Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-3111

Technical session 4a: Slope stability and landslides

Séances techniques 4a: Stabilité des pentes et glissements de terrain

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1 INTRODUCTION

There is a total of 35 papers submitted to the Technical Sessin "4a: Slope Stability and Landslides". The Sesssion Chairman is Prof. H. Nakamura, Session General Reporter is Prof. K.T. Chau, Session Secretary is Prof. K. Tateyama, and the Secretary of Paper Presentation and Poster Discussion is Dr. K. Sawada. Five panelists of the sessions are Prof. L. Picarelli (Italy), Prof. L. Vulliet (Switzerland), Prof. W.A. Lacerda (Brazil), Prof. D.G.Fredlund (Canada) and Prof. A. Yashima (Japan). The Session is scheduled on the afternoon of September 13, 2005 (Tuesday). The main purpose of this general report is to summarize the issues that these 35 technical papers addressed. Some essential issues raised by these papers will be given at the end of this general report.

Although it is my honor to to be invited by the conference administration to serve as the General Reporter, it also poses a difficult job for me. Due to limitation of time and of printing space, it is impossible for me to review all 35 papers in great details and pressent them here. In addition, my summary to be given here will evitably be constrained by my personal educational background and my previous research works. Although my PhD training on theoretical and applied mechanics may shape my interests towards the theoretical aspects of the problem, my previous works on theoretical, experimental and field aspects of landslides (Chau, 1995, 1997, 1998, 1999; Chau & Cho, 2001; Chau & Wong, 2001; Chau et al., 2004b), debris flows (Chau & Lo, 2004; Chan & Chau, 1999) and rockfalls (Chau et al., 2004a, 2001, 2002, 2003) should allow me to have a more balanced stand on different topics and issues. Nevertheless, if I do not do full justice to any author, please offer me your forgiveness and understanding.

Table 1. Paper distributions among continents

Continent	Paper No.
Africa	1
Asia	10
Europe	17
North America	4
South America	3

Table 1 summarizes the number of papers from each continents. Geographically, 17 papers are from Europe, 10 from Asia, 4 from North America, 3 from South America and 1 from Africa. It appears that Europe is most active in slope stability and landslide research, at least for this particular conference. Table 2 compiles the country distribution of all 35 papers. A total of 20 conutries were represented, including 8 from Japan, 3 from Canada and Italy, 2 from Greece, Norway and Brazil, and 1 from each of the following countries: Algeria, Austria, The Netherlands, Macedonia, Pakistan, USA, Ecuador, Slovenia, Germany, Spain, Russia, Switzerland, Czech Republic and China.

Table 2. Geographical distribution of 35 papers

Country	Paper No.	Country	Paper No.
Algeria	1	Japan	8
Austria	1	Macedonia	1
Brazil	2	Netherlands	1
Canada	3	Norway	2
China	1	Pakistan	1
Czech Rep.	1	Russia	1
Ecuador	1	Slovenia	1
Germany	1	Spain	1
Greece	2	Switzerland	1
Italy	3	USA	1

Note that this distribution may not be accurate since some authors from China are working and submitting paper from Japan (e.g. Wang et al., 2005). There are also papers that are results of international collaboration such that two countries are involved, including Malvick et al. (2005) and Bhattari et al. (2005). In total, there are 5 papers submitted by two different countries (Bhattarai et al., 2005; Malvick et al., 2005; Farooq et al., 2005; Nadim et al., 2005; Orense et al., 2005). But, in the counting in Table 2, we refer to the first author only. There is also paper from Canada working on debris flows in Hong Kong and Nepal (Law & Paudel, 2005). Therefore, more international collaborations may be expected in the future.

It should be mentioned here that a new international organization focused on landslides was recently established at the 2002 Kyoto International Symposium on "Landslide Risk Mitigation and Protection of Cultural and Natural Heritage." It is called International Consortium on Landslides (ICL) comprising experts from international, national, scientific, governmental, nongovernmental, and academic organizations. There are currently 49 members and an official journal called *Landslides* published by Springer.

Table 3. Number institutes involved in each paper

Number of institutes	Paper No.
1	16
2	16
3	2
4	1

In terms of institutional collaborations, Table 3 compiles the number of collaborating institutes, companies or universities for each paper. Note that different departments or sections within the same institute count only 1. There are roughly half of the submitted papers are resulted of collaborations between at least two institutions. Due to complexity of the landslide problems and the interests among different stakeholders, the trend is that there has been more collaborations between companies and universities and among different universities.

2 CLASSIFICATION OF PAPERS UNDER DIFFERENT ASPECTS

To help readers to search for information from this Section 4a, different aspects of these papers are grouped in a tabular form under different aspects. More specifically, a breif summary of all 35 papers is given in Table 4. The columns are under aspects of field, experimental and theoretical, causes of landslides, facilities being affected, and the adopted remediations, together with a brief remark of each papers. For the sake of brevity and to save space, a paper number is assigned to each reference (i.e. P1, ...Pi, ... P35) as shown in Reference Section according to alphabetical order. The notes below Table 4 depicts the abbreviations and symbols used in Table 4. It must be noted that the classification used in Table 4 is by no means unique and other grouping technique is possible. In addition, the grouping is done according to my understanding of the papers and they may not be very accurate.

2.1 *Field studies*

In 19 out of these 35 papers (see Table 4), some aspects of field studies and geological studies have been included. Field studies may include the following: a geological description of the studied areas and slopes, lithology, geomorphology, ground water condition, perched ground water table, degree of saturated versus seasons, permeability of soils, historical rainfall records prior to each landslide, soil types, the engineering background of the sites, borehole data, and ground profile (that may include the mechanical properties of geomaterials underneath the ground surface). The apparatus for the field explorations include hand augers and boring machines.

In addition, a major component of the field tests may include monitoring of the slope and slope-related geo-structures (such as retaining wall, socket walls, anchors, soil nails, anchors and geosynthetics). The monitoring devices include penetrometers, geodetic survey markers, electrical resistance tomography devices, GPS satellites, piezometers, extensometers, inclinometers, tiltmeters, and earth pressure cells. These monitoring devices are mainly deployed for measuring slope displacement, velocity, piezometric levels, degree of saturation and stress field.

Among the 19 field-study-papers, there are 11 studies include field monitoring (see Table 4). Clearly, field monitoring has been a widely adopted and is a recognized technique for landslide studies. Numerical as well as theoretical models are simply nice mathematical pieces without the verification from field monitoring data.

A number of studies deserve to be particularly mentioned here. Tommasi et al. (2005) analyzed and presented 20 year data of piezometers and probe inclinometers and gave a strong relation between slope movement and piezometric data for overconsolidated clayey slopes, provided that a properly-selected-prolonged-delay required for water seepage is allowed for. Similar field monitoring for slopes composing other types of soils of permeability of different order and for different geological formations is needed. The study by Thielen et al. (2005) on ERT (or electrical resistance tomography) incorporated with geotechical and geological methods is a good way to have 3-D data and information on the degree of saturation of suction slopes and its evolution with time during rain infiltration.

2.2 *Laboratories studies*

Among 35 papers, 22 of them consists of laboratory studies of some kinds (e.g. Table 4). Among the more standard ones are water content, specific gravity of solid particles, void ratio, density, degree of saturation, particle size distribution, fine contents, liquid and plastic limits (Atterberg lmits), plasticity index, direct shear box test, ring shear tests, triaxial tests, unconfined compression, torsion hollow cylinder tests, and oedometer tests (compressibility and swelling indices).

In addition to these standard testing, there are many experimental studies devoted to more specialized laboratory tests, such as 1-g shaking table tests on water film phenomenon (e.g. Ishizawa et al., 2005; Kabasawa & Kokusho, 2005; Malvick et al., 2005), centrifuge test (Malvick et al., 2005), specialized simple shear test to eliminate constrained boundary conditions (Shigemura & Tokue, 2005), big ring shear test for in-situ soil samples containing roots of vegetation (Cazzuffi & Crippa, 2005), big shear box for pullout of soil nails (Yin et al., 2005), CSD (or constant shear stress drained test) for sandy soil (Farooq et al., 2005), wetting-drying-freezing-thawing cycle tests for clay degradation (Gullà et al., 2005), PIV (or particle image velocimetry) test for investigating the dynamics of subaqueous sediment gravity flows (Miyamoto et al., 2005), physical model test for slope under various seepage conditions (Orense et al., 2005), and dynamic properties tests for soil nails (Salloum et al., 2005).

There are also studies mentioning the use of mineralogy and SEM (scanning electronic microscope) in studying the microstructures of soils. This area is found important in Hong Kong as landslides are known to be conducive to slopes containing a clay seam of certain mineralogy and microstructures.

Therefore, it can be concluded that experimental study remain a popular and useful approach to examine the problems related to landslides.

2.3 *Theoretical slope analysis*

Theoretical studies can be roughly subdivided into numerical analysis, hazard analysis, and data analysis.

