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Mitigation of landslide impacts, strategies and challenges for the 21st century

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Abstract

Reliable methods for mitigation of landslide impacts must be based on the latest developments in knowledge and advanced methods of analysis and synthesis. An interdisciplinary approach is essential for effective solutions to landslide problems. Prevention or mitigation of landslide disasters requires understanding the factors which often lead to catastrophic landsliding and the simulation of conditions under which such failures may occur. The analysis of rainfall-triggered landsliding in saturated soils requires a proper understanding of how the factor of safety decreases with increase in pore water pressure. On the other hand, for landsliding in unsaturated soils it is necessary to understand the decrease of factor of safety with decrease in soil suctions (negative pore pressures) which is associated with increase in the field water content during rainfall infiltration. Landslide risk management requires understanding and assessment of susceptibility and hazard. In particular, for regional assessment, landslide susceptibility and hazard mapping and zonation are necessary. Mitigation of landslide impacts is facilitated by the use of research -based thresholds of rainfall and/or pore water pressure and/or displacement. These thresholds can be used for the development and application of early warning systems. Monitored data on landslide movements and pore water pressures can be very useful for updating hazard and risk scenarios. Such data also contribute to the capacity for landslide management in near real-time. The paper refers to some of the findings in the regional case study from Wollongong region, New South Wales Australia.

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Mitigation of Landslide Impacts, Strategies and Challenges for the 21st Century

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Abstract

Reliable methods for mitigation of landslide impacts must be based on the latest developments in knowledge and advanced methods of analysis and synthesis. An interdisciplinary approach is essential for effective solutions to landslide problems. Prevention or mitigation of landslide disasters requires understanding the factors which often lead to catastrophic landsliding and the simulation of conditions under which such failures may occur. The analysis of rainfall-triggered landsliding in saturated soils requires a proper understanding of how the factor of safety decreases with increase in pore water pressure. On the other hand, for landsliding in unsaturated soils it is necessary to understand the decrease of factor of safety with decrease in soil suctions (negative pore pressures) which is associated with increase in the field water content during rainfall infiltration. Landslide risk management requires understanding and assessment of susceptibility and hazard. In particular, for regional assessment, landslide susceptibility and hazard mapping and zonation are necessary. Mitigation of landslide impacts is facilitated by the use of research –based thresholds of rainfall and/or pore water pressure and/or displacement. These thresholds can be used for the development and application of early warning systems. Monitored data on landslide movements and pore water pressures can be very useful for updating hazard and risk scenarios. Such data also contribute to the capacity for landslide management in near real-time. The paper refers to some of the findings in the regional case study from Wollongong region, New South Wales Australia.

Keywords: Landsllide Risks, Susceptibility, Hazard, Rainfall Threshold

1 INTRODUCTION AIMS AND SCOPE

The importance of understanding the occurrence of various geo-hazards and addressing their impacts has been growing for many decades throughout the world. There is considerable concern that the frequency and magnitude of disastrous natural events is increasing due to climate change and due to human action such as deforestation and unwise development of land. With rapid growth of world population and increasing urbanization, the impacts of disastrous events continue to increase dramatically. The adverse impacts of landslides on residential houses, roads, railway lines and other infrastructure often do not receive attention from the media unless there is loss of life. There is generally no insurance available for damage due to landslides which is in sharp contrast to the situation with other major natural hazards. Consequently the adverse impact of landslides on individuals and communities is even more severe than is apparent from initial assessments.

The cumulative economic and environmental losses of landslides to local communities and regions are often significantly large if not as dramatic as those associated with major earthquakes and floods. Moreover, landslides are often associated with significant flood and earthquake events. A recent example is the landsliding associated with major floods in the Himalayan region of Uttarkhand State in India during the monsoon of late June and early July 2013. Thousands of lives were lost and tens of thousands of people rendered homeless. In such cases the losses due to landslides are lumped with the primary events (flood, earthquake) rather than accounted for separately as losses due to landsliding .Thus landslide losses are not communicated as effectively as losses from other natural hazards.

The following example will illustrate the significant annual costs of landslide management within an urban context with particular reference to roads and other infrastructure in the Wollongong region of New South Wales, Australia (also known as the Illawarra region). Research has shown that landsliding within the Illawarra has cost at least $300 million since 1950, at an annual average cost of around $4.8 million (Palamakumbure et al, 2013). This is a very conservative estimate based on accessible reports of projects that have been implemented mainly by public organisations. It is also important to appreciate this region is a very small part of urbanised Australia both by size and population. Moreover, landslide impacts in this region are far less severe than the worst examples around the world.

This same research shows that seven lives have been lost in the Illawarra due to landsliding since 1900. Long-term Illawarra coastal escarpment retreat rates derived from geomorphologic analysis are around 0.6m/ka. Rates determined from a University of Wollongong inventory of landslides suggest very similar rates of escarpment retreat, from 0.1 to 1 m per 1000 years. This research on retreat rates aids the assessment of landslide frequency and will enable better assessments of the frequency of land sliding and therefore enhance landslide risk management practice.

The main aim of this paper is to highlight modern approaches to the assessment of landslide hazard and risk .This is considered to be an essential part of a strategic approach for mitigation of landslide impacts.

Only two main aspects of the Wollongong regional case study will be presented to illustrate the use of a strategic approach.

These two aspects are:

- Landslide susceptibility and hazard zoning.
- Rainfall thresholds for triggering of landslides.

While reference is made in some early sections of this paper to seismically triggered landslides, that subject is outside the scope of this paper. Detailed consideration of advances in an observational approach is also outside the scope of this paper. Similarly, reliability approaches have been excluded for space limitations. Attention is focussed on landslides in soil. Due to space limitations detailed consideration of landslides in rock is outside the scope of this paper .Also excluded for the same reason are falls and flows in both soil and rock.

1.1 LANDSLIDE TYPES AND CONTEXT OF OCCURRENCE

It is important to study the occurrence, geographical distribution and frequency of landslides in order to fully understand the causes and the role of triggering factors such as rainfall, earthquakes, stream erosion and deforestation. In general, landslides are characterized by particular shapes with well-defined slip surfaces .Thus one may encounter slides with planar or curved slip surfaces or wedge shapes. There are various landslide types such as:-

Debris slides, mudslides, rockslides

Mudflows and debris flows

Soil and rock falls , topples, avalanches

It is important to appreciate that landsliding is often a progressive process in time before as well as after the initial visible occurrence of an event. One must try to distinguish between:

- An initial, localized failure of limited volume.
- Current volume may have resulted from a process of spatial progression.
- Current volume may have resulted from a process of spatial retrogression.

Strain-softening of soil from peak to residual shear strength is one of the concepts considered to be necessary for analysis of slope progressive failure process in the development of slope instability. Similarly, one must invoke relevant concepts and observational approaches to understand and simulate the extension of landslides by progression or retrogression.

The speed of mass movements can vary from extremely slow to extremely fast. The impacts of landslides depends on the volume of the moving mass, its composition , speed and travel distance as well as on the vulnerability of elements at risk such as houses ,bridges, roads and other infrastructure. Thus understanding of landslide impacts requires appreciation of:

- Causes, triggering agents and historical context
- Magnitude such as volume and velocity
- Spatial distribution , frequency and potential travel distance
- Elements at risk and their vulnerability

Assessment of site-specific slope stability requires knowledge of soil and rock mechanics and engineering geology. Understanding of the regional distribution of landslides requires a strong earth-science perspective. The role of geomorphology and hydrogeology can be very useful for a better understanding of the causes of mass movement. Thus an interdisciplinary approach is very important and often indispensible. The type of landslide and the mechanisms of failure are significantly influenced by the nature of soil and rock as well as by climatic conditions and tectonic activity

Thus it is very useful to learn important details such as:

- Soil and rock strata and the weathering profile
- Tectonic activity and its influence
- Seepage pattern in saturated soil and suctions in residual soil
- Frequency of landslide triggering agents

In particular, local geological and geotechnical details (soil structure, permeability, presence of suctions, saturation, pore pressure, existing slip surfaces) can be very important for devising and implementing practical solutions (drainage measures, restraining structures). Such details can also contribute to a better understanding of potential failure mechanisms.

In considering the potential for landsliding, first time landslides must be distinguished from the re-activation of landslide displacements along pre-existing slip surfaces. Thus, it is very important to identify areas or zones that have been subjected to landsliding in the recent or remote past. Some existing landslides may be active while others may be dormant. In some cases, there may be considerable uncertainty about the potential mobility of landslide masses.

