and analytical methods to inform decison-making for risk avoidance.

Hazard mapping and the development of early warning systems help complete the picture by communicating the risk of landsliding both spatially and temporarily to planners, developers and the public. These are seen to be topics of general growth and increasing sophistication, as new tools are introduced to improve their accuracy.

While the themes covered in this session are broad, it is evident that the development of new knowledge on engineered slopes is enhancing the resilience of our infrastructure and hence, our lives. It is to be hoped that by looking across these themes, we can link up the knowledge therein, ensuring continued improvements over the next four years.

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