2012

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Robin Chowdhury
University of Wollongong, robin@uow.edu.au

Phillip Flentje
University of Wollongong, pflentje@uow.edu.au

Gautam Bhattacharya
Bengal Engineering and Science University, bhattacharyag@gmail.com

http://ro.uow.edu.au/engpapers/4424

Publication Details

Chowdhury, R., Flentje, P. & Bhattacharya, G. (2012). Geotechnics in the 21st Century, uncertainties and other challenges, with particular references to landslide hazard and risk assessment. Journal of Life Cycle Reliability and Safety Engineering, 1 (2), 27-43.

GEOTECHNICS IN THE 21st CENTURY, UNCERTAINTIES AND OTHER CHALLENGES

with particular reference to landslide hazard and risk assessment

Robin Chowdhury* Emeritus Professor, University of Wollongong, Australia

Phil Flentje, Senior Research Fellow, University of Wollongong Australia

Dr. Gautam Bhattacharya, Professor, BESU, Shibpur, India

(* Invited Keynote Speaker, ISEUSAM-2012 Conference, January 2012, BESU, Shibpur,India)

INTRODUCTION

There are significant challenges for the future development and application of geotechnical engineering. Developments in research, analysis and practice have taken place to advance knowledge and practice. While the scope of the profession and its discipline areas is already vast, significant extension is required in the areas of hazard and risk assessment and management. In particular, the field of natural disaster reduction requires the development of innovative approaches within a multi-disciplinary framework. Very useful and up-to-date information on the occurrence frequency and impact of different natural disasters is being assessed and analyzed by a number of organizations around the world. However, geotechnical engineers have not played a prominent part in such activities so far. Reference may be made to the research and educational materials developed on a regular basis by the Global Alliance for Disaster Reduction (GADR) with the aim of information dissemination and training for disaster reduction. Some selected illustrations from GADR are presented in an Appendix to this paper .The role of geotechnical engineers in implementing such goals is obvious from these illustrations

The variability of soil and rock masses and other uncertainties have always posed unique challenges to geotechnical engineers. In the last few decades, the need to identify and quantify uncertainties on a systematic basis has been widely accepted. Methods for inclusion of such data in formal ways include reliability analysis within a probabilistic framework. Considerable progress has been made in complementing traditional deterministic methods with probabilistic studies. Nevertheless, the rate of consequent change to geotechnical practice has been relatively slow and sometimes half-hearted. Reviewing all the developments in geotechnical engineering which have taken place over the last thirty years or more would require painstaking and critical reviews from a team of experts over a considerable period of time and the subsequent reporting of the findings in a series of books. In comparison, the scope of this keynote paper is humble. Experienced academics who have been engaged in serious scholarship, research and consulting over several decades should be able to reflect on recent and continuing trends as well as warning signs of complacency or lack of vision .In this spirit, an attempt is made to highlight some pertinent issues and challenges for the assessment and management of geotechnical risk with particular reference to slope stability and landslides.

The writers of the present paper present some highlights of their own research through case study examples. These relate to aspects of regional slope stability and hazard assessment such as a landslide inventory map, elements of a relational database ,rainfall intensity duration for triggering landslides , continuous monitoring of landslide sites in near-real time, landslide susceptibility and hazard maps. The paper concludes with reflections on continuing and emerging challenges. For further details the reader may refer to Chowdhury & Flentje (2008), Flentje et al (2007, 2010) and a comprehensive book (Chowdhury et al, 2010)

In order to get a sense of global trends in geotechnical analysis and the assessment and management of risk, reference may be made to the work of experts and professionals in different countries as reported in recent publications. The applications include the safety of foundations, dams and slopes against triggering events such as rainstorms, floods earthquakes and tsunamis.

Following is a sample of 5 papers from a 2011 conference related to geotechnical risk assessment and management, GeoRisk 2011.Despite covering a wide range of topics and techniques, it is interesting that GIS-based regional analysis for susceptibility and hazard zoning is not included amongst these publications. Such gaps are often noted and reveal that far greater effort is required to establish multi-disciplinary focus in geotechnical research. This is clearly a continuing challenge for geotechnics in the 21st century.

- A comprehensive paper on geo-hazard assessment and management involving the need for integration of hazard, vulnerability and consequences and the consideration of acceptable and tolerable risk levels.(Lacasse and Nadim,2011) .
- Risk assessment of Success Dam, California is discussed by Bowles et al(2011) with particular reference to the evaluation of operating restrictions as an interim measure to mitigate earthquake risk. The potential modes of failure related to earthquake events and flood events are discussed in two companion papers.
- The practical application of risk assessment in dam safety (the practice in U.S.A) is discussed in a paper by Scott (2011)
- Unresolved issues in Geotechnical Risk and Reliability(Christian and Baecher,2011)
- Development of a risk-based landslide warning system (Tang and Zhang,2011)

Their first paper (Lacasse and Nadim, 2011) has a wide scope of topics and discusses the following six case studies:

1 Hazard assessment and early warning for a rock slope over a fjord arm on the west coast of Norway. The slope is subject to frequent rockslides usually with volumes in the range 0.5-5 million cubic meters.
2 Vulnerability assessment, Norwegian clay slopes in an urban area on the South coast of Norway

3 Risk assessment -2004 Tsunami in the Indian Ocean
4 Risk mitigation-quick clay in the city of Drammen along the Drammensfjord and the Drammen River.
5 Risk mitigation-Early Warning System for landslide dams, Lake Sarez in the Pamir Mountain Range in eastern Tajikistan
6 Risk of tailings dam break-probability of non-performance of a tailings management facility at Rosia Montana in Romania

UNCERTAINTIES AFFECTING GEOTECHNICS

The major challenges in geotechnical engineering arise from uncertainties and the need to incorporate them in analysis, design and practice. The geotechnical performance of a specific site, facility ,system or regional geotechnical project may be affected by different types of uncertainty such as the following (with examples in brackets):

- Geological uncertainty (geological detail)
- Geotechnical parameter uncertainty (variability of shear strength parameters and of pore water pressure)
- Hydrological uncertainty (aspects of groundwater flow)
- Uncertainty related to historical data (frequency of slides, falls or flows)
- Uncertainty related to natural or external events (magnitude ,location and timing of rainstorm, flood, earthquake, tsunami)
- Project uncertainty (construction quality, construction delays)
- Uncertainty due to unknown factors (effects of climate change)

On some projects, depending on the aims, geotechnical engineers may be justified to restrict their attention to uncertainties arising from geological, geotechnical and hydrological factors. For example, the limited aim may be to complement deterministic methods of analysis with probabilistic studies to account for imperfect knowledge of geological details and limited data concerning measured soil properties and pore water pressures. It is necessary to recognize that often pore pressures change over time and, therefore, pore pressure uncertainty has both spatial and temporal aspects which can be critically important.

During the early development of probabilistic analysis methods researchers often focused on the variability of soil properties in order to develop the tools for probabilistic analysis. It was soon realized that natural variability of geotechnical parameters such as shear strength must be separated from systematic uncertainties such as measurement error and limited number of samples. Another advance in understanding has been that the variability of a parameter, measured by its standard deviation, is a function of the spatial dimension over which the variability is considered. In some problems, consideration of spatial variability on a formal basis is important and leads to significant insights.

An important issue relates to the choice of geotechnical parameters and their number for inclusion in an uncertainty analysis. The selection is often based on experience and can be justified by performing sensitivity studies. A more difficult issue is the consideration of ‘new’ geotechnical parameters not used in traditional deterministic or even in probabilistic studies. Thus one must think ‘outside the box’ for ‘new’ parameters which might have significant influence on geotechnical reliability. Otherwise the utility and benefits of reliability analyses may not be fully realized. As an example, the residual factor’ (defined as proportion of a slip surface over which shear strength has decreased to a residual value) is rarely used as a variable in geotechnical slope analysis. Recently, interesting results have been revealed from a consideration of ‘residual factor’ in slope stability as a random variable (Chowdhury and Bhattacharya, 2011,Bhattacharya and Chowdhury 2011).Ignoring the residual factor can lead to overestimate of reliability and thus lead to unsafe or unconservative practice.

For regional studies such as zoning for landslide susceptibility and hazard assessment, historical data about previous events are very important. Therefore uncertainties with respect to historical data must be considered and analyzed carefully. Such regional studies are different in concept and implementation to traditional site-specific deterministic and probabilistic studies and often make use of different data-sets.). A successful knowledge-based approach for assessment of landslide susceptibility and hazard has been described by Flentje (2009).

If the aim of a geotechnical project is to evaluate geotechnical risk, it is necessary to consider the uncertainty related to the occurrence of an external event or event that may affect the site or the project over an appropriate period of time such as the life of the project.

Consideration of project uncertainty would require consideration of economic, financial and administrative factors in addition to the relevant technical factors considered above. In this regard the reader may refer to a recent paper on georisks in the business environment by Brumund(2011) ;the paper also makes reference to unknown risk factors.

For projects which are very important because of their size, location, economic significance, or environmental impact, efforts must be made to consider uncertainty due to unknown factors. Suitable experts may be co-opted by the project team for such an exercise.