1.2 MAIN TRIGGERING FACTORS

The main external influencing factors for landsliding are rainfall and earthquakes and geotechnical engineers as well as geoscientists are familiar with these as triggering agents There is a good deal of understanding of the failure mechanisms associated with these two external agents. However, there is a vast scope for more research to fill in the gaps in knowledge and understanding. Moreover, there are other influencing factors as well which can be important in particular situations. For example, consideration of coastal landslides requires understanding of wave action and sea level fluctuations among other factors.

Rainfall triggered landsliding is ubiquitous around the world and the frequency of occurrence of such landslides is high relative to seismically induced landslides. In this paper attention is focused mainly on rainfall-triggered landslides.

In regions of high tectonic activity or seismicity, significant landslides occur during large earthquake events (typically magnitude 5 and above). Many examples of landslides in different regions of the world have been reported in the geotechnical and geosciences literature. Earthquakes of large magnitude can cause enormous landslide damage over very large areas.

For example large, deep-seated rockslides occurred in Limestone Mountains of Sichuan province in China following the May 2008 earthquake. High tectonic activity in many regions may also alter the characteristics of soils and rock with consequences for landsliding potential. For example, many regions in the Himalayan zones of India, Pakistan and Nepal are characterized by sedimentary rocks (siltstone ,mudstone, sandstone ,limestone).These are extensively folded and faulted near major thrust faults and may also be highly fractured. Slopes in such areas are also highly susceptible to landsliding during rainfall. However, further consideration of earthquake-triggered landslides is outside the scope of this paper.

1.3 MAIN TYPES OF LANDSLIDE IMPACT

Main types of landslide impact include:

- Loss of life and injury
- Damage to buildings and infrastructure
- Disruption of services, loss of business and loss of confidence.
- Loss of land resource.
- Environmental degradation.

2 RAINFALL TRIGGERED LANDSLIDING

Rainfall triggered landslides occur frequently in many areas of the world and, in extreme events, such landsliding can be widespread and catastrophic. Based on long-term research it is important to determine threshold magnitudes and intensities of rainfall which can trigger landsliding. Both soil and rock slopes can fail during heavy or prolonged rainfall. However, depending on the type of soil mass or the type of rock mass there are often significant differences in the way that infiltration and seepage of water trigger slope failure. It is useful to consider three categories briefly: (1) slopes in jointed hard rock masses (2) slopes in saturated or unsaturated soils and (3) slopes in fractured and weathered rock masses.

(1) Open vertical joints in slopes within hard rock may rapidly fill up with rain water which then exerts lateral pressure. This is an additional disturbing force in the equilibrium equation of a rock slope. Consequently a landslide will occur if the water pressure in a joint is high enough to decrease the factor of safety to and below the threshold of F=1.In rock slopes, existing geological discontinuities often control the potential failure mechanism. Once the appropriate mechanism is identified, an appropriate wedge type of limit equilibrium analysis (2D or 3-D) is carried out. In addition to the lateral water pressure in vertical cracks or joints, rainfall-induced pore pressure may act on the potential slip surface which is usually a basal discontinuity.

(2) For slopes in soil, the process and mechanism of landsliding differs significantly from that for jointed hard rock slopes. Firstly, the potential slip surface is generally not well defined and the search for a critical slip surface is an important part of the analytical process. Secondly, the process of flow through a porous medium (seepage) must be understood in order to find the distribution of pore pressure along a potential slip surface. For saturated soil slopes, the seepage process is reasonably well understood and only positive pore water pressures are to be considered. The situation with regard to unsaturated soils, also called partially saturated soils, is more complex since suctions or negative pore pressures exist above the water table and it is necessary to understand and simulate the process by which such suctions are eliminated during infiltration. Rainfall induced failures in unsaturated residual soils occur in many areas of the world. Such failures in the residual soils of Hong Kong are especially well known. The development of conditions for slope failure is significantly different in unsaturated soils in comparison to those in saturated soils. In the rest of this paper attention is focused only on landslides in soil.

An important point concerns the stress path relevant to rainfall-triggered slope instability. Considering a typical soil element is a slope undergoing changes in pore pressure during rainfall, the stress path to failure is horizontal rather than an inclined line relevant to loading stress path in a standard cylindrical compression test. Thus the shear strength parameters relevant to analysis should ideally be obtained from constant shear stress drained tests(CSD) rather than the consolidated drained tests(CD).The stress path followed in CSD tests is similar to the field stress path that seems relevant to a rainfall induced instability.

(3) It is important to differentiate the behaviour of slopes in fractured or weathered rocks from that of slopes in jointed hard rock. The mechanism of landsliding would depend on the degree of fracturing, the degree and depth of weathering and the coefficient of permeability of the fractured or weathered mass. Potential slip surfaces may be of arbitrary shape .Therefore, methods of analysis to be used for such slopes may be similar to those applicable to soil slopes. In weathered rocks, depending on the extent of weathering, the original mass structure consisting of discontinuities may still be present. This would influence the mechanical behaviour and seepage pattern within a weathered rock mass.

2.1 SLOPES IN SATURATED SOILS

Pore water pressure increases during rainfall and may reach a critical value at which the factor of safety, F, decreases to and below the threshold (F=1). Thus the development of high positive pore water pressure is often the key to such failures.

A rising water table level during rainfall is an obvious indication of rising pore water pressures. In some situations involving slopes in layered soils, increases in artesian pore water pressures may also occur during significant rainfall events.

In general, the theory of steady seepage is useful in determining the pattern of groundwater flow and the distribution of pore pressures in a saturated slope and the surrounding area. Geotechnical engineers are very familiar with numerical solution of such seepage problems.

The magnitude and intensity of rainfall would also have a direct influence on the speed, extent and type of landslide that may occur. Therefore; one should be concerned about the rate of decrease of the factor of safety. The likelihood of a catastrophic failure at a potential landslide site would increase with the increase in the rate of decrease of safety factor. Consequently, depending on the vulnerability of the exposed elements, the total risk will also increase. Other factors which might influence the likelihood of catastrophic failure include adverse geotechnical and erodibility characteristics of soils.

For a regional consideration of landslide occurrence, it is important to highlight the spatial variability of rainfall magnitude during a single rainfall event. Catastrophic landsliding in a region would be characterized by multiple landslide occurrences during a single rainfall event. It can be very useful to define a threshold rainfall event which can lead to widespread landsliding. This can be achieved by careful analysis of past events and observational approaches.

Mitigation of landslide disasters, therefore, requires an understanding of widespread regional landslide occurrences as well as the rate of decrease in factor of safety at significant or major individual landslide sites. Thus a comprehensive landslide inventory must be established as discussed in more detail in subsequent sections of this paper.

2.2 SLOPES IN UNSATURATED SOILS

In many regions of the world; slopes are characterized by upper soil layers which have negative pore pressures or suctions. The initial factor of safety is, therefore, high and can be very high during long dry periods between significant rainfalls. During a rainfall event , as water infiltrates into the unsaturated zone, suctions are eliminated at a rate which depends on the coefficient of permeability of the unsaturated soil. The factor of safety along the wetted part of the slope decreases. Once the wetting front has advanced significantly, the factor of safety along a potential slip surface may fall below the threshold (F=1) thus triggering a complete failure.

Steady seepage theory no longer applies to a slope which has an unsaturated soil zone. Three important differences must be noted. 1) The governing differential equation for unsaturated seepage includes, in addition to the two terms in the steady seepage equation, a term representing the change of pore pressure with time. 2)The coefficients of permeability, in both horizontal and vertical directions, for unsaturated soil are different from those applicable to saturated soil. 3) There is an additional term Q which representing the flux on the exposed boundary. During periods of rainfall Q represents the time rate of infiltration. During rainfall, the field water contents increase, the suctions decrease and thus factor of safety decreases. During dry periods Q represents the time rate of evaporation from the same exposed surface. During dry periods field water contents decrease, suctions increase and thus factor of safety increases. Thus the slope is subjected to cycles of decreasing and increasing suctions and, correspondingly, cycles of decreasing and increasing factor of safety.

2.2.1 NUMERICAL ANALYSIS AND SOIL WATER CHARACTERISTIC CURVE

In order to simulate the change in the factor of safety with time, unsteady seepage analysis must be coupled with limit equilibrium analysis. Distribution of suctions from the seepage analysis must be included in the input data for the limit equilibrium analysis. The factor of safety will fluctuate significantly with time because of the change in Q. Moreover, as suctions change the location of the critical factor of safety changes. Thus fluctuations in F may appear even more abrupt than would be the case if the location of potential slip surface were kept fixed. However, a fixed location for potential slip surface is not a realistic assumption. Another important point is that a soil mass may not be perfectly homogeneous and, therefore, elimination of suctions during rainfall may be accompanied by development of positive pore water pressure in some locations. Field monitoring may assist in identifying assessing such cases.

Analysis and simulation must take into consideration the possible development of a perched water table during rainfall. This may result from local stratification or other factors. For example, part of a potential slip surface may be subjected to positive pore water pressure where the shear strength may decrease earlier and faster than at other parts of the slip surface. The potential for spatial progression of failure can also be considered in such situations.

Considerable research has been carried out about the relationship of soil suction to other soil properties. It has been shown that, for a particular soil, volumetric water content at any location is directly related to suction or negative pore water pressure The relationship is non linear and the curve is called a soil-water characteristic curve. The shape of the curve depends on the type of soil. Numerical solution of the differential equation of unsteady flow can thus be achieved by substituting soil water content for suction using the soil-water characteristic curve.

Broadly speaking, for a specific soil, the lower the soil water content, the higher the suction and, therefore, higher the apparent factor of safety of a slope. Conversely, as rainfall increases, soil water content increases and, therefore factor of safety decreases. If research has been carried out to obtain a reliable soil-water characteristic curve for a sloping soil mass, it is feasible to infer the suction at a particular location based on measured field water content at the same location. Thus the distribution soil water content along a potential slip surface may allow an approximate estimation of factor of safety of a slope in an unsaturated soil at any particular stage of a rainfall event.

The numerical solution of the governing differential equation can also enable the estimation of the rate of decrease of the factor of safety. This may help in assessing the likelihood of catastrophic failure under the assumed conditions of rainfall.

If the water table is at a relatively shallow depth, decrease of suctions in the unsaturated zone may be followed by the increase in water table level. Thus pore water pressures may become positive in some zones which were subject to suctions before the occurrence of rainfall.

Even if the water table location is rather deep, a perched water table may develop due to soil stratification or other reasons. The pore pressures below such a water table would be positive by definition. Thus there may be some uncertainty about the potential failure mechanism unless a careful investigation has been made.

3 APPROACHES, METHODS AND STRATEGIES

Most geotechnical engineers are familiar with methods of geotechnical slope stability analysis which may be applied to both soil and rock slopes. Limit equilibrium methods are still popular and very useful. However, powerful and versatile stress-deformation approaches such as the finite element method have been widely available in recent decades. Such methods have particular advantages in significant projects. Due to geotechnical, geological and other uncertainties, probabilistic methods and risk analysis approaches have also been developed..

One of the benefits of recent research progress is that methods for dealing with landslides and their impacts can include a variety of perspectives. A prudent selection of one or more approaches and strategies would depend upon the scale of the project, its regional context, site-specific location, the available resources and the time-frame for its operation.

Approaches for analysis and understanding may include:

- Deterministic or/and probabilistic methods
- Regional or/and site-specific investigation
- Ladslide inventory and mapping using GIS
- Observational approach or/and modeling and simulation
- Hazard, vulnerability and risk assessment

Strategies for minimizing impacts may include one or more of the following:

- Development controls based on susceptibility and hazard zoning
- Preventive strategies adopted during slope assessment and design
- Remedial actions such as restraining works after landslide occurrence.
- Early Warning Systems

Strategic approaches for management of landslides and for geotechnical risk generally have been discussed by Chowdhury and Flentje (2008), Chowdhury et al (2010, 2012). Before decisions can be made concerning the management of landslides and the mitigation of their impacts, it is necessary to make careful assessments of the potential for instability of specific sites or regions. The limitations of traditional analytical approaches for slope stability assessment are now widely recognized .Experience has shown that assessing the potential of slope instability based on the conventional factor of safety can be misleading. Because of significant uncertainties concerning geological details, geotechnical parameters, pore water pressures and external triggering factors, an understanding of spatial and temporal variability of different factors is very important. Often a deterministic and predictive approach is not sufficient on its own. Observational approaches are very useful for both site-specific and regional assessment and management. Assessment of landslide susceptibility, hazard and risk may require the application of probabilistic concepts and approaches.(Chowdhury and Flentje 2011,Chowdhury and Bhattacharya, 2011).

It is important to survey modern approaches for developing economic and effective solutions for specific sites of instability or to develop strategies for long-term planning of urban development and transportation routes in mountainous regions.

3.1 IMPORTANCE OF RESOURCES FOR DESIGN AND RESEARCH

To highlight the importance of context and the available resources, the phases of a road construction project in mountain areas may include:

- Feasibility study
- Preliminary design
- Detailed design
- Construction
- