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Strategic Approaches for Management of Risk in Geomechanics

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ABSTRACT: This paper outlines the challenges facing geomechanics and advocates some strategies for dealing with these challenges. Advancement of geomechanics and its application in the past may be seen in a historical context as serving the needs of society such as the development of infrastructure and natural resources. The needs of society are changing rapidly due to population growth, increasing urbanisation and globalisation. Climate change poses specially challenges, the impacts increasing with time. Therefore, development of new strategies is essential. For example, greater attention should be given to the development of interdisciplinary approaches. It is vitally important that systematic methods be developed for assessment of geohazards, their magnitude, spatial distribution, frequency and impact. Thus probabilistic approaches should complement traditional methods of analysis, however sophisticated. Comprehensive analyses of uncertainties are important. Modern tools such as GIS should be used more widely and developed further. Probabilistic framework is essential for risk assessment and management. Preventive risk management solutions should be adopted more widely. There is a vast scope for the development of observational approaches beyond their traditional role. Two case studies have been included to demonstrate the value of some evolving methods and strategies

1 Introduction

1.1 Advancing traditional geomechanics

Historically geomechanics has been concerned with understanding the engineering behaviour of soil and rock masses as well with assessing and assuring the stability and reliability of foundations, earth structures and slopes. From the beginning of the disciplines of soil mechanics and rock mechanics, there has been increasing recognition and acceptance that consideration in analysis and design of both geological and geotechnical aspects are necessary for the success of geotechnical engineering projects. Almost 50 years back, Casagrande (1965) highlighted the role of 'calculated risk' in earthwork and foundation engineering. However, several decades would pass before the broad concepts of risk assessment in geomechanics began to be discussed. Indeed it is only in the last decade that attention was drawn to the advantages of quantitative risk assessment (QRA). Indeed the enormous significance of geohazards was not appreciated and dealing with their impact received very little attention during the development of geomechanics and of geotechnical engineering as a profession

Deterministic concepts of analysis have dominated theoretical and analytical developments as well as the practice of geotechnical engineering. Only in the last few decades has the importance of probabilistic concepts been recognized. Systematic analysis of uncertainties is an important step in probabilistic analysis. Geotechnical engineers face important new challenges and, therefore, strategic thinking should include considerations of hazard and risk with particular reference to phenomena or events (natural or human-induced) which are likely to have adverse consequences on geotechnical projects. In this regard, the desirability of adopting interdisciplinary approaches has been advocated from time to time. Yet, there is often insufficient emphasis on strategic thinking and on team-building. To meet future challenges advancement is required both in the conceptual and application areas of geomechanics. For example, Peck (1969) proposed the 'observational method' in applied soil mechanics and it proved to be a valuable tool for improving geotechnical design in the face of uncertainty. Yet development of more comprehensive observational approaches did not take place for many decades. Indeed, it is only very recently that strategies have been developed for risk management based on observation approaches which focus on real-time monitoring (Flentje and Chowdhury, 2006, 2007). To further advance the science and practice of geomechanics, the scope of observational approaches must continue to be developed well beyond real-time monitoring for risk management. For example, major issues such as phenomena associated with climate change require comprehensive observational approaches in order to advance knowledge, obtain detailed data, and

develop strategies for dealing with the impacts (McInnes et al,2007)

1.2 Importance of probabilistic approaches complementing deterministic studies

In recent decades, the important role of statistics and probability in geomechanics studies and projects has come into sharp focus. The importance and ubiquity of uncertainty in geomechanics is widely recognized and, therefore, it is important to understand and acknowledge uncertainties in geo-processes and also identify and analyse different types of geotechnical uncertainty, both spatial and temporal. These include natural variability of geotechnical parameters and systematic uncertainties including statistical uncertainty and bias. Having adopted appropriate geotechnical models and methods of analysis for a project, the associated uncertainties must be identified and quantified. The overall uncertainty associated with the performance functions can then be evaluated. Consequently, deterministic performance indicators such as 'factor of safety' can be complemented by more meaningful indicators such as 'reliability index'. Moreover probabilities of failure (or probabilities of inadequate performance) can be estimated for individual potential failure modes. More importantly, a probabilistic framework enables evaluation of spatial and temporal hazard and the associated risk based on the vulnerability of structures and systems. Probabilistic framework also enables new questions to be framed and scenarios formulated that could not be conceived within a deterministic framework. It is important to understand the temporal aspects of probability and risk. Thus it is customary and convenient to work in terms of annual failure probability of an earth structure or slope and annual risk of loss of life for a project associated with a hazard.

Some applications of using a probabilistic framework for projects have been mentioned by Flentje(1998), Aleotti and Chowdhury (1999), Chowdhury et al (2002), Chowdhury and Flentje (2003), Ko et al (2004, 2005) and Wilson et al(2005).

1.3 Scope of the paper

A brief reference is key factors which have influenced the historical development of geomechanics. Four examples of catastrophic geotechnical failures and one example of a new industry are given to demonstrate how these events stimulated further research in geomechanics and thus facilitated progress in the profession. The paper then outlines the need for a broad perspective in order to tackle major new challenges which are with us now and which will intensify in the future as a consequence of external factors including increasing natural hazards and climate change. Importance of multi-disciplinary approaches and the impact of geo-hazards is highlighted. The paper then provides some details of two case studies which highlight, respectively, (1) knowledge-based assessment of regional landslide susceptibility and hazard assessment within a GIS framework (2) risk management along a section of road (about one km long) adjoining steep coastal cliffs which posed very high risk for human safety in spite of significant expenditures on remedial measures implemented from time to time. The highlight of the final risk management strategy was a bridge which has now been constructed.

The first case study concerns an important coastal region and urban area for which long-term planning and sustainable physical development requires hazard assessments using the best available knowledge, methods and techniques. Maps of landslide susceptibility and hazard will form the basis for detailed site-specific assessments of risk and for decision making.

The second case study involved a process which included such a detailed assessment. This particular short section of road has been subject to frequent slides and rock falls over several decades. Final options for risk management were developed after quantitative assessments of risk in different zones were made with and without remedial/risk management appropriate to each zone. For each of the final alternatives these risk components were integrated to evaluate total risk. While the case studies are concerned with assessment of landslide susceptibility and hazard as well as risk management, the strategies and techniques featured have a much wider application in modern geomechanics.

2 Historical development of geomechanics with some examples

The emphasis in geotechnical engineering has always been on achieving appropriate solutions to specific problems and projects using a number of steps such as site investigation, soil and rock testing, modelling, empirical methods, mathematical analysis, field measurements, observation (monitoring) and design. Depending on the type and importance of the project and the availability of resources, some or all of these elements may be considered essential.

The historical development of all branches of engineering during the twentieth century has been shaped by the changing needs of society. More broadly the development of engineering has been influenced by political, economic and social transformations in the world. Major influencing factors include the increase in world population, growth in urbanization, issues of war and peace, increasing environmental problems and dynamic emerging forces of developing technology.

Progress in individual areas of geotechnical engineering has been spurred by catastrophic geotechnical failures as well as other major events. For geotechnical engineering developments in the second half of the twentieth century this can be supported by numerous examples. Provided below are just four examples of catastrophic events and then one contrasting example showing the influence of a major new industry.

2.1 Vajont Slide

The catastrophic failure of Vajont landslide in Italy in 1963 highlighted the inadequacy of our knowledge concerning progressive action and progressive failure within a sliding mass of soil and rock and the unpredictable dynamics of such exceptional landslides. Many lessons have been learnt from that disaster including the collateral consequences of a large landslide mass falling into a reservoir. Some important questions raised by that landslide have still not been answered fully. However, the Vajont disaster has led to increased research in rock and soil mechanics and to many further developments in the profession. More importantly, the disaster is an excellent example of a system failure which proved to be extremely costly and irreversible although the main component, the dam itself, survived intact. For any dam-reservoir system to be successful the performance and interaction of a number of geotechnical and structural elements must be analysed and effective risk assessment and management must be carried out.

2.2 Seismic failure of an Earth Dam

The 1971 failure of the lower San Fernando Dam in California, USA exposed our lack of knowledge concerning seismic shaking of earth dams and the inadequacy of pseudo-static analysis for the seismic safety of dams and slopes. Newmark (1965) had already proposed the sliding block method of seismic analysis. The failure of the lower San Fernando dam acted as a catalyst for the application of Newmark's approach in geotechnical practice. Following the failure, there was also greater research interest in mechanisms of seismic failure of earth structures and especially in earthquake-induced liquefaction.

2.3 Earth Dam Failure Due to Inadequate Design for Internal Erosion

The 1976 failure of Teton Dam in Idaho, USA came as a great shock not only to those involved in its design and construction but also to the profession as a whole. Here was a seemingly routine project, located in the most technologically advanced country, which failed because of important technical mistakes and not because of any extreme natural event or emergency. Post-failure studies led to the recognition of erodible materials in the core of the dam and its foundation. The initiation of internal erosion was believed to be due to cracking associated with hydraulic fracturing of the materials deep in the core trench. This insight was gained from stress-deformation analyses carried out by the finite-element method (FEM). Consequently, this tragedy led to greater emphasis in the use of advanced numerical methods and their further development. These comprehensive enquiries and reviews highlighted deficiencies in analysis, design and construction and led to swift actions with regard to dam safety evaluation. Many significant dams throughout the United States were assessed, over the next decade, from analytical, design and observational perspectives.

2.4 Earthquake effects in Soft Soils

The Mexico city earthquake of 1985 was a major disaster for the economy of the country as a consequence of the extensive damage to buildings and infrastructure. Mexico city is located on soft clay sediments, the presence of which amplified the earthquake ground motion to a significant extent leading to many collapsed and tilted structures. The disaster again alerted geotechnical engineers to the need for further research including careful field observation, experimental studies, modelling of site response and numerical analysis of soil-soil-structure interaction under seismic conditions.

2.5 Offshore Geotechnics

In contrast to geotechnical earthquake engineering, offshore geotechnics was spurred by oil exploration and, more specifically, by the construction of offshore oil drilling platforms. Of course previous research provided the initial impetus and continuity. For example, as a part of geotechnical earthquake engineering, research had already been carried out concerning the behaviour of soils under dynamic or repetitive loading. The insights gained from that research were useful for the analysis, design and construction of offshore foundations. Moreover, the development and application of techniques for centrifuge modelling and testing received a boost. Increasingly more sophisticated numerical modelling was also developed in order to simulate the behaviour of offshore foundations. These numerical methods complemented centrifuge modelling techniques.

3 Dealing With New Challenges in Geotechnical Engineering

3.1 Significant long-term issues

The long-term future of geotechnical engineering will be influenced by many factors. In order to discuss where the profession is going, it is essential to consider first where it is now and how it got to this point. It would also be useful to consider the unique challenges that are facing the world today, the truly global issues such as climate, sea level rise, rapid population growth and depleting resources (water and energy). Due to space limitations, even a brief review of such issues is outside the scope of this paper.

However, it is important to highlight increasing urbanization, and consequently the increasingly adverse consequences of major natural events. There is a huge gap between the material conditions and development capacities of rich and poor societies. In some cases this gap is widening rather than narrowing. Consequently, the adverse impact of geotechnical failures and catastrophic natural events is greater in the poorer societies. Moreover, there is a huge variability in the living conditions of people within many societies or countries and this is reflected dramatically in poor quality of infrastructure in some regions. At the extreme end of the spectrum, one must bear in mind the absence of essential infrastructure such as roads, railways lines and clean piped water in many regions of the poorer societies. Lack of education in the general population and the lack of adequate preparation and skills amongst the minority who are educated highlight the increasing need for training for upgrading of skills and knowledge.

It is extremely difficult to predict in any depth or detail the events which will shape the profession in the long-term or the major new research areas that might need to be developed in this 21st century. However, it is clear that bold new strategies and continuing research will provide us with the ability to solve the problems of the future.

3.2 Importance of multi-disciplinary approaches

Many areas of geotechnical engineering require an integrated and multi-disciplinary approach. Geotechnical engineering can no longer be regarded merely as a subset of civil engineering and/or mining engineering. Such a narrow perspective will stifle progress and innovation. Links between the geosciences and geotechnical engineering must be strengthened. For example, the use of geographical information systems (GIS) has served very well the need for organizing, validating, displaying and interpreting and managing surface and subsurface data and yet the full potential of such tools has yet to be realized by geotechnical engineers. Cooperation with geoscientists is also required for the development of specific areas of study and application such as geotechnical earthquake engineering, coastal engineering and marine geomechanics.

One must look at the big picture for understanding past developments and present practices and for developing valid perspectives of the future. This should not mean simply following well-worn paths and considering progress only in terms of improvements, adjustments and modifications of the current elements of what is regarded as good practice.

3.3 Geo-hazards and their Impact

From a strategic perspective, the impact on geotechnical facilities and projects, of natural events such as rainstorms, floods, earthquakes and tsunamis must be considered. This requires consideration, in each case of the magnitude, temporal frequency and spatial distribution. Often rare and infrequent events have large magnitudes and wide spatial distribution. The strategies for dealing with geo-hazards must be tailored to the characteristics of their occurrence as well as their potential impacts in relation to the elements at risk and the vulnerability of those elements. Traditional geotechnical approaches may be successful for dealing with frequent events of low to medium magnitude. On the other hand, more innovative methods and bold strategies may be needed for dealing with potentially catastrophic events which are infrequent or rare.

Moreover, it is important to note that, considered globally, natural events of large magnitude may not be infrequent or rare. Even in the last few years, some exceptionally catastrophic events have occurred leading to hundreds of millions of dollars in economic damage, the loss of thousands of lives, the disruption of whole communities, significant environmental damage and an expectation of adverse long-term effects in each instance. Examples include the Sumatran earthquake and tsunami (26 December, 2004), the Pakistan earthquake (8 October, 2005) and hurricane Katrina (23-31 August, 2005). The catastrophic impact of such events is associated with the vulnerability of the structures and systems serving the communities and the environment. Inadequate geotechnical performance can often be identified as one of the weak links in the systems that fail. More importantly, one can identify the inadequacy of strategic planning by geotechnical engineers and others.

There are thus many lessons to be learnt concerning future progress in geotechnical engineering. Aspects highlighted in the three events mentioned as examples above, include the planning and the construction of roads

and infrastructure, the design of embankments and dykes and the assessment of hazard and the management of risk

Putting all this together, it is clear that further developments in geomechanics must facilitate fuller understanding and more reliable assessment of failure susceptibility and hazard associated with constructed geotechnical and structural facilities, natural slopes and on-going geotechnical projects. As a consequence, effective strategies for risk management can be developed. These should include preventive risk management strategies as well as real-time or near real-time strategies risk. Damage control, restoration and risk management after the event is usually ineffective and may, in fact, be counterproductive in relation to future.

Adopting new paradigms may be desirable or even necessary. As an example of present and future challenges, let us consider key information related to natural hazards and the losses inflicted as a consequence of these hazards. Such data places the need for risk management strategies in sharp focus the number of people killed as a consequence of natural disasters during the 20th century, compiled from various sources by Bryant et al (2005) is shown in Table1. The second last column shows the date and country of the highest death toll event in each category. It is important to note that the poorer nations feature prominently in this data.

Table 1. Number of people killed, injured or displaced globally due to natural hazards during the 20th century (based upon WHO, 2002). Tsunami statistics updated to 26 December 2004. Before then, tsunami ranked eighth in terms of death in the 20th century. Modified from Bryant et al (2005).

Type of Hazard	Global deaths	Global deaths (%)	Global Injuries	Global Homeless	Largest death toll event and date	Death toll of largest event
Floods	6 851 740	66.01	1 033 572	123 009 662	China, July 1931	3 700 000
Earthquakes	1 816 119	17.50	1 147 676	8 953 296	Tangshan, China, July 1976	242 000
Tropical cyclones	1 147 877	11.06	906 311	34 272 470	Bangladesh, Nov 1970	300 000
Tsunami ¹	337 693	3.25	125 789	1 500 000	Indian Ocean, Dec 26 2004	228 432
Volcano	96 770	0.93	11 154	197 790	Martinique, May 1902	12 000
Landslides, avalanches, mud flows	60 501	0.53	8 071	3 759 329	Mount Huascarán, Peru, 1970	18 000
Extra-tropical storms	36 681	0.35	117 925	12 606 891	Northern Europe, Feb 1953	2 541
Heat wave	14 732	0.14	1 364	0.00	India, May 1998	3 000
Tornado	7 917	0.08	27 887	575 511	Bangladesh, Apr 1989	400.00
Cold wave	6 807	0.07	1 307	17 340	India, Dec 1982	800.00
Fires	2 503	0.02	1 658	140 776	USA, Oct 1918	1 000
Total	10 379 340	100.00	3 382 714	185 033 065		

¹ Data from National Geophysical Data Centre Tsunami Database (2005) and Intergovernmental Oceanographic Commission (2003). Also included in Chowdhury and Flentje (2007)

A recent study of landslide events worldwide (Petley et al, 2005) showed that the majority of fatalities associated with landslides occur in the less developed countries and also that there is a close correlation between global climate change and the number of fatalities from landslide events. Landslide fatality data for the period 1980-2000 is presented in Table 2. It is clear that the fatalities are much greater in the developing countries in absolute terms and also greater as a proportion of the population

4 Modern risk management strategies

Dealing with new challenges requires new strategies which must include comprehensive and reliable methods for dealing with uncertainty while using the power and capacity of conventional methods more fully. Here we consider geomechanics issues in an urban context with specific relevance to slope stability, landslide susceptibility, hazard and risk. Three aspects of relevant risk management strategies are considered as examples, namely, regional assessments using powerful tools such as GIS (Geographical Information Systems), a comprehensive real-time observational approach and preventive risk management.

New tools such as geographical information systems (GIS) enable the organization, analysis, synthesis and modeling of regional data concerning a large number of geotechnical, geological and geomorphological variables. Isolated, site-specific analyses concerned with isolated slopes and individual earth structures are no longer sufficient. A geological database and a landslide inventory of any region can be developed and used effectively with the power of GIS. Moreover, we can also apply proven geomechanics methods such those based on the limit equilibrium concept, however simplified, over vast areas. Taking advantage of statistical and probability concepts,

failure susceptibility maps can be prepared with a high level of confidence. With available information on influencing factors and the frequencies of natural events, hazard can be assessed and hazard maps prepared. With due attention to elements at risk and their vulnerability, assessment and management of risk over large regional areas can be facilitated on a rational basis. More importantly, every aspect of assessment can be updated when there is significant new data available concerning spatial or temporal variables or the uncertainty associate with them.

Table 2. Landslide fatality data for the period 1980 to 2000 for the main continental areas: after Petley et al (2005).

Continent	Deaths	Population density	Total population in millions	Deaths per million per year
N. America	62	16	307	0.01
Europe	535	30	795	0.03
Africa	612	26	860	0.03
S. Asia	2596	305	1300	0.1
E. & SE. Asia	5125	193	2205	0.11
Australasia	119	4	33	0.17
C. Asia	1958	9	80	1.17
S. America	57365	19.5	351	7.78
C. America	38250	64	174	10.47

¹ Data from National Geophysical Data Centre Tsunami Database (2005) and Intergovernmental Oceanographic Commission (2003). Also included in Chowdhury and Flentje (2007)

While instrumentation and monitoring is employed frequently on important projects of geotechnical engineering, observational approaches have often been used within the framework of flexible design strategies. With the power of modern communication technologies, web site development and GIS-based susceptibility and hazard assessments, observational approaches can be expanded to real-time monitoring, decision-making and risk management.

Within a probabilistic framework, hazard and risk associated with individual sites can be assessed. To assess the total regional hazard or risk, one can integrate the hazard or risk of individual sites within that region using the basic concepts of probability (Such integration would not be possible within a conventional deterministic framework. For example, one can not sum up the factors of safety at different locations along a section of road to come up with a sensible factor of safety over the whole stretch!)

Having assessed the total risk, it is important to compare that to acceptable or tolerable levels of risk based on relevant criteria. If calculated risk is considered unacceptable, risk mitigation strategies may be considered. These may include preventive risk management strategies as well as risk management linked with and consequent on the occurrence of specific failure events .The latter may be called 'after-the-event 'risk management strategies.

5 Case Study one – Knowledge based assessment of landslide Susceptibility and Hazard using GIS in Wollongong New South Wales, Australia

5.1 Study Area

The city of Wollongong is located on a narrow coastal plain approximately 70km south of Sydney in the state of New South Wales (NSW), Australia. The population of the Wollongong area is approximately 200,000 people. The plain is triangular in shape with a coastal length of 45km and is up to 17km wide in the south and extends to its apex in the north near the suburb of Thirroul. The coastal plain is bounded to the north, west and south by an erosional escarpment of Neogene Age ranging in height from 300 m up to 500 m.

Processes and mechanisms of slope failure are controlled in Wollongong by factors such as stratigraphy, geotechnical strength parameters, hydrogeology, geomorphology, slope inclination pore water pressure, rainfall and the actions of man. Prolonged and/or intense rainfall is typically the trigger for significant landsliding. The average annual rainfall for Wollongong varies from 1200mm on the coastal plain and up to 1600mm or more along the top of the escarpment. Among the landslide types are slides, flows and falls .The magnitude and frequency of landslides in each category varies over a wide range .Many slide category landslides have speeds ranging from very slow to extremely slow and yet, over the long-term, some of these have a great destructive potential. Risk management and long-term planning of urban development can be facilitated by regional studies of susceptibility, hazard and risk. Detailed geotechnical studies including conventional slope stability assessment

and probabilistic studies at individual sites are carried out as required. The following is concerned with a regional study featuring a modern quantitative assessment of landslide susceptibility and hazard.

5.2 Knowledge-based Data Mining

The landslide research team at the University of Wollongong have developed a GIS-based methodology for identifying and mapping zones of slide category landslide susceptibility. The process involves the use of known landslide areas as one half of the model training, the other half comprising randomly selected points from within the model area outside known landslide areas. The Data Mining analysis undertakes a process of pattern recognition of the training data and develops a rule set which defines the data. This process is automated by the DM software and is confined by several user defined parameters, such as the number of rules required and the number of occurrences required before a rule is generated. Each rule is assigned a numerical confidence value defined by the Laplace ratio. Rules which relate to the presence of a landslide are assigned positive confidence values and rules which indicate the non-presence of a landslide are assigned negative confidence values. The rule set is then re-applied within the GIS software using the ESRI Model Builder extension to produce the Susceptibility grid with floating decimal point values ranging from 1 to -1.

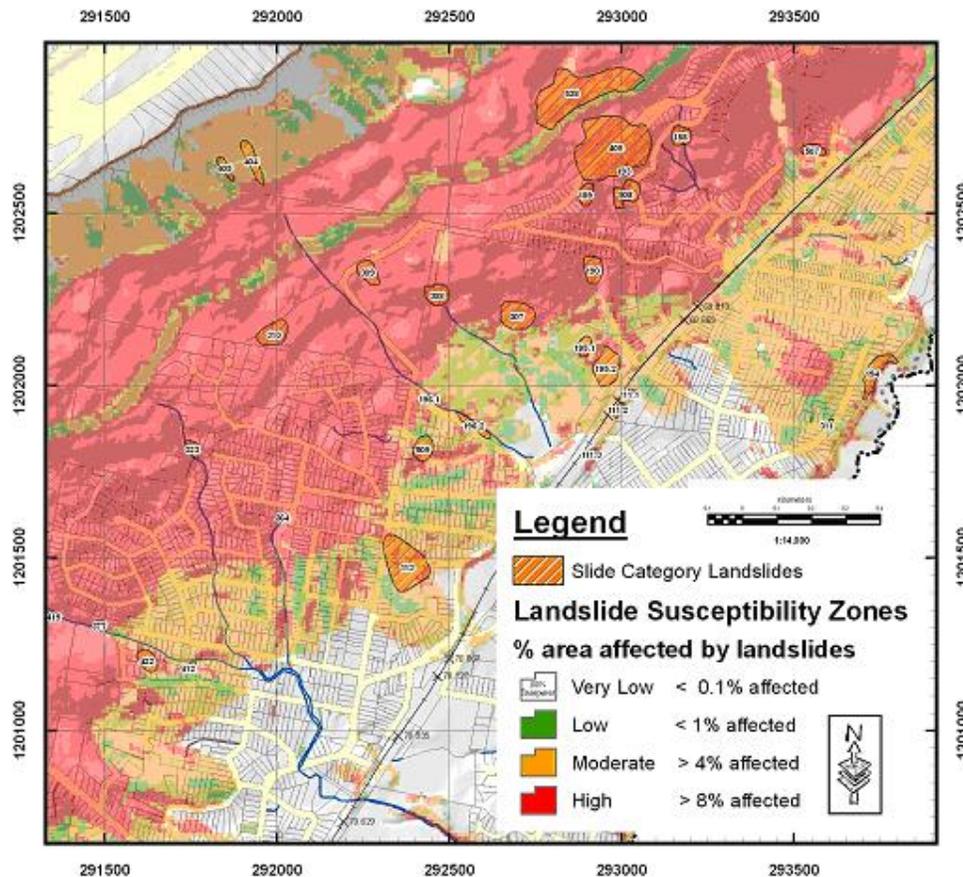


Figure 1. Landslide Susceptibility map of a part of Wollongong's northern suburbs – after Flentje and Chowdhury (2006). Also included in Flentje et al (2007b)

It is important to understand that the factors influencing landslide occurrence and recurrence such as geology, slope angle, geomorphology, drainage etc must be represented within the GIS format. In addition, the spatial distribution of existing landslides must also be available in the same format.

Susceptibility zones (Figure 1) have been classified as (a) high susceptibility with ~ 8% of this area subject to landslides and containing 57% of the known landslide population, (b) moderate susceptibility with 4% of this area subject to landslides (contains 35% of known landslides), (d) low susceptibility with 0.85% of area subject to landslides (contains 3.7% of known landslides), and (e) very low susceptibility with <0.1% of the area subject to landsliding and yet representing 71% of the study area. The high susceptibility zone identifies over 2,300 hectares of land, outside of known landslides, as being highly susceptible to landsliding. Furthermore, the model also identifies over 13,000 hectares as having a very low susceptibility to landsliding.

5.3 Landslide hazard assessment and zoning

The spatial frequency of landsliding has been determined for each Susceptibility Zone as summarised in Table 3 and Figure 2 and thereby giving each zone Hazard status. Here, the percentage of each zone affected by landslides has been normalised and divided by the number of years represented by the coverage of the Landslide Inventory. In this case, the Wollongong landslide Inventory covers a period of 126 years, 1880 to 2006. Other techniques of assessing annual likelihoods of landsliding (i.e. process rates) are being investigated.

Table 3. Summary of landslide zoning frequency and volume.

Hazard Description	Map Colour	% of Zone affected by Slides (S)	Zone area as % of Study Area	% of Total Slide Population in Hazard Zone	Landslide Annual Average Frequency (1950 - 2006)	Relative Susceptibility of Zone (S/Total) = Sr	Relative Annual Likelihood (Hazard) (Sr/T) where T = 126 years	Maximum Landslide Volume (m ³)	Average Landslide Volume (m ³)
Very Low		0.10	70.86	4.1	1.65E-02	7.36E-03	5.84E-05	36,300	3,500
Low		0.85	6.47	3.7	1.72E-02	6.46E-02	5.13E-04	4,700	1,450
Moderate		4.12	9.23	35.1	2.21E-02	3.12E-01	2.48E-03	45,000	5,700
High		8.12	13.44	57.1	2.47E-02	6.16E-01	4.89E-03	720,000	28,700

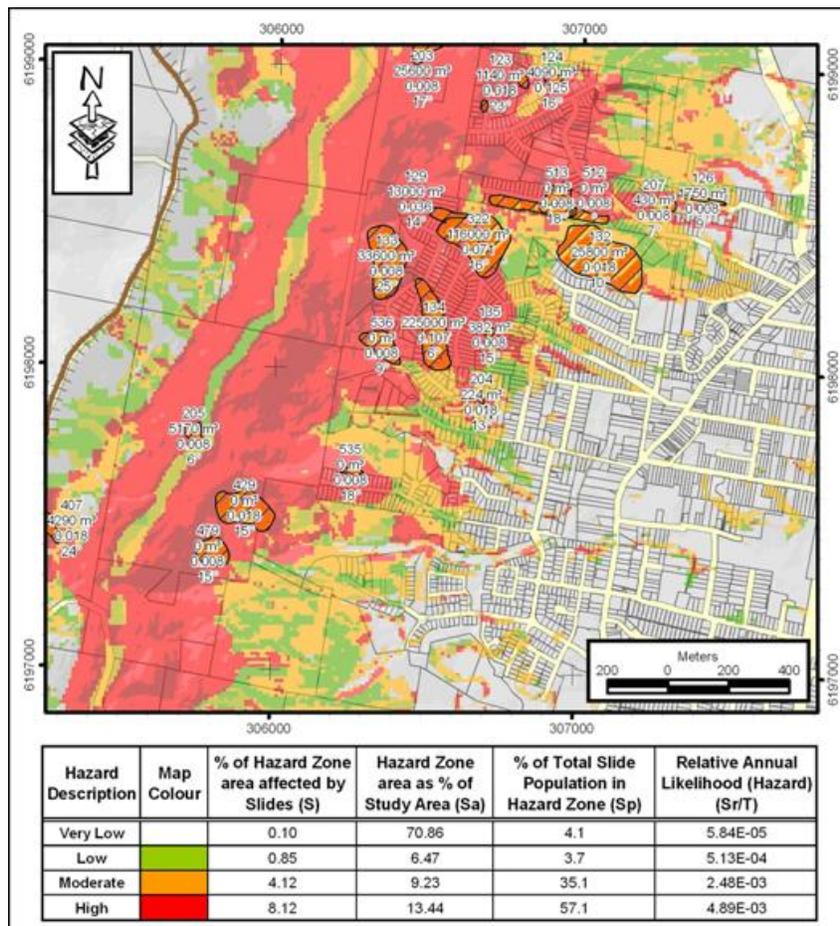


Figure 2. Segment of the Landslide Hazard Map. (after Flentje et al 2007b)

The landslide hazard zoning maps have been enhanced with additional detail regarding landslide volume, frequency and travel distance (Table 1 and Figure 3). This information appears as unique landslide site labels for each site and with text boxes appearing on the AO map sheet frames outlining the distributions and averages of these values for each of the individual hazard zones.

On both the landslide Susceptibility and landslide Hazard maps, each landslide site is identified and labelled with its own unique Site Reference Code. On the Hazard maps, the label for each landslide also includes its volume (m³) as the second label component. Landslide Frequency has been calculated from the total number of known recurrences at each landslide site as recorded in the Landslide Inventory. The specific landslide frequency for each landslide appears as the third label for each landslide.

The 'profile angle' appears as the fourth label for each landslide site. This profile angle has been determined by digitising a point mid way along the rear main scarp and at the toe and querying the elevation at each of these

6 Case study Two –Remediation and Preventive risk management along a coastal road

6.1 Introduction

This success story concerns a section of a coastal road along steep cliffs .The coastal road is the well known Lawrence Hargraves Drive (LHD). in Greater Wollongong area, NSW, Australia This particular section of road extends from Clifton in the south to Coalcliff in the north, a distance of 1350m, and is subject to landsliding and rockfalls especially during and after heavy rainstorms Before risk management was carried out, the landsliding and rockfalls had a significant potential for economic loss and for human injury and fatality in spite of extensive remediation at several locations over several decades. Several studies were carried out including geological and geotechnical investigations, stability studies, hazard identification and quantitative risk assessment (QRA). In the early stages several conventional stabilisation measures were again implemented in some zones of this difficult section of road. The final permanent solution included a bridge which bypasses locations and zones subject to landslides and rockfalls where conventional remedial measures were unlikely to be successful in reducing risk to safe levels over the long-term. This bridge has two contiguous sections ,a 455m long balanced cantilever and a 210 m long incrementally launched bridge, a total length of 665m.Following detailed assessment of hazard and risk in individual zones ,a number of alternative solutions for risk management were compared as to their benefits and costs. The bridge solution for the 665m length combined with other measures over the rest of the remaining 695m length was finally approved and implemented. Construction was completed in December 2005 and the bridge named the 'Seacliff Bridge'. A photograph of the section of road before bridge construction is shown on the right of Figure 3 and another photograph, after construction of the bridge is shown on the left of the same figure. A cross section of the coastal escarpment at LHD is shown in Figure 4. This shows the different geological units, alternating strong and weak layers (sandstone and claystone respectively), such sequence facilitating rockfalls and landsliding along the escarpment. The estimated slope retreat rates are also shown on the left of the figure. Two well-developed, vertical to sub-vertical joint sets are prominent structural features in this area and the stratigraphy is affected by a series of normal faults.

Risk assessment considerations and details of this project have been discussed by Wilson et al (2005 while Moon et al (2005) have considered this project as an example for the development and use of size frequency models and assessment of coastal retreat rates.

6.2 Hazard identification and quantitative risk assessment process (QRA)

The section of road consists of two bays separating three headlands On this basis five geotechnical domains were defined,GD1 (Southern headland),GD2(Southern amphitheatre,GD3(Middle headland),GD4(Northern amphitheatre) and GD5(Northern headland).The two bridges bypass GD2 and GD3 and most of GD1 avoiding hazards due to debris flows ,rock falls and embankment sliding.

For the risk assessment process it is necessary to estimate the likelihood, the elements at risk and the consequences. For the landslides/rockfalls/debris flows, size – frequency relationships were first developed based on available data and judgement (total volume may be validated in relation to slope retreat rates modelled separately). The assessment of landslide likelihood also involved assessment of percentage of landslides reaching the road. The elements at risk include mainly cars and people outside cars who might be on the road. Based of available data, a traffic volume of 4000 vehicles per day was considered. Several scenarios for the collision between landslides at elements at risk were considered. The probability of a landslide of a certain size hitting car and of car hitting a landside was based on vehicle traffic per day and vehicle speeds. Vulnerability of persons was based on crash statistics, experience and judgement. Thus for a particular hazard, location and slope unit risk as annual probability of loss of life was calculated using a spread sheet approach.

The risk for each geotechnical domain(GD1,GD2,GD3,GD4,GD5) and total risk was then calculated for four cases ,Case A (the site as before 2002 without further remedial measures), case B (in the period from late 2002 to late 2003 after some remedial measures such as rock fall fencing and catch drains), case C (considering the



Figure 3. The Sea Cliff Bridge constructed as risk management solution to ongoing rockfalls, debris flows and landslides. b The original slopes with problematic Lawrence Hargrave Drive near base of cliffs between Coalcliff and Clifton.

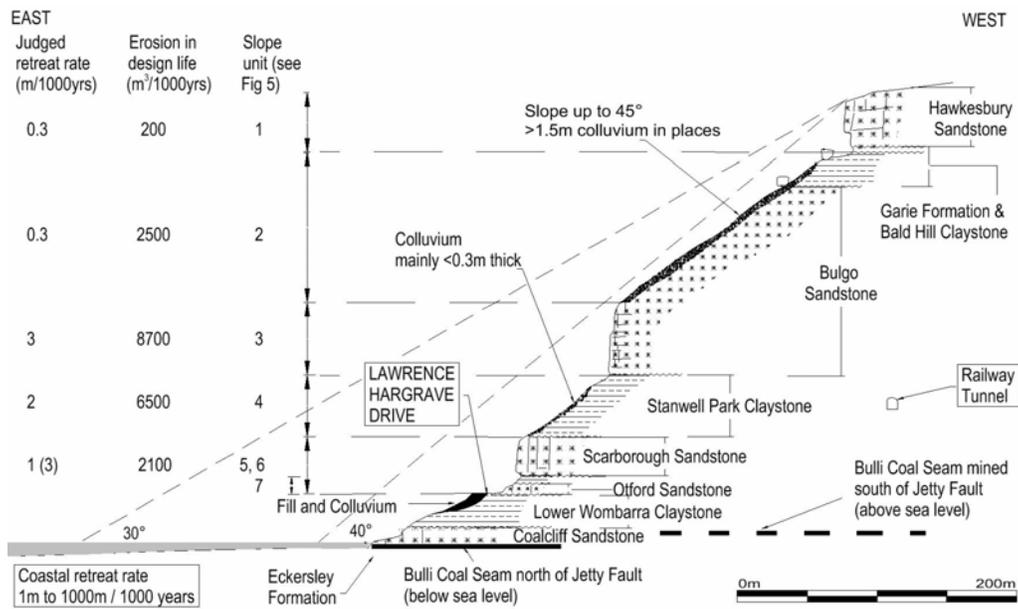


Figure 4. Cross section of coastal escarpment at Lawrence Hargrave Drive showing slope units and slope retreat rates. The section is through the highest Bulgo Sandstone cliff (second bay from foreground in Figure 3) after Moon et al (2005)

projected effect of the bridges but without any other remediation), and case D (effect of bridges plus the projected effects of proposed remedial geotechnical works elsewhere). The total annual risk varied from 1 in 10 with no

remediation to 1 in 100 for use of bridge without remedial measures in other sections and to less than 1 in 100,000 if both the bridge solution and the remedial measures were implemented.

It is important to note that annual total risk of 1 in 10 or even 1 in 100 is considered to be unacceptable. RTA guidelines may be interpreted to imply that risk levels are required to be less than 1 in 1000 (tolerable) and 1 in 10,000 or lower (acceptable).

6.3 Significance of the project and community consultation

The project highlights the benefits of strategic thinking for preventive risk management and how quantitative risk assessment can advance the practice of geomechanics. The project also highlights the benefits of an interdisciplinary approach involving geotechnical engineers and geoscientist and other civil and structural engineers. The process of decision-making was marked by close interaction between the community, businesses, engineers from the private and public sectors and two levels of government, namely the Wollongong City Council and the NSW state Roads and Traffic Authority (RTA).

As stated earlier, it was one of several alternatives for dealing with approximately a one kilometre length of a landslide and rock fall-prone coastal road. Conventional techniques had already been applied over a number of years but, based on assessment using modern approaches, the estimated annual probability of loss of human life (ranging widely from 1 in 10 to 1 in 100) was considered to be unacceptable. The road was then closed by the RTA for a couple of years. There was vigorous community opposition to this closure since it adversely affected the daily life and businesses of two groups of residents at either end of the 1 km section of roadway.

Yet the risk to the users, the local community generally and the tourists and visitors could not be ignored. The RTA and their geotechnical consultants developed a number of alternatives for a permanent solution and finally the New South Wales government approved the proposal costed at approximately \$A50 million which included the 650m of bridge.

6.4 Justifying public expenditure

Public expenditure is justified where the intersection of likelihood and vulnerability implies levels of risk which are unacceptable. Such was the situation for the site in the LHD case discussed above. One may consider a starkly contrasting situation in the same region where no public expenditure was considered to be justified. A spectacular slide-flow landslide occurred as a consequence of an exceptional rainstorm in August 1998 at Mount Kembla. However, the location was well away from the major roads and the railway lines passing through the region. The risk to the private property (on the site itself) from future reactivation, on the basis of a hazard-consequence matrix approach was assessed to be high. However, the risk to adjacent property or to human safety was assessed to be extremely low. Thus the owner was simply asked to seek geotechnical advice to manage his own property

6.5 Final Comment

In summary this case study highlights strategies and approaches which are required for advancing the conceptual and applied aspects of geotechnical engineering such as interdisciplinary approaches for evaluating hazards, carrying out QRA, thinking outside the box for risk management, the need for community consultation and above all using public funds for preventive risk management

7 Conclusions

Geomechanics has developed to serve the needs of society such as building of infrastructure and the development of natural resources. There has been comparatively less emphasis on developing strategies, methods and techniques for dealing with geo-hazards. All the evidence indicates that the frequency and adverse impacts of natural hazards are increasing. This is not surprising considering the tremendous growth rates in population, the alarming increase in urbanisation and the lack of policies and preparedness in many societies around the world for dealing with hazards, natural and human-induced. Moreover, the needs of society are also changing and it is important to identify new challenges that geomechanics faces and to develop new strategies for dealing with those challenges. Major global phenomena such as climate change are already having an impact on many aspects of the world and these impacts will become more prominent with time. Geomechanics will face enormous challenges from these changes.

This paper has advocated much greater emphasis on developing interdisciplinary approaches and for working not only with geoscientists but other professionals for evolving new strategies and for using new methods. Regional studies should go hand in hand with site-specific studies. Methods for assessing failure susceptibility, hazard and risk should be refined and tailored to meet different situations. Greater attention should be given to understanding uncertainties in geological processes, geotechnical parameters and numerical models as well as to systematic

uncertainties. Both qualitative and quantitative risk assessment should be developed further. Probabilistic approaches should be used not only to complement deterministic solutions but also to provide the framework for new insights concerning the analysis and performance of earth structures, foundations and slopes.

Sophisticated analytical models and tools, knowledge-based modelling and spatial tools such as GIS should be adopted more widely and developed further in addition to simple but robust analytical and probabilistic methods. This requires greater efforts in research and technology transfer from research teams to the profession, and from the developed societies to the developing world along with the commitment of adequate resources for such tasks. Two case studies have been presented to illustrate how interdisciplinary approaches and innovative strategies facilitate desirable outcomes for the benefit of society and for enhancing the status of the discipline of geomechanics and of the engineering profession.

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