General Report of TC 208
Slope Stability in Engineering Practice

Rapport général du TC 208
La stabilité des talus dans la pratique de l'ingénieur

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ABSTRACT: This General Report reviews 37 papers from 21 countries or provinces that were submitted to the conference on the topic of slope stability in engineering practice. These papers serve either to advance the state-of-the-art, else to inform the state-of-practice. Further, by developing new knowledge, else refining existing knowledge, the observations reported in the papers and the conclusions that are drawn from them provide for improved decision-making in the face of risk and uncertainty.

RÉSUMÉ : Le présent rapport général passe en revue les 37 communications provenant de 21 pays et provinces qui ont été soumis au Congrès sur le sujet traitant de la stabilité des talus dans la pratique de l'ingénieur. Les communications ont comme objectif soit de faire évoluer l'état des connaissances, soit de rendre compte de la pratique actuelle. Par le développement de nouvelles connaissances ou par l'affinement de connaissances existantes, les observations relatées dans ces communications et les conclusions qui en sont tirées permettent d'améliorer les processus décisionnels face aux risques et aux incertitudes.

KEYWORDS: Slope stability, landslide, debris flow

1 INTRODUCTION

Slope stability in engineering practice is considered by many to be a broad-ranging subject, and this viewpoint is perhaps supported by the diversity of papers submitted to the conference. Yet, in reality, studies of slope stability in engineering practice are unified by the common objective of a better understanding of (i) the spatial and temporal variation of demand and capacity at the point of origin and (ii) the magnitude and travel distance of the event along its path of movement downslope. All of the papers submitted to the conference address these objectives in one form or another. In this regard, the findings of the papers serve either to advance the state-of-the-art, else to inform the state-of-practice. More importantly, by developing new knowledge, else refining existing knowledge, the observations reported in the papers and the conclusions that are drawn from them provide for improved decision-making in the face of risk and uncertainty.

This General Report reviews 37 papers from 21 countries or provinces that were submitted to the conference on the topic of slope stability in engineering practice.

1.1 *Focus / approach of papers*

Table 1 indicates that there is overlap in the focus of many of the papers, with 24 of them sharing two or more approaches or topics. This is particularly evident for papers that have a case study element with 14 of these linking to a numerical model, detailed field study and/or risk assessment. It is encouraging to see that such case studies are being increasingly presented with a critical and quantitative assessment of the factors that may have contributed to a slope failure occurring. A further 4 of the case study papers directly link to implementation of mitigation measures (*Şengör et al.; Coutinho and da Silva; Bozo and Allkja; Chang and Huang*), although with the exception of the paper by *Şengör et al*, other than qualitatively showing the utility of such measures, the outcomes are neither analysed nor presented in detail.

Table 1. Number of papers by approach or focus.

Approach / focus	Papers
Case study	21
Numerical - deterministic	9
Numerical - probablistic	6
Field study / instrumentation	6
Experimental / physical model	6
Risk assessment	6
Mitigation measures	6

In contrast, it is interesting to note that 4 of the 9 papers that use deterministic numerical models do not attempt to validate against any particular field situation. In these cases, the models in question may be still at the development stage (*Saha; Nonoyama et al.; Law et al.)* else the authors intend to illustrate a potentially general mechanism of failure (*Dey et al*.).

A total of 6 papers present a detailed study of a particular area via field instrumentation or discuss the development of instrumentation for monitoring of slope instability, while a further 6 papers present an experimental analysis of soil behavior or a detailed physical model of a particular scenario. These approaches are important to enable an understanding of fundamental mechanisms of slope instability and can be very important to determining the details of complex interactions between, for example, groundwater and precipitation on rainfall-induced landslides, or sediment supply and frequency of debris flows.

Six papers take a risk assessment approach – either for a defined area for site-specific purposes related to risk assesement or for a more regional approach that is more appropriate to concern of risk management.

1.2 *Type of instability investigated*

Table 2 shows the types of landslide failures that are discussed in the papers. Approximately 30% of the papers are on rainfall-induced landslides, 8% on earthquake-induced landslides (solely) and nearly 30% on debris flows or flow-slides, with multi-hazard landslides (mostly earthquake coupled with debris flow) accounting for 10%. The remaining papers address progressive slides (4%) or the triggering / landslide type is unspecified (19%).

The fact that there are 10 papers on debris flows or flow slides is a marked increase on previous years. For the 16th International Conference on Soil Mechanics and Geotechnical Engineering, Chau (2005) noted that only two papers dealt with debris flows. While as Chau (2005) has pointed out, there are dedicated conferences on debris flows elsewhere, the inclusion of these papers in a broader geotechnical forum is promising in terms of applying geotechnical rigor to a problematic subject of global concern.

The recognition of landslides within a multi-hazard causal framework is also extremely important, although the number of papers presented is still relatively small. As determined by Lin et al. (2004), amongst others, earthquakes can lead to worsening conditions for landslides and debris flows, while landslides can be the precursor of debris flows particularly where the landslide meets a body of water or ice. A thorough understanding of the complexity of such scenarios is believed warranted, because the state-of-the-art must continue to inform the state-of-practice and, on occasion, the cutting-edge of practice is challenged to address some very challenging realities of risk management.