SLOPE ANALYSIS METHODS

Limit Equilibrium and Stress deformation Approaches

Deterministic methods can be categorized as limit equilibrium methods and stress-deformation methods. Starting from simple and approximate limit equilibrium methods based on simplifying assumptions, several advanced and relatively rigorous methods have been developed.

The use of advanced numerical methods for stress-deformation analysis is essential when the estimation of strains and deformations within a slope is required. In most cases, two-dimensional (2D) stress-deformation analyses would suffice. However, there are significant problems which need to be modeled and analyzed in three-dimensions. Methods appropriate for 3D stress-deformation analysis have been developed and used successfully. Advanced stress-deformation approaches include the finite-difference method, the finite-element method, the boundary element method, the distinct element method, and the discontinuous deformation analysis method.

Progressive Failure

Progressive failure of natural slopes, embankment dams and excavated slopes is a consequence of non-uniform stress and strain distribution and the strain-softening behavior of earth masses. Thus shear strength of a soil element, or the shear resistance along a discontinuity within a soil or rock mass, may decrease from a peak to a residual value with increasing strain or increasing deformation. Analysis and simulation of progressive failure requires that strain-softening behavior be taken into consideration within the context of changing stress or strain fields. This may be done by using advanced methods such as an initial stress approach or a sophisticated stress-deformation approach. Of the many historical landslides in which progressive failure is known to have played an important part, perhaps the most widely studied is the catastrophic Vaiont slide which occurred in Italy in 1964. The causes and mechanisms have not been fully explained by any one study and there are still uncertainties concerning both the statics and dynamics of the slide. For further details and a list of some relevant references, the reader may refer to Chowdhury et al (2010).

Probabilistic approaches and simulation of progressive failure

A probabilistic approach should not be seen simply as the replacement of a calculated ‘factor of safety’ as a performance index by a calculated ‘probability of failure’. It is important to consider the broader perspective and greater insight offered by adopting a probabilistic framework It enables a better analysis of observational data and enables the modeling of the reliability of a system. Updating of reliability on the basis of observation becomes feasible and innovative approaches can be used for the modeling of progressive failure probability and for back-analysis of failed slopes. Other innovative applications of a probabilistic approach with pertinent details and references are discussed by Chowdhury et al (2010)

An interesting approach for probabilistic seismic landslide analysis which incorporates the traditional infinite slope limit equilibrium model as well as the rigid-block displacement model has been demonstrated by Jibson et al (2000).

A probabilistic approach also facilitates the communication of uncertainties concerning hazard assessment and slope performance to a wide range of end-users including planners, owners, clients and the general public.

GEOTECHNICAL SLOPE ANALYSIS IN A REGIONAL CONTEXT

Understanding geology, geomorphology and groundwater flow is of key importance. Therefore judicious use must be made of advanced methods of modeling in order to gain the best possible understanding of the geological framework and to minimize the role of uncertainties on the outcome of analyses (Marker, 2009; Rees et al, 2009).

Variability of ground conditions, spatial and temporal, is important in both regional and site-specific analysis. Consequently probability concepts are very useful in both cases although they may be applied in quite different ways.

Spatial and temporal variability of triggering factors such as rainfall have a marked influence on the occurrence and distribution of landslides in a region (Chowdhury et al, 2010, Murray, 2001)

This context is important for understanding the uncertainties in the development of critical pore-water pressures. Consequently, it helps in the estimation of rainfall threshold for on-set of landsliding. Regional and local factors both would have a strong influence on the combinations of rainfall magnitude and duration leading to critical conditions.

Since earthquakes trigger many landslides which can have a devastating impact, it is important to understand the causative and influencing factors. The occurrence, reach, volume and distribution of earthquake-induced landslides are related to earthquake magnitude and other regional factors. For further details and a list of some relevant references, the reader may refer to Chowdhury et al (2010).

REGIONAL SLOPE STABILITY ASSESSMENTS

Basic Requirements

Regional slope stability studies are often carried out within the framework of a Geographical Information System (GIS) and are facilitated by the preparation of relevant data-sets relating to the main influencing factors such as geology , topography ,drainage characteristics and by developing a comprehensive inventory of existing landslides . The development of a digital elevation model (DEM) facilitates GIS based modeling of landslide susceptibility, hazard and risk within a GIS framework. Regional slope stability and hazard studies facilitate the development of effective landslide risk management strategies in an urban area. The next section of this paper is devoted to a brief discussion of GIS as a versatile and powerful system for spatial and even temporal analysis. This is followed by a section providing a brief overview of sources and methods for obtaining accurate spatial data. The data may relate to areas ranging from relatively limited zones to very large regions .Some of these resources and methods have a global reach and applicability. Such data are very valuable for developing digital elevation models (DEMs) of increasing accuracy. For regional analysis, a DEM is, of course, a very important and powerful tool.

Landslide Inventory

The development of comprehensive databases including a landslide inventory is most desirable if not essential especially for the assessment of slope stability in a regional context. It is important to study the occurrence and spatial distribution of first-time slope failures as well as reactivated landslides.

Identifying the location of existing landslides is just the beginning of a systematic and sustained process with the aim of developing a comprehensive landslide inventory.

Among other features, it should include the nature, size, mechanism, triggering factors and date of occurrence of existing landslides. While some old landslide areas may be dormant, others may be reactivated by one or more regional triggering factors such as heavy rainfall and earthquakes.

One comprehensive study of this type has been discussed in some detail in Chapter 11 of Chowdhury et al (2010). This study was made for the Greater Wollongong region, New South Wales, Australia by the University of Wollongong (UOW) Landslide Research Team (LRT). In this paper this study is also referred to as the WOLLONGONG REGIONAL STUDY.

A small segment for the Wollongong Landslide Inventory for the Wollongong Regional Study is shown as Figure 1. The elements of a Landslide Relational Database are shown as Figure 2. Some details of the same are shown in Figures 3 and 4. A successful knowledge-based approach for assessment of landslide susceptibility and hazard has been described by Flentje (2009) and is covered in some detail in a separate section of this paper

ROLE OF GEOGRAPHICAL INFORMATION SYSTEMS (GIS)

GIS enables the collection, organization, processing, managing and updating of spatial and temporal information concerning geological, geotechnical, topographical, and other key parameters. The information can be accessed and applied by a range of professionals such as geotechnical engineers, engineering geologists, civil engineers and planners for assessing hazard of landsliding as well as for risk management. Traditional slope analysis must, therefore be used within the context of a modern framework which includes GIS. Amongst the other advantages of GIS are the ability to deal with multiple hazards, the joining of disparate data and the ability to include decision support and warning systems (Gibson and Chowdhury, 2009).

Papers concerning the application of basic, widely available, GIS systems as well as about the development of advanced GIS systems continue to be published. For instance, Reeves and West (2009), covering a conference session on ‘Geodata for the urban environment’, found that 11 out of 30 papers were about the ‘Development of Geographic Information Systems’ while Gibson and Chowdhury (2009) pointed out that the input of engineering geologists (and, by implication, geotechnical engineers) to urban geohazards management is increasingly through the medium of GIS.

Consequently, 3D geological models have been discussed by a number of authors such as Rees et al (2009) who envisage that such models should be the basis for 4D process modeling in which temporal changes and factors can be taken into consideration. They refer, in particular, to time-series data concerning precipitation, groundwater, sea level and temperature. Such data, if and when available, can be integrated with 3D spatial modeling.

SOURCES OF ACCURATE SPATIAL DATA RELEVANT TO THE DEVELOPMENT OF DIGITAL ELEVATION MODELS

Over the last decade, Airborne Laser Scan (ALS) or Light Detection and Ranging (LiDAR) techniques are increasingly being applied across Australia to collect high resolution terrain point datasets. When processed and used to develop Geographic Information System (GIS) Digital Elevation Models (DEMs) the data provides high resolution contemporary terrain models that form fundamental GIS datasets. Prior to the advent of this technology, DEMs were typically derived from 10 to 50 year old photogrammetric contour datasets. When processed, ALS datasets can comprise point clouds of many millions of ground reflected points covering large areas hundreds of square kilometers, with average point densities exceeding one point per square meter. Collection, processing and delivery of these data types are being enhanced and formalized over time. Increasingly, this data is also being collected in tandem with high resolution geo-referenced imagery.

Airborne and Satellite derived Synthetic Aperture Radar (SAR) techniques are also being increasingly developed and applied internationally to develop terrain models, and specifically differential models between return visits over the same area in order to highlight the changes in ground surfaces with time. This is being used to monitor landslide movement, ground subsidence and other environmental change.

NASA and the Japan Aerospace Exploration Society have just recently (mid-October 2011) and freely released via the internet the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) - ASTER GDEM v2 global 30m Digital Elevation Model as an update to the year 2000 vintage NASA SRTM Global DEM at 90m and 30m pixel resolutions. This global data release means moderately high resolution global Digital Elevation Model data is available to all.

The development of ALS terrain models and the free release of the global ASTER GDEM v2 have important implications for the development of high resolution Landslide Inventories and Zoning Maps world wide. These datasets mean one of the main barriers in the development of this work has been eliminated.

OBSERVATIONAL APPROACH-MONITORING AND ALERT SYSTEMS

Geotechnical analysis should not be considered in isolation since a good understanding of site conditions and field performance is essential. This is particularly important for site-specific as well as regional studies of slopes and landslides. Observation and monitoring of slopes are very important for understanding all aspects of performance; from increases in pore-water pressures to the evidence of excessive stress and strain, from the development of tension cracks and small shear movements to initiation of progressive failure, and from the development of a complete landslide to the post-failure displacement of the landslide mass.

Observation and monitoring also facilitate an understanding of the occurrence of multiple slope failures or widespread landsliding within a region after a significant triggering event such as rainfall of high magnitude and intensity (Flentje et al, 2007; Flentje, 2009).

Observational approaches facilitate accurate back-analyses of slope failures and landslides. Moreover, geotechnical analysis and the assessment of hazard and risk can be updated with the availability of additional observational data become on different parameters such as pore-water pressure and shear strength. The availability of continuous monitoring data obtained in near-real time will also contribute to more accurate assessments and back-analyses. Consequently, such continuous monitoring will lead to further advancement in the understanding of slope behavior.

One part of the Wollongong Regional Study is the development of rainfall intensity - duration curves for the triggering of landslides overlaid with historical rainfall average recurrence interval (ARI) curves as shown in Figure 5. From the very beginning of this research, the potential use of such curves for alert and warning systems was recognized. In fact, this research facilitated risk management in the Wollongong Study Area during intense rainfalls of August 1998 when widespread landsliding occurred.

More recent improvement and extension of this work involves the use of data from our growing network of continuous real-time monitoring stations where we are also introducing the magnitude of displacement as an additional parameter. Aspects of this research are shown in Fig.5 and, as more data become available from continuous monitoring, additional displacement (magnitude)-based curves can be added to such a plot.

Two examples of continuous landslide performance monitoring are shown in Figures 6 and 7. Figure 6 relates to a coastal urban landslide site (43,000m3) with limited trench drains installed. The relationship between rainfall, pore water pressure rise and displacement is clearly evident at two different time intervals in this figure. Figure 7 shows data from a complex translational landslide system (720,000m3) which is located on a major highway in NSW Australia. In the 1970’s landsliding severed this artery in several locations resulting in road closures and significant losses arising from damage to infrastructure and from traffic disruptions.

After comprehensive investigations, remedial measures were installed. At this site, a dewatering pump system was installed, which continues to operate to this day. However, this drainage system has been reviewed and upgraded from time to time. Since 2004, this site has been connected to the Continuous Monitoring Network of the University of Wollongong Landslide Research Team. Interpretation of the monitoring data shows that movement has been limited to less than 10mm since the continuous monitoring commenced as shown in Figure 7 (Flentje et al 2010) However, the occurrence of even this small movement was considered unacceptable by the authorities. Hence, pump and monitoring system upgrades commenced in 2006 and have been completed in 2011.

SUSCEPTIBILITY AND HAZARD ASSESSMENT (WOLLONGONG REGIONAL STUDY)

The susceptibility model area and the data-sets

The area chosen within the Wollongong Region for modeling landslide susceptibility (Susceptibility Model Area) is 188 square km in extent and contains 426 Slide category landslides.

The data sets used for this study include:

- Geology (mapped geological formations,21 variables)
- Vegetation (mapped vegetation categories,15 variables)
- Slope inclination (continuous floating point distribution)
- Slope aspect (continuous floating point distribution)
- Terrain units (buffered water courses, spur lines and other intermediate slopes)
- Curvature (continuous floating point distribution)
- Profile curvature (continuous floating point distribution)
- Plan curvature (continuous floating point distribution)
- Flow accumulation (continuous integer), and
- Wetness index (continuous floating point distribution)

Landslide inventory

The landslide inventory for this study has been developed over a fifteen year period and comprises a relational MS Access and ESRI ArcGIS Geodatabase with 75 available fields of information for each landslide site. It contains information on a total of 614 landslides (Falls, Flows, Slides) including 480 slides. Amongst the 426 landslides within the Susceptibility Model Area, landslide volumes have been calculated for 378 of these sites. The average volume is 21800 m^3 and the maximum 720,000 m^3.

Knowledge-based approach based on Data Mining model

The specific knowledge-based approach used for analysis and synthesis of the data sets for this study is the Data Mining (DM) process or model .The DM learning process is facilitated by the software “See 5” which is a fully developed application of “C4.5” (Quinlan,1993). The DM learning process helps extract patterns from the databases related to the study. Known landslide areas are used for one half of the model training, the other half comprising randomly selected points from within the model area but outside the known landslide boundaries. Several rules are generated during the process of modeling. Rules which indicate potential landsliding are assigned positive confidence values and those which indicate potential stability (no-landsliding) 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 .The complete process of susceptibility and hazard zoning is described in Flentje (2009) and in Chapter 11 of Chowdhury et al (2010).

Susceptibility and Hazard zones

On the basis of the analysis and synthesis using the knowledge-based approach, it has been possible to demarcate zones of susceptibility and hazard into four categories:

1 Very Low Susceptibility (or Hazard) of landsliding (VL)
2 Low Susceptibility (or Hazard) of landsliding (L)
3 Moderate Susceptibility (or Hazard) of landsliding (M), and
4 High Susceptibility (or Hazard) of landsliding (H)

A segment of the landslide Susceptibility map is shown in Figure 8 below. A segment of the landslide hazard map, an enlarged portion from the bottom left of Fig. 8, is reproduced as Figure 9. Relative likelihoods of failure in different zones, estimated from the proportion of total landslides which occurred in each zone over a period of 126 years are presented in columns 1 and 2 of Table 1 below. This information is only a part of the full table presented as Table 11.3 in Chowdhury et al (2010).

Table 1. Failure Likelihood and Reliability Index for each Hazard Zone(after Chowdhury et al,2010)

Hazard Zone Description	Failure Likelihood	Reliability Index
Very Low	7.36×10^{-3}	2.44
Low	6.46×10^{-2}	1.51
Moderate	3.12×10^{-1}	0.49
High	6.16×10^{-1}	-0.3

ESTIMATED RELIABILITY INDICES AND FACTORS OF SAFETY

An innovative concept and has been proposed by Chowdhury&Flentje (2011) for quantifying failure susceptibility from zoning maps developed on the basis of detailed knowledge-based methods and techniques within a GIS framework. The procedure was illustrated with reference to the results of the Wollongong Regional Study and the relevant Tables are reproduced here. Assuming that the factor of safety has a normal distribution, the reliability index was calculated for each zone based on the associated failure likelihood which is assumed to represent the probability of failure. These results are presented in the third or last column of Table 1.

Table 2. Typical mean value of Factor of Safety F for each Hazard Zone considering coefficient of variation to be 10 %.(after Chowdhury& Flentje, 2011)

Hazard Zone Description	Reliability Index	Mean of F ($V_F = 10\%$)
Very Low	2.44	1.32
Low	1.51	1.18
Moderate	0.49	1.05
High	-0.3	0.97

Assuming that the coefficient of variation of the factor of safety is 10%, the typical values of mean factor of safety for each zone are shown in Table 2. The results were also obtained for other values of the coefficient of variation of the factor of safety (5%, 10%,15% and 20%). These results are shown in Table 3.

Table 3. Typical mean Factor of Safety with different values of coefficient of variation (%.(after Chowdhury& Flentje, 2011)

V_F%	Mean of F for different Hazard Zones			
	Very Low	Low	Moderate	High
5	1.14	1.08	1.02	0.98
10	1.32	1.18	1.05	0.97
15	1.57	1.29	1.08	0.96
20	1.95	1.43	1.11	0.94

Most of the landslides have occurred during very high rainfall events. It is assumed here ,in the first instance, that most failures are associated with a pore water pressure ratio of about 0.5(full seepage condition in a natural slope). Furthermore ,assuming that the ‘infinite slope’ model applies to most natural slopes and that cohesion intercept is close to zero, the values of factor of safety can be calculated for other values of the pore pressure ratio(0.2,0.3and 0.4) for any assumed value of the slope inclination. The results shown below in Table 4 are for a slope with an inclination of 12 degrees for pore pressure ratios in the range 0.2-0.5.

Table 4. Typical mean Factor of Safety with different values of pore pressure ratio (slope inclination i = 12˚, V_F = 10%).(after Chowdhury& Flentje,2011)

Pore water pressure ratio	Mean of F for different Hazard Zones			
	Very Low	Low	Moderate	High
0.5	1.32	1.18	1.05	0.97
0.4	1.61	1.44	1.28	1.18
0.3	1.90	1.70	1.51	1.40
0.2	2.19	1.95	1.74	1.61

Discussion on the proposed concept and procedure

The above results were obtained as a typical F value or a set of F values referring to each hazard zone. However, taking into consideration the spatial variation of slope angle, shear strength and other factors, this approach may facilitate the calculation F at individual locations. Well-documented case studies of site-specific analysis would be required for such an extension of the procedure. Other possibilities include estimation of the variation of local probability of failure .The approach may also be used for scenario modeling relating to the effects of climate change .If reliable data concerning pore pressure changes become available, failure susceptibility under those conditions can be modeled and the likelihood and impact of potential catastrophic slope failures can be investigated.

DISCUSSION, SPECIFIC LESSONS OR CHALLENGES

The focus of this paper has been on hazard and risk assessment in geotechnical engineering. Advancing geotechnical engineering requires the development and use of knowledge which facilitates increasingly reliable assessments even when the budgets are relatively limited. Because of a variety of uncertainties, progress requires an astute combination of site-specific and regional assessments. For some projects, qualitative assessments within the framework of a regional study may be sufficient. In other projects quantitative assessments, deterministic and probabilistic may be essential.

In this paper, different cases have been discussed in relation to the Wollongong Regional Study. Firstly reference was made to the basis of an alert and warning system for rainfall-induced landsliding based on rainfall-intensity-duration plots supplemented by continuous monitoring. The challenges here are obvious. How do we use the continuous pore pressure data from monitoring to greater advantage? How do we integrate all the continuous monitoring data to provide better alert and warning systems? This research has applications in geotechnical projects generally well beyond slopes and landslides.

The examples concerning continuous monitoring of two case studies discussed in this paper illustrate the potential of such research for assessing remedial and preventive measures. The lesson from the case studies is that, depending on the importance of a project, even very low hazard levels may be unacceptable. As emphasized earlier, the decision to upgrade subsurface drainage at the cost of hundreds of thousands of dollars over several years was taken and implemented despite the shear movements being far below disruptive magnitudes as revealed by continuous monitoring. The challenge in such problems is to consolidate this experience for future applications so that costs and benefits can be rationalized further.

The last example from the Wollongong Regional Study concerned the preparation of zoning maps for landslide susceptibility and hazard. Reference was made to an innovative approach for quantitative interpretation of such maps in terms of well known performance indicators such as ‘factor of safety’ under a variety of pore pressure conditions. The challenge here is to develop this methodology further to take into consideration the spatial and temporal variability within the study region.

CHALLENGES DUE TO EXTERNAL FACTORS

Beyond the scope of this paper, what are the broad challenges in geotechnical hazard and risk assessment? How do we deal with the increasing numbers of geotechnical failures occurring globally including many disasters and how do we mitigate the increasingly adverse consequences of such events? What strategies, preventive, remedial and other, are necessary? These trends have developed in spite of significant progress in our understanding of natural processes and in spite of the successful development of experimental, analytical and design tools.

Often catastrophic landslides are caused by high magnitude natural events such as rainstorms and earthquakes. It is also important to consider the contribution of human activities such as indiscriminate deforestation and rapid urbanization to landslide hazard. There is an increasing realization that poor planning of land and infrastructure development has increased the potential for slope instability in many regions of the world.

Issues concerned with increasing hazard and vulnerability are very complex and cannot be tackled by geotechnical engineers alone. Therefore, the importance of working in interdisciplinary teams must again be emphasized. Reference has already been made to the use of geological modeling (2D, 3D and potentially 4D) and to powerful tools such as GIS which can be used in combination with geotechnical and geological models.

At the level of analysis methods and techniques, one of the important challenges for the future is to use slope deformation (or slip movement) as a performance indicator rather than the conventional factor of safety. Also at the level of analysis, attention needs to be given to better description of uncertainties related to construction of slopes including the quality of supervision.

Research into the effects of climate change and, in particular its implications for geotechnical engineering is urgently needed (Rees et al 2009; Nathanail and Banks, 2009). The variability of influencing factors such as rainfall and pore-water pressure can be expected to increase. However, there will be significant uncertainties associated with estimates of variability in geotechnical parameters and other temporal and spatial factors. Consequently geotechnical engineers need to be equipped with better tools for dealing with variability and uncertainty. There may also be other changes in the rate at which natural processes like weathering and erosion occur. Sea level rise is another important projected consequence of global warming and climate change and it would have adverse effects on the stability of coastal slopes.

CONCLUDING REMARKS

A wide range of methods, from the simplest to the most sophisticated are available for the geotechnical analysis of slopes. This includes both static and dynamic conditions and a variety of conditions relating to the infiltration, seepage and drainage of water. Considering regional slope stability, comprehensive databases and powerful geological models can be combined within a GIS framework to assess and use information and data relevant to the analysis of slopes and the assessment of the hazard of landsliding. The use of knowledge-based systems for assessment of failure susceptibility, hazard or performance can be facilitated by these powerful tools. However, this must all be based on a thorough field work ethic.

It is important to understand the changes in geohazards with time. In particular, geotechnical engineers and engineering geologists will face long-term challenges due to climate change. Research is required to learn about the effects of climate change in greater detail so that methods of analysis and interpretation can be improved and extended. Exploration of such issues will be facilitated by a proper understanding of the basic concepts of geotechnical slope analysis and the fundamental principles on which the available methods of analysis are based.

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25.

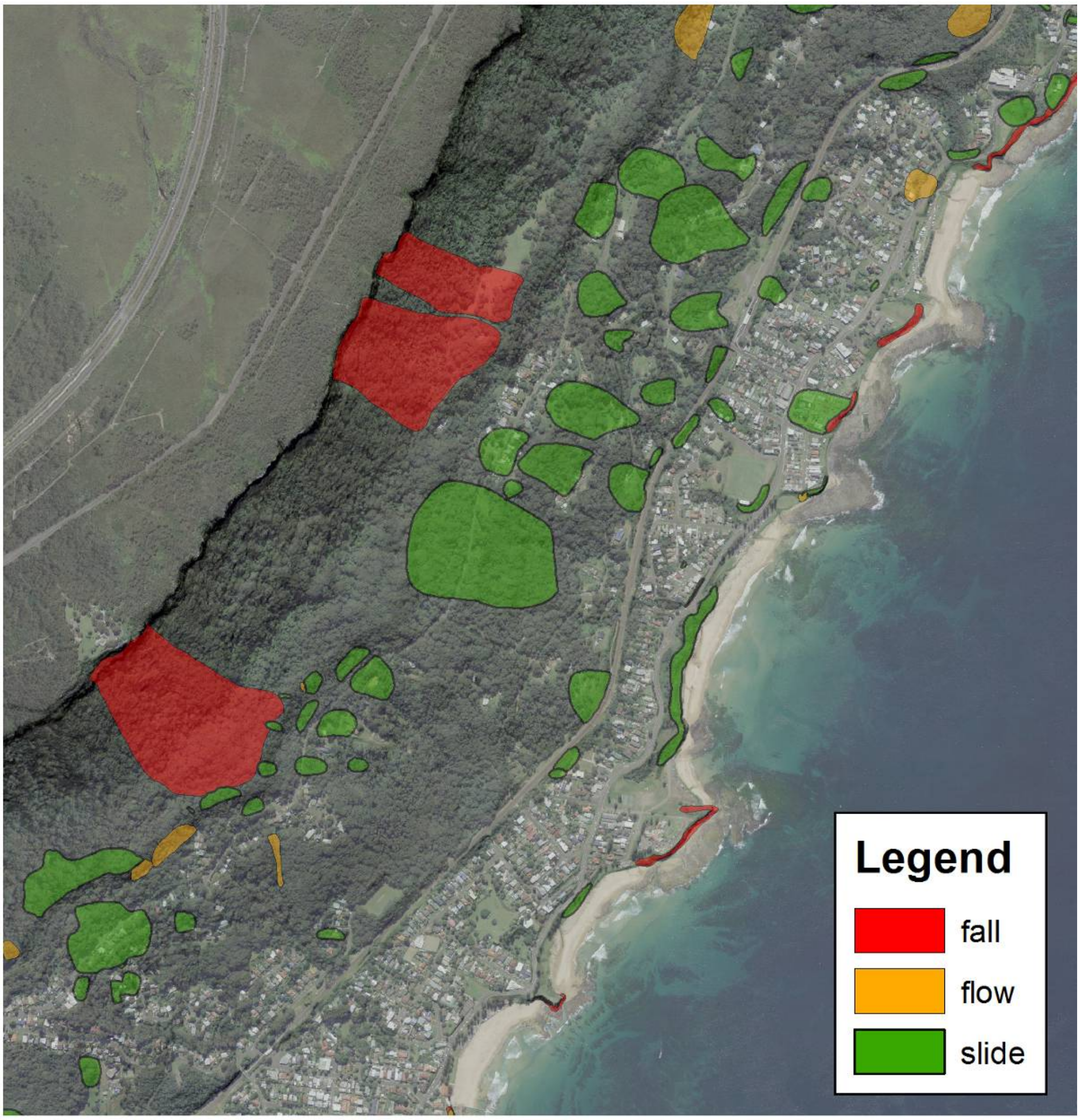


Figure 1. Segment of the University of Wollongong Landslide Inventory.

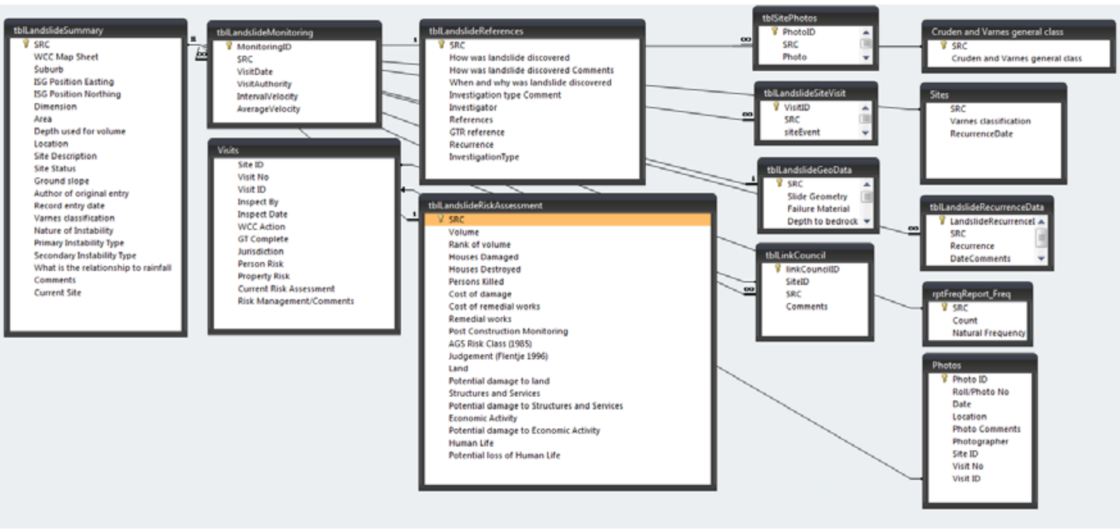


Figure 2. Elements of a Landslide Relational Database.

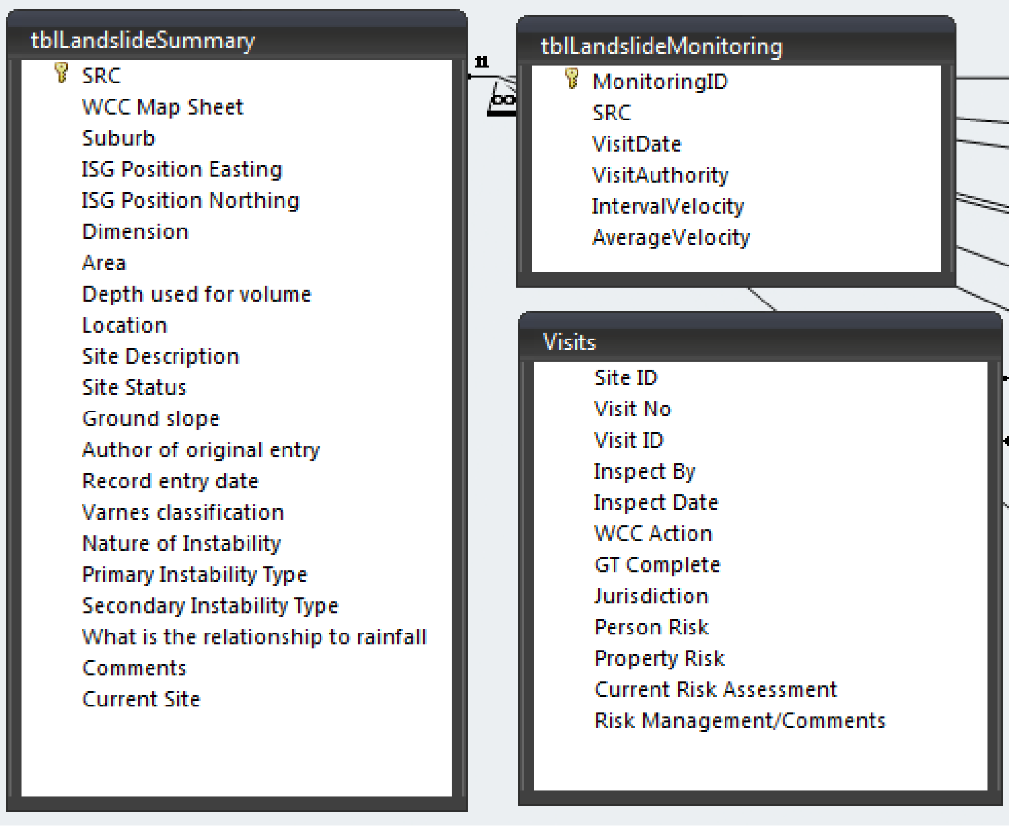
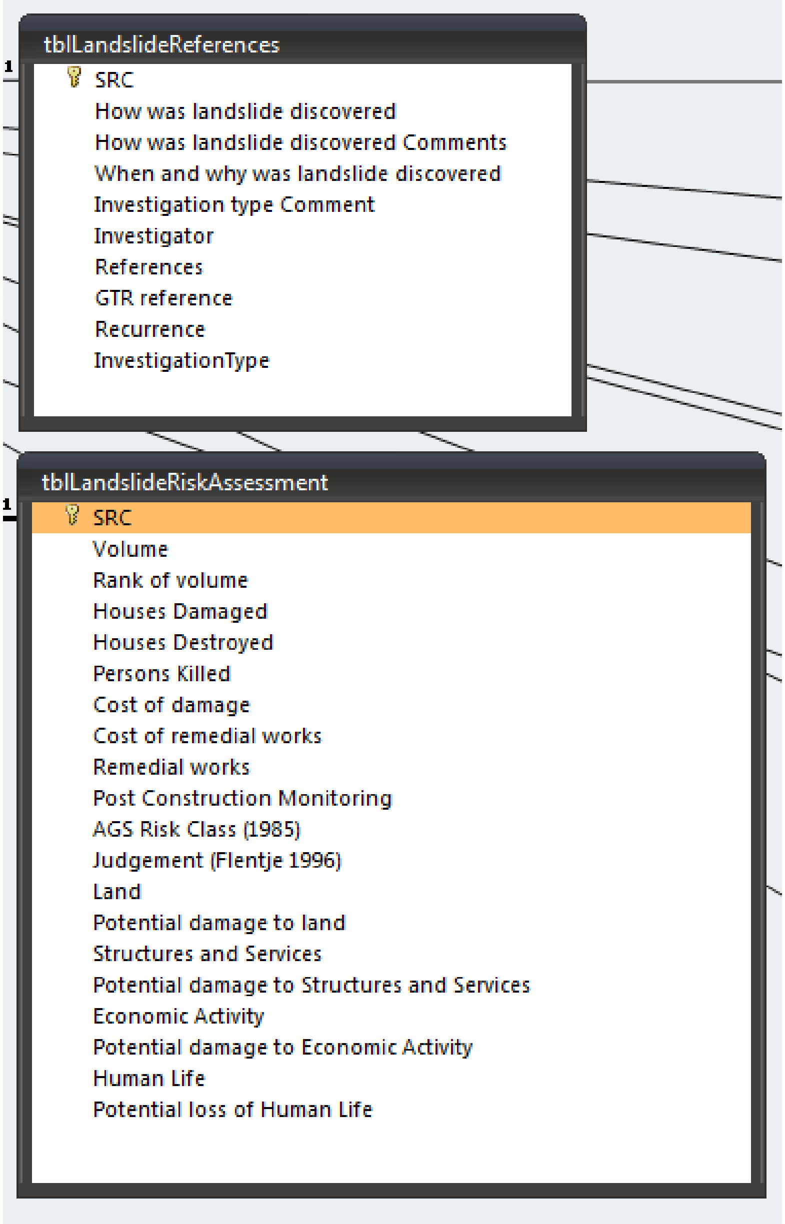


Figure 3. Details of main tables of Relational Database shown above.



tblLandslideReferences
- SRC
- How was landslide discovered
- How was landslide discovered Comments
- When and why was landslide discovered
- Investigation type Comment
- Investigator
- References
- GTR reference
- Recurrence
- InvestigationType

tblLandslideRiskAssessment
- SRC
- Volume
- Rank of volume
- Houses Damaged
- Houses Destroyed
- Persons Killed
- Cost of damage
- Cost of remedial works
- Remedial works
- Post Construction Monitoring
- AGS Risk Class (1985)
- Judgement (Flentje 1996)
- Land
- Potential damage to land
- Structures and Services
- Potential damage to Structures and Services
- Economic Activity
- Potential damage to Economic Activity
- Human Life
- Potential loss of Human Life

Figure 4. Details of selected tables of Relational Database shown above.

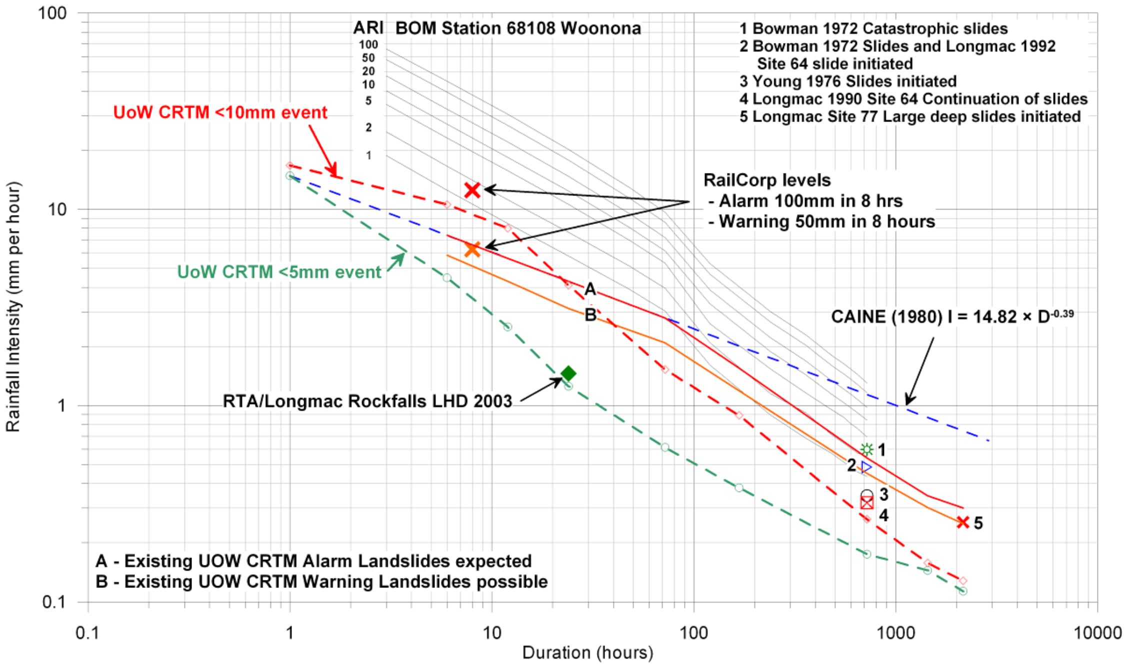


Figure 5. Interpreted threshold curves for landsliding in Wollongong, superimposed on Annual Recurrence Interval curves for a selected rainfall station.

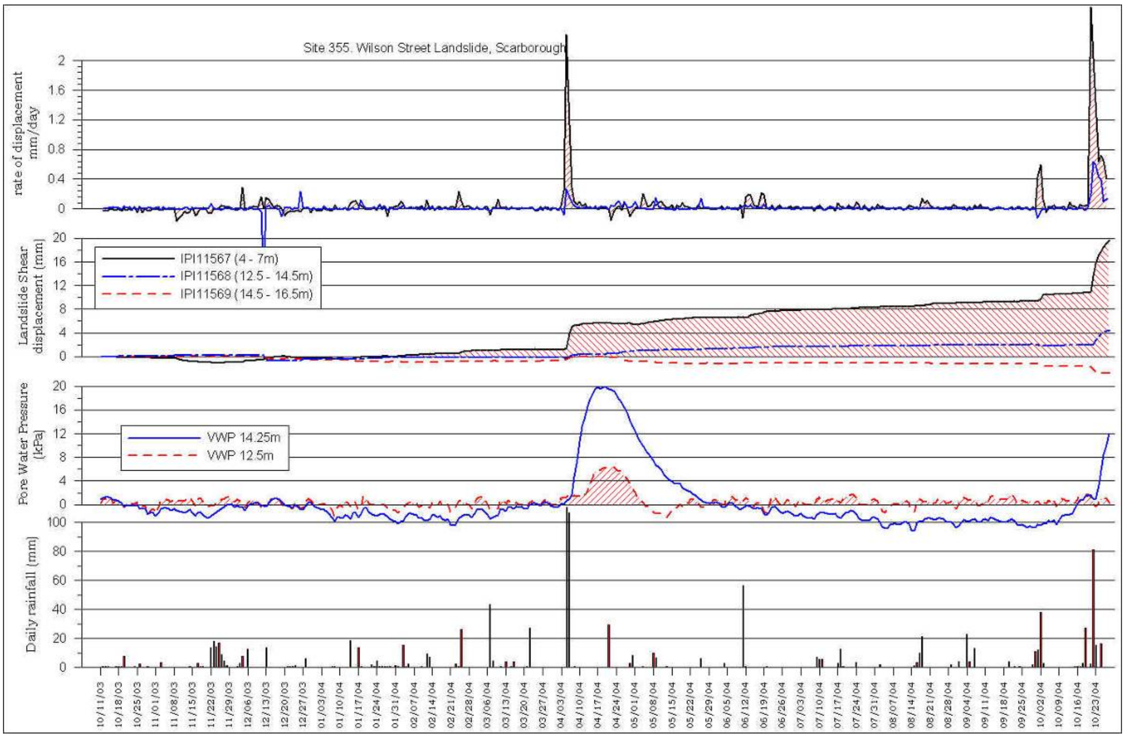


Figure 6. Hourly logged continuously recorded rainfall, pore water pressure, landslide displacement and rate of displacement data for a 43,000m^3 urban landslide site in Wollongong.

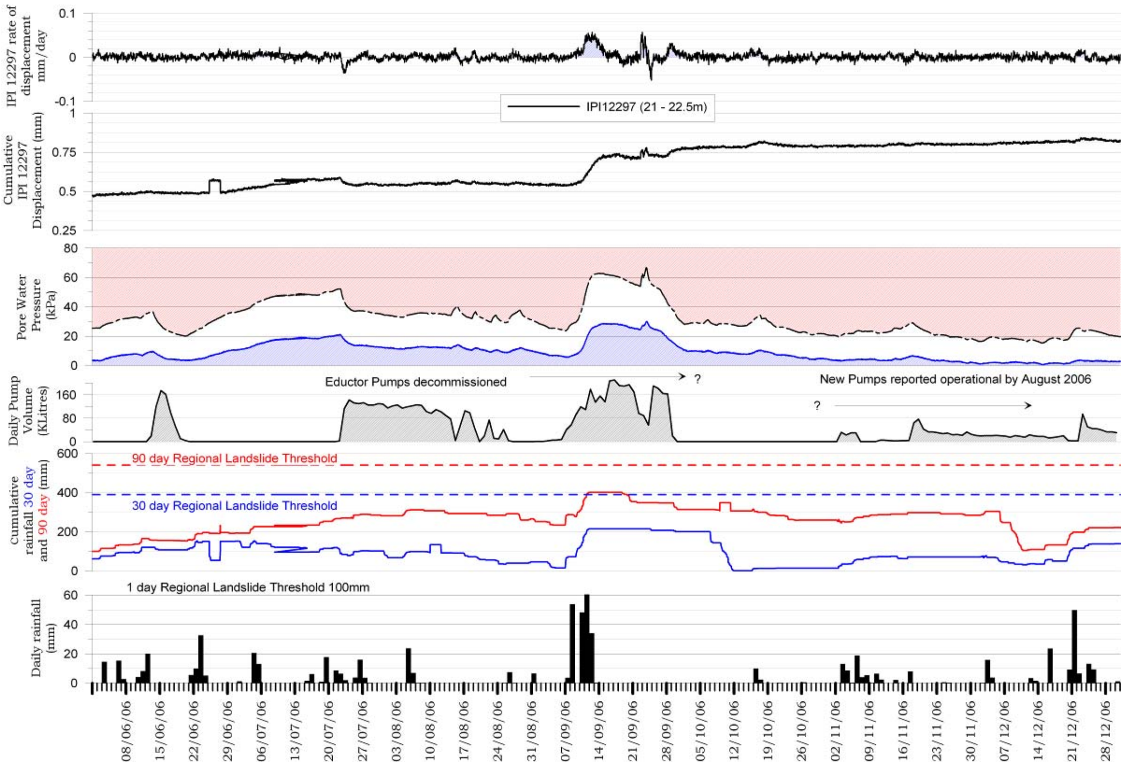


Figure 7. Hourly logged, continuously recorded rainfall, groundwater pump volumes, pore water pressure, landslide displacement and rate of displacement data for a 720,000m^3 landslide affecting a major transport artery in Wollongong.

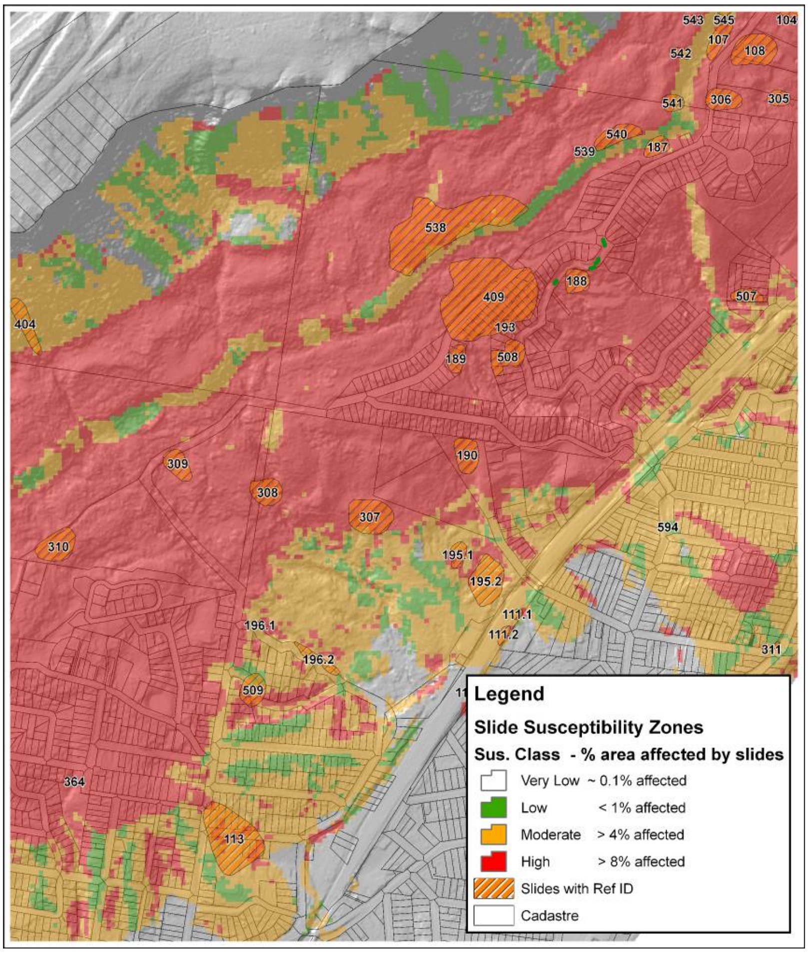
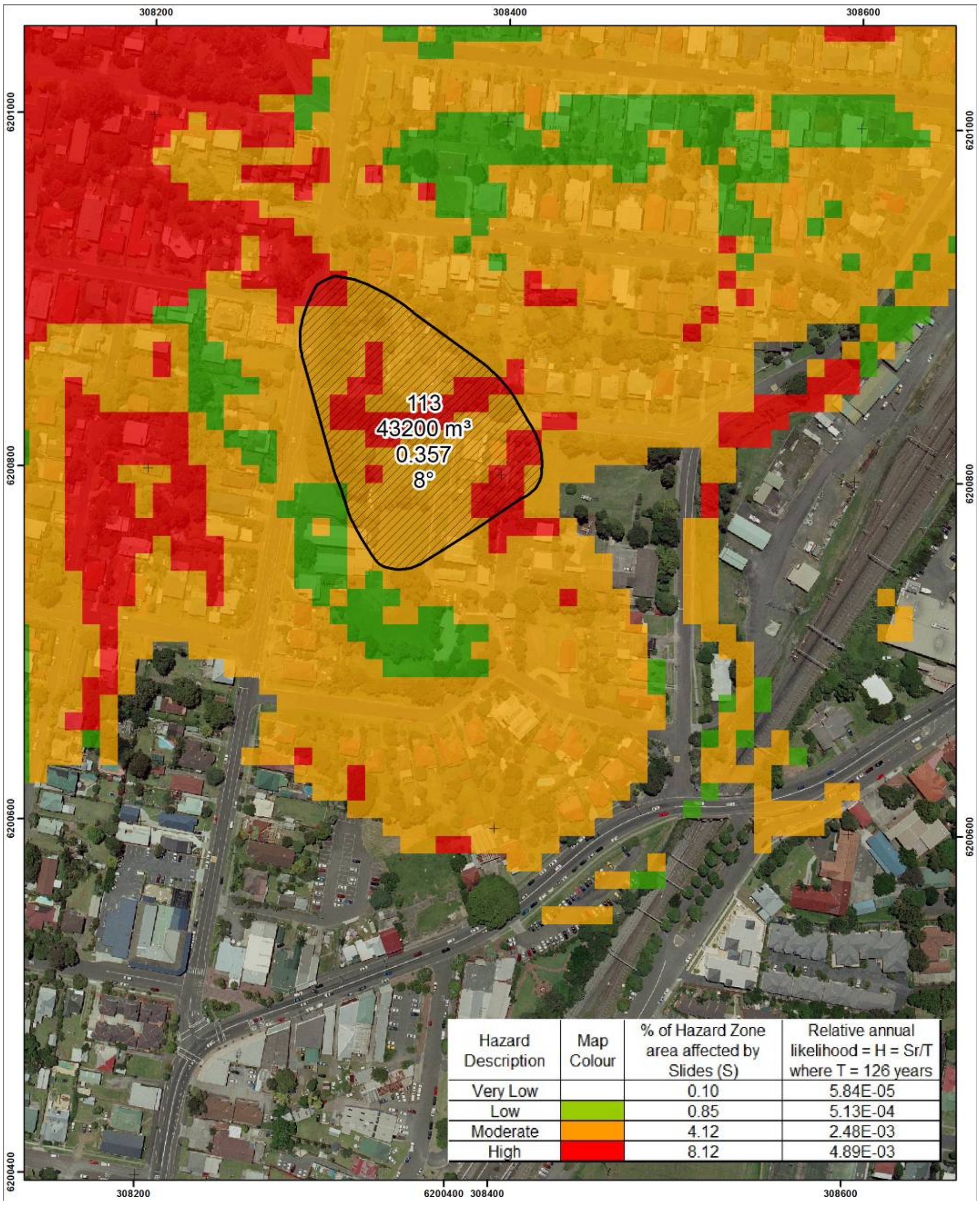


Figure 8. Segment of Landslide Inventory and Susceptibility Zoning Map, Wollongong Local Government Area, New South Wales, Australia.



Hazard Description	Map Colour	% of Hazard Zone area affected by Slides (S)	Relative annual likelihood = H = Sr/T where T = 126 years
Very Low		0.10	5.84E-05
Low	🟩	0.85	5.13E-04
Moderate	🟧	4.12	2.48E-03
High	🟥	8.12	4.89E-03

Figure 9. Segment of Landslide Hazard Zoning Map from the bottom left corner of Fig.8, Wollongong Local Government Area, New South Wales, Australia. Landslide label shows four important particulars of each landslide stacked vertically. These are (1) Site Reference Code,(2) landslide volume,(3) annual frequency of reactivation derived from inventory and(4)landslide profile angle. Hazard zoning in legend shows relative annual likelihood as explained in the text.

APPENDIX I— SELECTED FIGURES FROM POWER POINT SLIDE SET ENTITLED “UNDERSTANDING RISK AND RISK REDUCTION” (HAYS 2011)

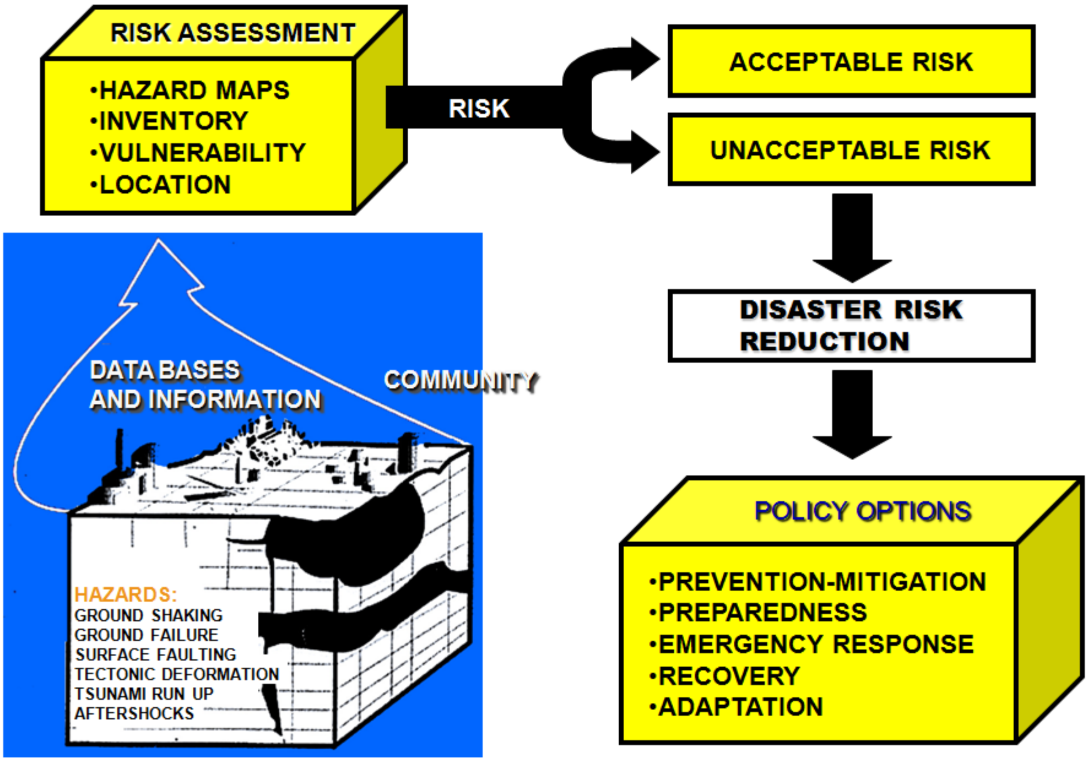


Figure A-1. Elements of Risk Assessment and Management for Natural Disasters courtesy of Walter Hays, 2011.

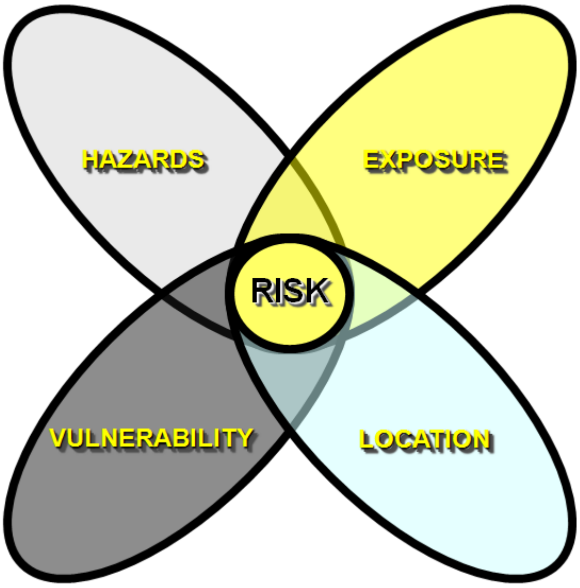
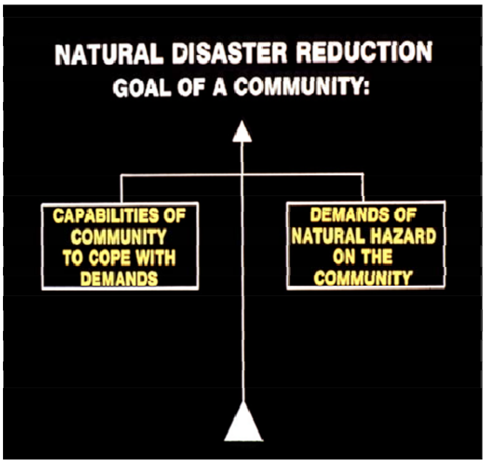


Figure A-2. Components of Risk courtesy of Walter Hays, 2011.

COMMON AGENDA FOR DISASTER RESILIENCE



- PREVENTION (CONTROL THE SOURCE)
- PROTECTION (BUILD TO WITHSTAND)
- LAND-USE CONTROL (AVOIDANCE)
- SITE MODIFICATION
- ALERT/WARNING/ MAPS/MONITORING
- RESPONSE TO ALERT/WARNING/ MAPS/MONITORING TO MOVE PEOPLE OUR OF HARM'S WAY

Figure A-3. Common Agenda for Natural Disaster Resilience, courtesy of Walter Hays, 2011.

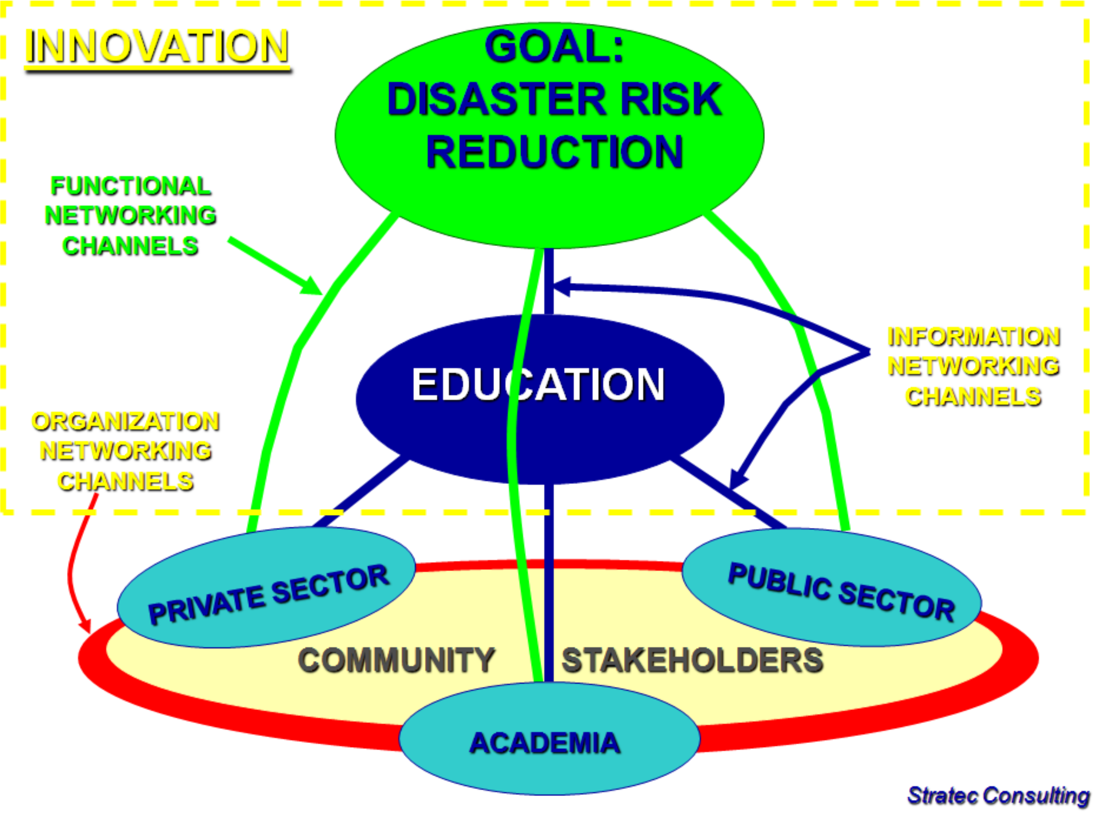


Figure A-4. The overall context for Innovation in Disaster Management and Reduction, courtesy of Walter Hays, 2011

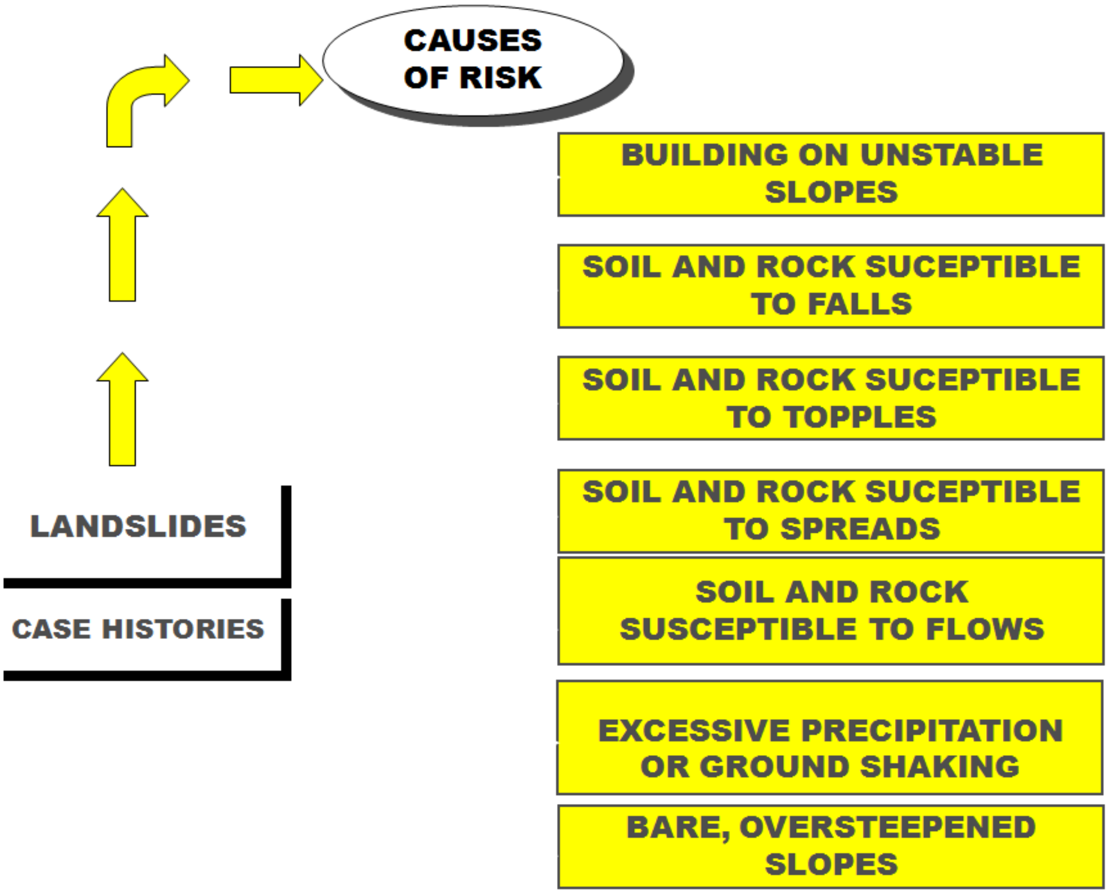


Figure A-5. Some causes of risk for landslides, courtesy of Walter Hays, 2011