Numerical analyses can at least be subdivided into two types: the traditional limit analysis for determining the factor of safety, and more versatile numerical simulation method, such as finite element method (FEM) for modeling slope deformation under excitations. Table 4 shows that many of these numerical studies using FEM incorporating nonlinear time-dependent soil behaviors and inhomogeneous ground situations. Among these papers, a popular choice of computer software is PLAXIS. There are also specially written FEM for their proposed model for simulating progressive failure of slopes (Yashima et al., 2005). Nine out of 35 papers used FEM analysis for either back analysis or simulations, whilst only 2 used limit analysis. It is perhaps true that limit analysis is still widely used daily in engineering practice of slope design, but, clearly, many authors recognized that the traditional limit analysis cannot predict landslide as a function of time and cannot predict the progressive and creeping nature of landslides. Therefore, numerical methods appear to be important in investigating the progressive process of landslides.

At least 4 papers conducted back analysis (either using FEM or limit analysis), and another 3 used data analysis of either geological information or past events. Three papers concern with hazard analysis of landslides (Bhattarai et al., 2005; Gitirana Jr. & Fredlund, 2005; Nadim et al., 2005). Of particular interest is the analysis of Bhattarai et al. (2005) who attempted to incorporate the variation of shear strength with other geological factors using GIS (Geographic Information System). However, the assertion that shear strength is a constant value for the same geological formation is arguable because the degree of weathering may play a very important role in the shear strength. Therefore, such approach must be carefully examined before adopting it to other regions.

Among all these analyses, it was a little surprise that only two papers deal with debris flow. This may due to the fact that debris flow deals with fluid more than solids and, thus, is a highly interdisciplinary topic. Researchers on debris flows can be from civil engineers, geologists, geophysicists, physicists, hydrologists, and applied mathematicians. There are also a separate international conference series (*International Conference on Debris Flows and Hazard Mitigation*) solely devoted to debris flows. The first, second, and third conferences have been held in San Francisco (USA), Taipei (China, Taiwan) and Davos (Switzerland). The details of the last conference can be referred to http://www.wsl.ch/hazards/3rdDFHM/welcome-en.ehtml. The next one will be held in Chengdu (China) in 2007.

Fig. 1 Panel discussion during the International Conference of Debris Flows and Hazard Mitigations at Davos in 2003

Researchers on debris flows are urged to attend the fourth international conference on debris flows and hazard mitigations at Chengdu, China.

In particular, Law & Paudel (2005) used DAN of Hungr of University of British Columbia (Canada) and FLO-2D of Dr. O'Brien of USA for simulating runout distance of debris flows. Back analysis was first conducted using past debris flow occurred in Hong Kong, calibrated against debris flow in Nepal and predicted runout for the massive debris flow events occurred on Lantau Island Hong Kong in 1993. Wang et al. (2005) considered numerical simulation by using model of Sassa for two debris flow events occurred in Japan, one triggered by earthquake and the other by rain.

Fig. 2. Rockfall problem in Sau Mau Ping (Hong Kong) on December 4, 1997.

A little disappointment to me is the lacking of research paper on rockfall problems. The only related work is the analytical solution devoted to the toppling of rock slope (Soriano et al., 2005). In fact, this is the only analytical analysis for this 4a Section. This is the only paper devotes solely to the instability of rock slopes, despite there are some papers on landslide in areas composing of both rocks and soils. Therefore, the current research works appears to slant to geological, experimental and numerical works, rather than analytical works; and slant to soil slopes, instead of rock slopes.

Figure 2 shows a case of rockfall occurred in Hong Kong on December 4, 1997. This particular rockfall is induced by blasting during the construction of a housing estate in Sau Mau Ping in Hong Kong. Rockfall is a major problem in many parts of the world and is an important in rock slope instability.

2.4 *Motivation of these works*

As expected, many of these studies are either directly motivated by rainfall-induced landslide and indirectly related rainfall. Table 4 shows at least 9 papers related to rainfall aspects of landslides. Another 6 papers are motivated by and targeted for earthquake-induced landslides. Of particular interest is the shaking table tests by Kabasawa & Kokusho (2005) on sandy soil slope containing a silt seam. It was shown by shaking table test that a thin layer of water is accumulated under the highly impermeable silt seam. The water film is resulted from the drained excess pore water pressure from the liquefied soil after subject to earthquake shaking. This phenomenon may be of importance to landslides in seismic regions. Further studies is needed.

There are also some studies focus on landslides induced by human activities, such as coal mining, construction of tunnels, buildings, and highway.

2.5 *Facilities affected by landslides and remediation*

Table 4 shows that 5 papers concern with landslides next to highway, 3 to railways, 2 to tunnels and 1 to hydropower plant. This compilation is clearly incomplete in the sense that affected facilities may not be mentioned explicitly in these papers. In mainland China, a lot of landslide problems are related to the construction of dams and hydropower plants (including the three gorges dam shown in Fig. 3), but unfortunately there is no representative papers being submitted to this conference.

Fig. 3. Illustration of three gorges dam and associated slope problems.

There are some papers devoted solely to the problems and effectiveness of special remediation technique of landslides. Among these papers, Salloum et al. (2005) and Yin et al. (2005) devoted their experimental effort on the problems related to soil nails. Dimitrievski et al. (2005) focuses on the use of a particular type of geosynthetics, called Enkadrain. Cazzuffi & Crippa (2005) developed ring shear tests on the effect of roots of vegetation in strengthening the shear strength of soils. However, the size, distribution, and spacing of the root contents in the in-situ soil samples are not given. The effectiveness of socket walls in

Table 4. Classification of 35 papers into different aspects.

Paper No.	Field studies	Lab.	Analysis	Causes	Facilities	Remediation	Remarks
P1	-	-	FEM/LA	-	Hydropower	-	Case study in Nepal
P2	Geological	√	-	Construction	-	retaining wall	Case study in Kabylie
P3	Geological	√	HA	Earthquake	Highway	-	GIS plus shear strength
P4	Geol./Mon.	-	-	-	Highway	Socket wall	Monitoring of socket wall
P5	Geol./Mon.	-	BA	Excavation		anchor	Case study in Greece
P6	Geological	√	-	-		vegetation	Effect of vegetation
P7	Geological	√	FEM	-	Railway	-	Progressive failure
P8	-	√	-	Earthquake	Tunnel	-	Liquefaction
P9	Geol./Mon.	-	FEM	Mining		geosynthetics	Use of geosynthetics
P10	-	√	-	Rain		-	CSD tests
P11	-	-	HA	-	Railway	-	Hazard analysis
P12	-	√	-	-		-	Degradation of strength
P13	-	√	EA	Earthquake		-	Shaking table tests
P14	-	√	EA	Earthquake		-	Shaking table tests
P15	Geological	-	DA	Rain	Highway	-	Data analysis for Brazil
P16	-	-	FLO2D	Rain		-	Runout of debris flow
P17	-	√	-	Earthquake		-	Shaking table/centrifuge
P18	Geol./Mon.	-	DA	Rain		-	Warning system
P19		√	-	-		-	Subaqueous sediment flow
P20	Geological	-	DA/HA	-		-	Global landslide hazard
P21	-	√	-	Rain		-	Model tests for slope
P22	Geol./Mon.	√	FEM	-		anchor	Case of Reberine landslide
P23	Geol./Mon.	√	FEM	-	Railway	pile	Monitoring of piled slope
P24	-	√	FEM	-		Soil nail	Soil nail dynamic properties
P25	-	√	-	-		-	Laboratory simple shear tests
P26	-	-	Analytical	-		anchor	Solution of toppling
P27	Geol./Mon.	-	-	Rain		drain	Slide on buried pipelines
P28	-	√	FEM	-		-	Long-term stability
P29	Geological	√	-	Rain		drain	ERT tomography
P30	Geol./Mon.	-	-	Rain		-	20 years monitoring
P31	Geol./Mon.	√	BA	Human Act.	Highway	-	Creeping of reactivated slide
P32	Geol./Mon.	-	FEM	Human Act.	Highway	-	2 case studies of clay slopes
P33	Geol./Mon.	√	BA	Earthquake		-	Fluidization of flowslide
P34	Geological	√	FEM/BA	Human Act.	Tunnel	retaining wall	Creeping failure near tunnel
P35	-	√	-	Rain		Soil nail	Laboratory test for soil nails

Notes:
1. Under “Field studies”, Geol./Mon. = Geological studies and field monitoring.
2. Under “Analysis”, FEM=Finite Element Method, HA=Hazard Analysis, BA=Back Analysis, EA = Energy Analysis, DA=Data Analysis, LA=Limit Analysis, and FLO2D is a computer software for simulating debris flow.
3. The Paper number P1,…, P35 are defined in the References Section.

controlling landslides is considered by Brandl & Blovsky (2005). As shown in Table 4, other remediation works include the use of anchors, piles, retaining walls, and drains.

3 CONCLUSIONS AND KEY ISSUES

In this General Report, we have tried to summary the topics that have been covered in the 35 papers submitted to Section 4a on “Slope stability and landslides”. Table 4 attempts to provide the authors with a complete picture of these landslide studies and different aspects of these studies, together with their motivations and corresponding remediation works. The remark in Table 4 also provides a quick look on the issue that each paper tries to address.

In general, it was found that geological and field studies are of fundamental importance to understand the landslide problems. The study by Thielen et al. (2005) on ERT (or electrical resistance tomography) incorporated with geotechical and geological methods is a good way to have 3-D data and information on the degree of saturation of suction slopes and its evolution with time. Of particular interest is the analysis of Bhattarai et al. (2005) who attempted to incorporate the variation of shear strength with other geological factors using GIS (Geographic Information System) for estimating landslide hazard.

Experimental works conducted in laboratory also of great importance. There are good signs on specialized experimental works on shaking table tests (Ishizawa et al., 2005; Kabasawa & Kokusho, 2005; Malvick et al., 2005), centrifuge (Malvick et al., 2005), physical model test (Orense et al., 2005), and specially designed simple shear test (Shigemura & Tokue, 2005), big ring shear test for insitu soils containing roots of vegetation (Cazzuffi & Crippa, 2005), big shear box for pullout of soil nails (Yin et al., 2005), CSD (or constant shear stress drained test) for sandy soil (Farooq et al., 2005), wetting-drying-freezing-thawing cycle tests for clay degradation (Gullà et al., 2005), PIV (or particle image velocimetry) test for investigating the dynamics of subaqueous sediment gravity flows (Miyamoto et al., 2005), and dynamic properties tests for soil nails (Salloum et al., 2005).

Numerical analysis using finite element method is replacing limit analysis as the norm of theoretical studies, although limit analysis remains very robust in daily engineering applications. Among other analysis techniques, data analysis, back analysis, energy analysis for dynamic case, and hazard analysis have been employed by different authors.

Landslide and slope instability have been found triggered by earthquake, rain and human constructions and activities. Buildings, tunnels, railway and highway are all at risk. Remediation techniques for improving stability discussed in these 35 papers include retaining walls, socket walls, anchors, vegetation, geosynthetics, piles, soil nails, and drains.

Although it is not explicitly tabulated in Table 4, there are at least 8 papers devote to the problem of creeping movement of slopes. There are also papers devote entirely to the development of models for predicting creeping (e.g. Ter-Martirosian & Proshin, 2005; Yashima et al., 2005).

Another subtle aspect that was not mentioned explicitly in Table 4 is that a number of papers raise the issues of suction effect on unsaturated soils, and its diminishing with the water filtration from rain (e.g. Thielen et al., 2005). This appears to be an important problem yet to be solved completely. More specifically, in addition to the fact that shear strength drops due to the decrease of suction or the increase of pore water pressure, there is a problem of softening of soil due to the increase of water content alone. This particular aspect needs to be considered more carefully in future studies.

The conclusion of the current research trend summarized in this report can only reflect the selection of problems made by the authors of these 35 studies, and it does not necessarily closely reflect the current trends in the research of slope instability and landslides. For the latter one, one should do a better literature survey on research works on other journal and conference publications. In the last few years, landslides have been of great interests to researchers in the world. According to the Science Citation Index (SCI) database maintained by ISI, the numbers of SCI papers related to the keyword of "landslides" are 79, 106, 125, 129, 152, 200, and 211 for 1998, 1999, 2000, 2001, 2002, 2003, and 2004 respectively. The increasing trend remains even though landslide is an "old" discipline that had been studied for hundreds of years.

There are a number of international conferences on landslides and slope stability being organized, including:

1. The first North American Landslide Conference (to be held in Vail, USA).
2. The Eleventh International Conference and Field Trip on Landslides (to be held in China).
3. The Fourth International Conference on Debris Flows and Hazard Mitigation (to be held in China).

An attempt to provide a more comprehensive review on the problem is made by Chau (2005), which is a "State-of-the-Art report" on landslides submitted to this conference. But, again completeness is not expected in such a short coverage. In retrospective, I am most grateful to Professor Oka for encouraging me to take parts in the 16th ICSMGE.

ACKNOWLEDGEMENTS

All previous works on landslides by KTC was fully supported by the Hong Kong Polytechnic University through ASD Project A226 and Infra-Faculty Project PE79 of the Faculty of Construction and Land Use, and by Research Grants Council of the Hong Kong Special Administrative Government (Project No. PolyU 5079/97E). The continuous support from GEO of the Hong Kong Government is appreciated. This report was completed when KTC was visiting University of Calgary (UC) in the summer of 2005 (August), the financial support from the host, Professor Ron C.K. Wong of UC, is greatly appreciated.

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