Table 2. Number of papers by instability type

Type of failure	Papers
Rainfall / pore pressure induced	11 (14)
Earthquake induced	3 (7)
Debris flow / flow slide	10 (11)
Multi-hazard	4
Progressive	2
Unspecified	7

(Parentheses indicate numbers that include multi-hazard papers)

1.3 *Breakdown of research papers by country*

Table 3 presents the number of papers from different countries and indicates an important reality with respect to where research activity is currently concentrated by region. As has been previously noted by Petley (2012), much of the work on landslides is carried out by researchers in developed economies, where the focus has moved from life impacts (which have been reduced over time due to the development of a relatively good understanding of catastrophic landslide behavior in these countries) to economic impacts (which may be more influenced by slower movements and low-magnitude, albeit high- frequency events). However, in emerging and developing economies, which have large numbers of landslides per annum, there is relatively little research on-going, the threat to life remains unacceptably large.

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

Country	Papers	Country	Papers
Norway	6	India	1
Japan	4	Korea	1
Taiwan / Chinese Taipei	4	Lebanon	1
USA	4	New Zealand	1
Hong Kong, China	3	Russia	1
Albania	2	Sweden	1
Brazil	1	Turkey	1
Canada	1	United Kingdom	1
Mainland China	1	Vietnam	1
Greece	1		

To illustrate this, Figure 1 after Petley (2012) presents the total number of publications on landslides found in ISI journals for each country (taken from provenence of the lead author's institution) against the recorded number of fatalities in those countries in the period from 2004 to 2010. He has divided the figure into three zones – termed research intensive, research active, and research inactive. The results clearly show that many countries which are least research active have some of the highest incidences of landslide fatalities.

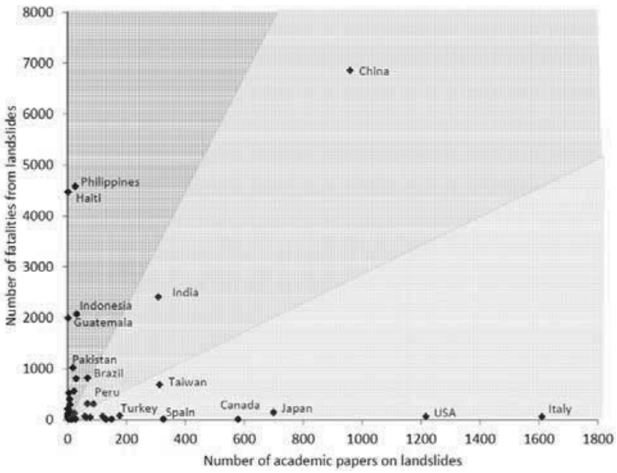

Figure 1. Total number of publications on landslides / slope stability by country in ISI journals from 2006-2010, reproduced from Petley (2012).

Using China as an example, Petley (2012) also showed that increasing the research intensity within a country prone to landslide activity can reduce the rate of fatalities experienced. Two decades of data from 1990 to 2013 are reproduced in Figure 2.

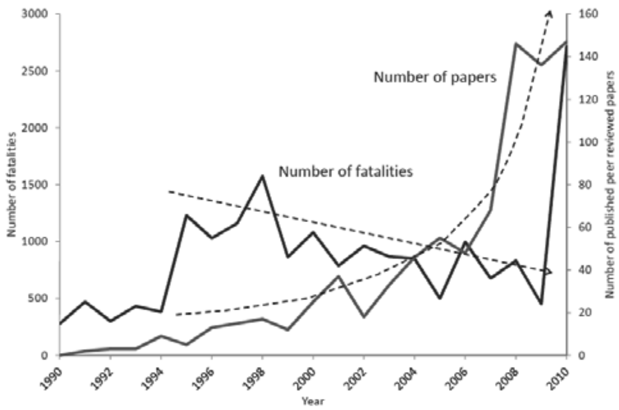

Figure 2. Example of the effect of increasing annual research on landslides on the rate of fatalities in China over 20 years, after Petley (2012). Note that a single landslide that occurred in 2010 in Gansu province killed over 1700 people, which distorts the overall dataset.

In the following section, papers are grouped by type of instability (Table 2).

2 RAINFALL / PORE PRESSURE INDUCED SLOPE INSTABILITY

3 This section discusses the major findings of the 11 papers on rainfall or elevated pore pressure induced landslides.

Two papers by *Wang et al.* and *Uchimura et al.* discuss the use of a tilt-sensor to detect the onset of instability in slopes that are experiencing creep movements. *Wang et al.* covers details of innovative sensor development and field installation. *Uchimura et al*. elaborates further on the use of the device coupled with volumetric water sensors within an experimental arrangement of artificial rainfall on natural ground. The experiments show that instability can be detected by an increase in the rate of change of the tilt angle, while the volumetric water content is related to the deformation, and is independent of the rainfall period. Some interesting observations are made regarding the influence of the soil water characteristic curve (SWCC) on the deformation behavior of an unsaturated slope undergoing infiltration – in particular, that a temporary reduction in deformation rate may not be indicative of increased stabilization, but rather an effect of the reduced rate of change of suction loss with infiltration. The finding is an excellent illustration of the potential for the state-of-the-art to influence the state-of-the-practice.

Nakata et al. examines the influence of pore pressure cycles on the collapse behavior of a slope in a study combining element testing of a standard sand with field monitoring of a natural slope. Plane strain compression tests carried out on Toyoura sand showed that cycles of pore pressure always led to soil hardening rather than increasing the likelihood of failure. In the field, it was found that the slope's behavior was a function of both the recent and antecedent rainfall, yielding a recommendation to monitor the groundwater level as well as the use of rainfall data to understand the fundamentals of collapse behavior.

Rahhal et al. presents a study on two landslides that occurred in Lebanon for which geotechnical parameters were obtained via laboratory testing. Slope stability analysis of one slide showed that a loss of cohesion in the clay, at the interface of the clay and underlying stiffer material, due to seasonal moisture infiltration, resulted in the instabilities that were reported. For the second study area, weakening and loss of cohesion in clay schist due to prolonged water contact was thought to be largely responsible for the instabilities recorded, with a minor contribution from cracks that were opened allowing water infiltration.

Jeng et al. present a study on the effects of heavy rainfall on a slope in northeastern Taiwan that is covered with a 10-20m depth of colluvium and instrumented with a surface monitoring system. The results from 295 locations of settlement and displacement monitoring locations are evaluated, together with the significance of rainfall on initiating ground movements. Figure 3 shows annual surface settlements of up to 20mm in the study area. From the analysis of the influence of typhoon rainfall on the ground displacements in different parts of the site, a threshold value curve of risk for rainfall was proposed for the area and a slope stabilization programme subsequently recommended by the authors. Once again, a careful series of field observations serve to influence the state-of-the-practice.

Kavvadas et al. presents the management of a mine site in Greece in which significant ground displacements are seen to occur with rainfall. Figure 4 shows a generally good correlation between surface velocities as determined at monitoring prisms (top) and rainfall records taken approximately 6km away (bottom). The data indicates a stick – slip mechanism and a regressive movement in which the velocity does not increase or decrease at a constant rate but undergoes abrupt changes. The authors posit that, during and after heavy precipitation, the water-filled tension cracks provide an increasing driving force. As displacement continues, the width of the cracks increases and the water level drops with a resulting dissipation of water pressure. This is a different mechanism to that of tertiary creep in which an increase in velocity of slope movement may be the precursor to imminent failure (Rose and Hungr, 2007).

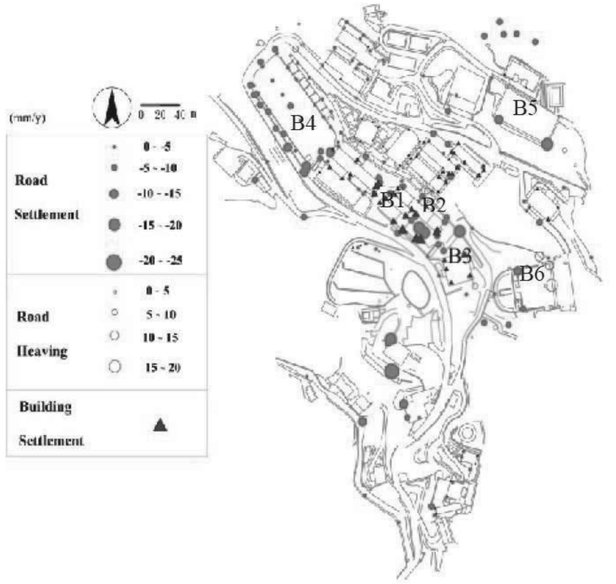

Figure 3. Jeng et al. Annual surface settlement distribution

Kavvadas et al. highlights the importance of understanding the underlying mechanism of slope deformation and, in doing so, shows that high mine slopes can operate under large rates of displacement, as long as the type of sliding mechanism is identified and continuously monitored. Finally, the paper shows that remedial measures can be incorporated in a mine plan in order to reduce movements, if not to arrest them entirely.

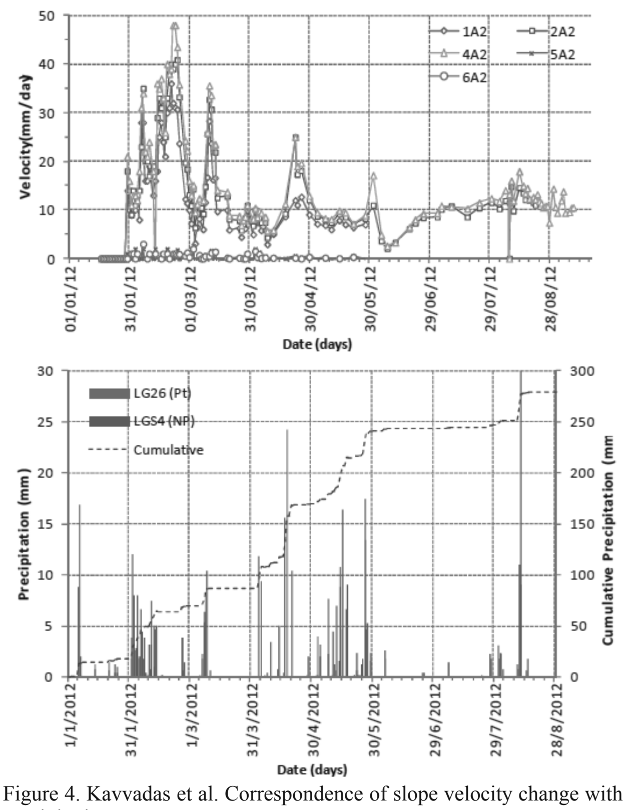

Figure 4. Kavvadas et al. Correspondence of slope velocity change with precipitation.

Coutinho and da Silva present a paper on the characterization, analysis and stabilization of a landslide located in a township in Brazil. The soil formation is characterised as sandy clay to silty sand (Barreiras formation) and residual granitic soil. The landslide was analysed as a two-part process during a precipitation event (Figure 5). The analysis suggested that the upper part of the slide zone failed first, due to a lower permeability zone, leading to elevated pore pressures in that zone during heavy rainfall. The upper slope failure then resulted in an additional surcharge loading and failure in the lower slide mass. This paper highlights the importance of local geological conditions on the triggering of slope instability and that localized heterogeneity can play a major role in the distribution of groundwater flow.

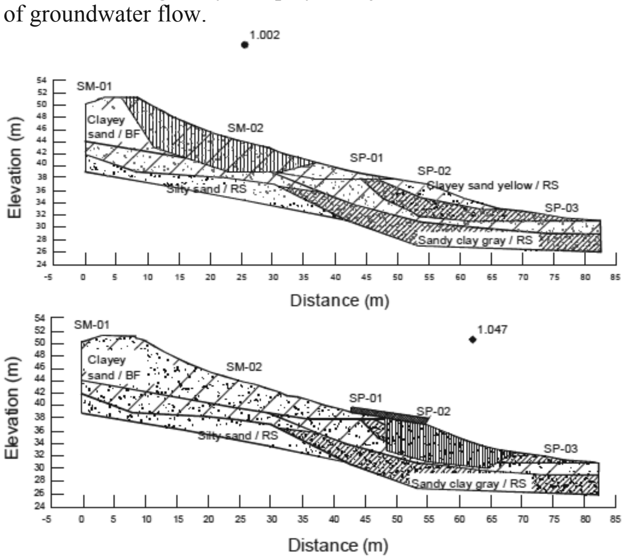

Figure 5. Coutinho and da Silva. Upper and lower slope failure models.

Son et al. present a study on landslide susceptibility zonation for an area in the south central coast of Vietnam developed using a Bayesian conditional probability model. Surveyed landslides from one year's rainy season were used as inputs to the model which was examined to develop suitable weighting factors on elements such as elevation, slope angle, drainage distance, geology etc. and was integrated with GIS analytical tools to produce the map. The reliability of the model can be improved as new landslide occurrences are updated annually in the landslide inventory.

Tremblay et al. discuss the influence of climate change on the risk of landslides and its assessment for a valley in Sweden. Notable effects of climate change are increases in annual precipitation and temperature and potential reduction in water levels in the river through dry summer periods (although controlled by the authorities) and increased river flows in winter (Figure 6). Each of these scenarios may lead to a decrease in slope stability around the river valley. Readers are referred to detailed risk assessment and reports available from SGI.

Li et al. discusses the detailed instrumentation and full-scale field monitoring programme for a study on the mechanisms of rainfall-induced sliding slope, through a study conducted for a new development in Hainan, China. Large variations of volumetric water content and matric suction at shallow depth in decomposed granitic soils, during the rainy season, may explain why so many slope failures have occurred in this region at times of heavy rainstorm activity. The paper also highlights the inherent difficulties associated with the protection of delicate monitoring instruments on an active construction site.

Harris et al. describes the implementation of an early warning system (EWS) for a highway embankment subject to rainfall induced landsliding. Volumetric water content sensors were installed at a cross section of the site. A 2D finite element model was then used to replicate the response of the sensors to rainfall, using monitored rainfall events as an input. Next, a limit equilibrium analysis was carried out and an artificial neural network was trained to predict the factor of safety obtained using the sensor readings as inputs. Data from rainfall forecasts are then used to establish a predicted factor of safety for the slope in real time, allowing road-users to be advised accordingly.

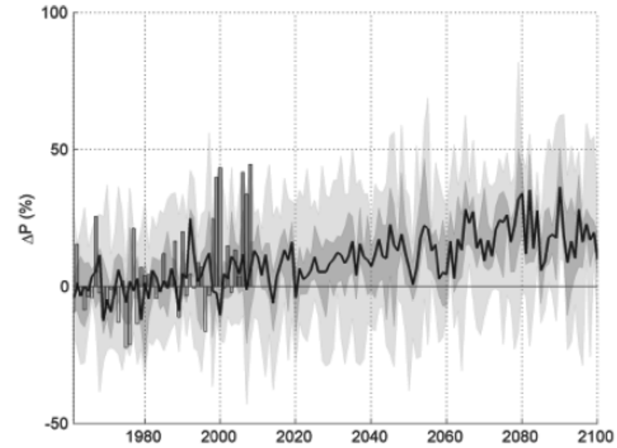

Figure 6. Tremblay et al. Percentage increase in precipitation with year from 16 climate scenarios after Bergstrom et al. (2011)

3 DEBRIS FLOWS AND FLOW SLIDES

In total 10 papers are presented on debris flow or flow slide initiation, and aspects of runout or travel distance if the specifics of entrainment of debris along the path of movement as taken into account (see Fannin and Bowman, 2010)

Several studies are presented that use statistical data to derive debris flow hazard potential in particular areas based on local topography and associated hydro-geological behavior. Some of these studies follow statistical-empirical methodologies that do not require precipitation inputs, and may be used for a general assessment of debris flow potential, while other studies include a temporal element by taking account of precipitation records. *Yune et al.* present a paper on debris flows that occurred in the Umyeon Mountain area of Seoul, Korea during the rainy season of 2011, determining that most were initiated from small slope failures induced by high-intensity rainfall. The paper discusses the application of a statistical landslide hazard map which has been developed on parameters such as slope angle and direction, strength of soil, hazard record, rainfall condition and plantation type. This map has demonstrated the ability to highlight areas that are vulnerable to heavy-rainfall-induced slope failure and resulting debris flow disasters.

Lin and Lin present a study on the analysis of debris flow torrents in Nantou County, Taiwan, using discriminant analysis based on 199 known debris flow torrents and 175 non-debris flow torrents. The influence factors included: watershed area, stream length, form factor, hypsometric integral, stream mean slope, slope distribution, slope aspect, and geological formation. In order to examine the feasibility of the model, the data sets of debris flow torrents and non-debris flow torrents not used in developing the estimation models were used for validation and prediction.

Cepeda et al. presents a probabilistic procedure based on a Monte Carlo simulation for run-out modeling of debris flows, in order to analyse the effect of uncertainties in the input parameters. The framework is based on a dynamic model, which is combined with an explicit representation of the different parameter uncertainties. The main goal is to present a framework to obtain potentially expected run-outs and intensities in areas where it is not possible to determine the rheological parameters on the basis of back analyses.

Two papers are presented that use experimental techniques to examine debris flow behavior. *Katzenbach and Bergmann* present a paper to understand some fundamental flow properties of saturated soil in a large-scale experimental apparatus. The study is designed to examine the influence of parameters such as grain size, grain shape and grain size distribution, water content and pressures on the flow behaviour. This paper focuses on coarse grained water-saturated soils, which excludes the complexities of cohesive internal forces. Initial results indicate the importance of particle size on the flow velocity of the granular mixture. Results are intended to supplement numerical work that is on-going.

Choi et al. present a paper on a series of flume tests that examine the influence of baffle row number on reduction of debris frontal velocity. The average frontal velocity of the debris flow downstream of the array of baffles was measured. Results show one row to be ineffective in reducing the debris frontal velocity, however, two to three rows of baffles exhibit notable frontal velocity reduction.

Law et al. present a related paper to that of *Choi et al*. on the dynamic interaction between a granular surge flow and baffles. In contrast however, Law et al. use the three-dimensional discrete element method with the granular flow medium modeled as spherical discrete elements and the baffles as rigid square objects. The location, velocity and forces acting on the individual elements during the impact and interaction process are presented. Assessment of the numerical results indicates that a single row of baffles is effective in reducing the kinetic energy and discharge of the granular flow. Interestingly, this actually runs counter to the findings of *Choi et al.* One possibility for this may be a difference in the relative size of largest particles to the baffle spacing used in the experiments by *Law et al*. and *Choi et al*. although data on this are not available from *Choi et al.*

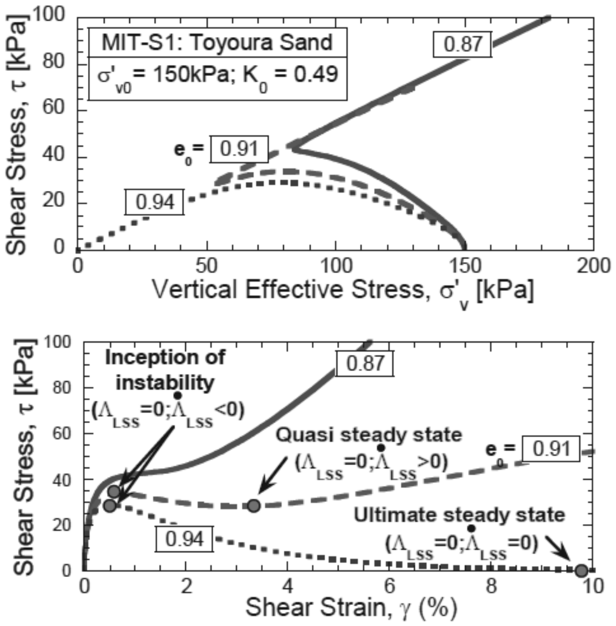

Figure 7. Buscarnera and Whittle. MIT-S1 constitutive model predictions for a sand in undrained shear at different initial void ratios.

Buscarnera and Whittle present a framework for evaluating the triggering of flow slides in infinite slopes using the anisotropic MIT-S1 model. The selected soil model is able to simulate realistic transitions in the contractive/dilative response of sands and enables the prediction of the shear perturbations able to induce instability (Figure 7), as well as the location of potentially unstable zones within the soil mass. In order to show the capabilities of the proposed approach, the methodology has been applied to the well-known case of slope failures in the Nerlerk berm: results suggest that static liquefaction is likely to have contributed to the failures. The analyses illustrate a unified methodology that combines the theory of material stability, the critical state framework for sands and data from in situ tests. The authors state that the methodology offers a simple, consistent and complete geomechanical framework for interpreting and predicting the triggering of flow slides that can be easily applied to other similar engineering cases.

Thakur et al. propose a new approach to assess the potential for flow slides via a new laboratory test procedure referred to as the quickness test. The test focuses on remoulded behaviour of sensitive clays in terms of a numerical value referred as quickness (Q). Based on their study, it is found that a Q < 15 % or remoulded undrained shear strength c_{ur} > 1 kPa seems to be the threshold limit above which the extent of retrogression of a landslide is limited to the initial slide. This criterion has been supported using data available from several Norwegian landslides in sensitive clays.

Winter et al. present fragility curves as a means of describing the vulnerability of elements at risk to impact by a debris flow. The specific category of element considered in the paper is a road. Expert engineering judgment was used to develop preliminary fragility curves, from a compilation of responses to a questionnaire. Analysis and interpretation of the collected data is made with reference to two events, in an attempt to relate event volume to the probability of a state of damage.

4 EARTHQUAKE INDUCED SLOPE INSTABILITY

Consideration of seismic slope stability occurs in several papers, two of which are considered here and five of which are more rationally addressed within the context of multi-hazard considerations in the section that follows this one.

Strenk and Wartmen present the findings of a sensitivity analysis conducted on an idealized slope, to examine uncertainty in seismic deformations established using the Newmark rigid-block method, given variability in ground motion. The effect was found to be most pronounced at low acceleration ratios, and little influence of frequency content and waveform was observed. The findings suggest that use of spectral matching to create variability in both intensity and frequency may be "of limited utility".

Paçi et al. presents a study on the stability of a new road located in a very disturbed tectonic zone where the rock quality is extremely poor. Active surface slides are very unstable due to water ingress especially during seismic events. Geotechnical parameters of the intact flysch / clay and limestone rock are determined from laboratory tests and empirical methods, while for residual parameters, a back-analysis is carried out using Plaxis 2D software. Hence, slope stability problems resulting from seismic loading are examined in two stages. The first model determines a critical sliding plane (if any) under an artificial accelerogram that takes account of near-source effects and then the second uses residual parameters for the soil strength mobilized within the sliding plane. The second model is used to define and design the engineering measures (walls, piles, anchored wires, nails, etc.). This two-step process, is a pragmatic approach for designing mitigation measures for prefailed slopes, and may also be used for pore-pressure induced instabilities (e.g. Tatarniuk and Bowman, 2012).

5 MULTI-HAZARD INSTABILITY OF SLOPES

Nadim and Liu present on the use of Bayesian networks to inform reasoning when there is uncertainty and reliance on expert judgment, such as is done in many branches of civil engineering (for example, avalanche risk assessment, dam risk analysis etc.). They built a network for consideration of earthquake-triggered landslides using the open-source MATLAB package BNT, and used it to conduct a sensitivity analysis. The method is believed to have merit in deciding where to take no action, versus installing a warning system, else opting for active countermeasures.

Chang and Huang present an interesting case study on the influence of the Chi-Chi earthquake in 1999 on a road above slope that had been stable. Although no obvious damages to the road were observed at the time of shaking, during Typhoon Nari in 2001, several parallel cracks developed along the road alignment – suggestive of underlying instability. Remedial work was initiated. Nonetheless, a loss of road base during the monsoon season the next year imposed a stop on the work. The remedial plan was revised and implemented, but failed again due to typhoons in 2005. The current repair works have been completed and generally show no major signs of slope distress. However, data from subsurface exploration and in-situ monitoring have shown signs of slope instability.

Figure 8 indicates potential slip surfaces in the upslope that would have impact on the road section. The downhill side slope also was not improved during the remedial works and its surface was bared with remains of previous slides. The upslope mitigation works are not useful for the stability of the downslope area and do not remove the concerns regarding the long-term stability of the road section and slopes at the site. Discussion addresses the potential for further remedial works, but it is pointed out that the cost of these may make a rerouting of the road desirable in the long term.

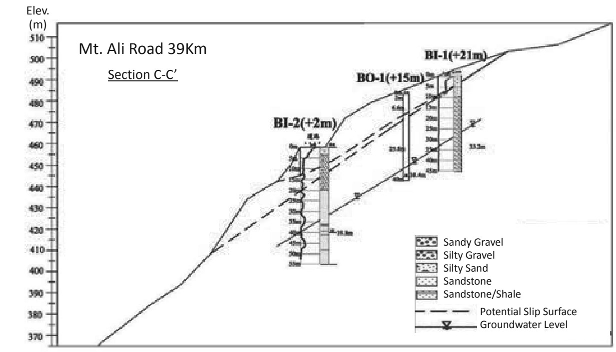

Figure 8. Chang and Huang. Instabilities detected by borehole investigation

Long and Tjok present a paper on submarine slope instability due to earthquake excitation leading to mass gravity flow which may pose risk for the integrity of offshore structures along the flow path. This paper demonstrates the ability of using a fully coupled nonlinear effective stress analysis to simulate the development of liquefaction and the instability of a liquefied slope. A prediction of run-out distance of subsequent debris flows is also made. The authors use a 1D model and parameters correlated with liquidity index in the absence of other data, although they also point out that estimation of run-out distance should be tested and calibrated to the case in question.

Quan Luna et al. present a study on the effects of earthquakes on subsequent slope stability, undertaken in an explicitly multi-hazard framework. The developed model is designed to give a rough spatial and temporal prediction of expected change in landslide hazard in an area following an earthquake. The model is able to describe the reduced impact of earthquakes with distance from the epicenter as well as how the soil looses strength due to shaking and gradually regains it with time. These reductions are then applied to an equilibrium stability analysis in order to compute new factors of safety on stability. The model is demonstrated by using a virtual region, and while further work is required to calibrate and validate the model with respect to real situations, it provides a mechanism whereby prospective outcomes from future hazards can be investigated in a conceptual manner.

Cohen-Waeber et al. presents data from a project combining GPS and InSAR time series analyses for the detailed characterization of spatial and temporal landslide deformation as a result of static and dynamic forces. A review of three independent InSAR time series analyses of the Berkeley Hills from 1992-2011 shows remarkable consistency. They reveal accelerated landslide surface deformation as a consequence of precipitation, though not in relation to seismic activity. Further, after a mild wet season in early 2012, the GPS instrumentation of several landslides in the Berkeley Hills has recorded well-defined precipitation triggered slope movement. In contrast, the occurrence of a nearby Mw = 4 earthquake did not appear to have produced a measurable effect (Figure 9). Both InSAR and GPS studies confirm strong correlation and sensitivity to periods of precipitation, and downslope sliding velocities of around 30 mm/year. These observations, taken over longer time periods will enable important insight on the triggering mechanisms and internal landslide behavior of this area.

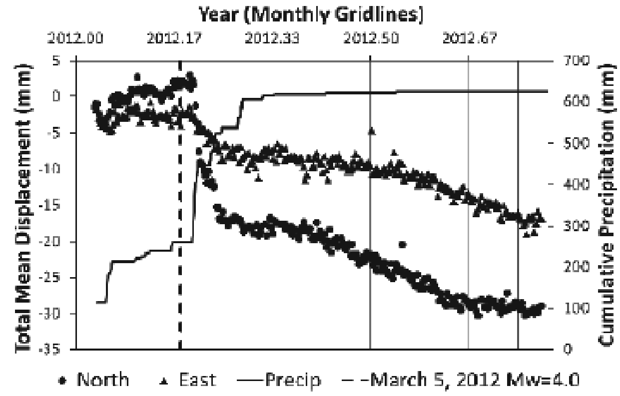

Figure 9. Cohen-Waeber et al. North (circles) and east (triangles) components of relative displacement with respect to reference site P224 shown together with cumulative precipitation (solid line) and time of Mw = 4 earthquake (dashed line).

6 PROGRESSIVE FAILURE OF SLOPES

Two contrasting papers on progressive failure are included – the first presents retrogressive failures in tuff over an existing landslide area, and the second investigates the strain softening behavior of sensitive clays leading to river bank erosion.

Şengör et al. present a paper on a landslide that occurred during foundation excavation of an industrial plant in Turkey. The instability occurred in a natural slope with a slope angle of 9°-13°. The sliding mass grew progressively backward into the slope as multistage rupture surfaces from the toe of the landslide developed. Back-analyses and laboratory tests were performed for the determination of shear strength parameters at the sliding surface. Mitigation measures included: two rows of stabilizing piles which were analyzed by FE independently for geotechnical and structural performance, permanent ground anchors, and surface drainage. The deformations of the system were measured by 12 inclinometers (8 in the soil, 4 in the piles) at each stage of the construction works and there have been no displacements in three years since completion.

Dey et al. present a study on upward progressive failure due to river bank erosion in sensitive Canadian clay which is numerically modeled using nonlinear post-peak strain softening behavior. Three cases are analyzed. In Case-I, the ground surface is horizontal and there is a 15m thick layer of sensitive clay below a 5m crust. The Case-II is same as Case-I but the ground surface is inclined upward at 4°. In Case-III only a 1.0 m thick sensitive clay layer parallel to the horizontal ground surface from the toe of the slope is assumed, with the crust the same as for Case I.. In Cases I and II global failure was found to occur. However, for Case-III, although global failure did not occur, the shear band propagation reduced the shear strength in the potential failure plane significantly over a large distance and the slope might be marginally stable for further loading. Hence it is shown that the pattern of propagation of shear band varies with soil type and slope geometry.

7 UNCLASSIFIED

This last group of papers includes some highly theoretical contributions and some highly pragmatic ones – both ends of which help to advance the state of knowledge or practice within the profession.

Saha develops a global population-based search procedure (APMA) and applies this to a classic slope-stability problem as originally defined by Spencer (1967). It does not require problem-specific knowledge in searching the critical slip-surface of a soil slope but rather is a heuristic technique based on the ‘generate-and-test’ strategy. The results show that a lower factor of safety may be obtained with this technique than is found by Methods-of-Slices that are commonly used.

Bogomolov et al. suggest a method for calculating the stability of a loaded slope, based on the combined use of the finite element method, complex function theory and the principle of virtual displacements, as formalized in a computer program by the authors. The method ensures that a minimal condition of the factor of safety K value at each point is obtained without simplifying assumptions.

Nonoyama et al. apply the SPH (Smoothed Particle Hydrodynamics) method to a series of slope stability problems. This numerical method, in which continuum-based constitutive relations are input, can handle large deformation problems because it is based on a free mesh system. This means it has the potential to describe the deformation of geomaterials from the initial state to subsequent large deformation and can be used to estimate deformation and failure conditions simultaneously. Using two example constitutive models, the authors present analysis of both simple slopes and those with countermeasures (piles) included and compare results to those obtained by the Fellenius method.

In their extremely practical contribution, *Yeh et al.* introduce the currently most adopted ground anchoring inspection system used in Taiwan for anchoring slopes. The paper also proposes a new method of ground anchoring assessment, in order to establish a standardized quantitative analysis procedure for professional reference. They find that four categories of assessment should be made: inspecting the exterior of the anchor, the anchor head, an endoscopy inspection and conducting lift-off tests. They also examine the most common shortcomings of anchor installation and suggest remedies.

Bozo and Allkja present a study on the cuttings constructed for the Vlora road in Albania. A description of the geological setting of the site and of the rock and soil profiles is provided. Using in situ and laboratory tests they have determined the type of cuts and their geometrical forms in a manner designed to protect both the environment and the stability of slopes. Correlations between in situ test results and soil types are given as well as classification data and strength data for the soils encountered. They have also carried out some classifications of cuts for the road taking into account the conditions of the terrain.

The paper by *Lo and Lam* highlights some key lessons learnt and observations made from selected landslide investigations by the Geotechnical Engineering Office (GEO) of the of the Civil Engineering and Development Department (CEDD) of Hong Kong. On average, about 300 landslides are reported to GEO in Hong Kong each year. The paper discusses the use of robust stabilization measures for cut slopes, improved rock slope engineering practices, enhanced practices in the monitoring and maintenance of water-carrying services affecting slopes and improvement to drainage detailing.

Du et al. propose a quantitative model for estimating the vulnerability of elements at risk from impact by a slope failure, where vulnerability is defined as a function of landslide intensity and of susceptibility of the element. A conceptual framework is described for the model, and commentary provided on parametric inputs to it, together with suggested values for those parameters. The authors acknowledge the limitations of the model in its current form, which arise from a need to calibrate some of the input parameters.

Lacasse et al. summarize the findings of a European Commission project, SafeLand and its related ‘toolbox’ that is web-based, which includes nearly 75 mitigation measures for different types of landslide. Features of the toolbox are described, which extend to estimates of cost-benefit factors and likely effectiveness, all of which are predicated on a ranking of the most appropriate mitigation measures. In this regard, the toolbox takes the form of a decision-support tool.

8 SUMMARY REMARKS

In engineering, like many other subjects of professional practice, it is important that the state-of-the-art continue to inform the state-of-the-practice. In reality, the state-of-the-practice involves risk management, whether it is done implicitly or explicitly. It is by developing new knowledge, else refining existing knowledge, that the findings of research enable improved decision-making in the face of risk and uncertainty. A total of 37 papers were submitted to the conference on the topic of slope stability in engineering practice.

Although they are broad-ranging in subject matter, they are unified by a common thematic objective of better understanding the spatial and temporal variation of demand and capacity at the point of slope instability, together with the magnitude and likely run-out or travel distance of the ensuing event. In many respects the findings of these studies are a timely reminder of the observations of Karl Terzaghi that “In soil mechanics the accuracy of computed results never exceeds that of a crude estimate, and the principal function of theory consists in teaching us what and how to observe in the field” (Goodman, 1999).

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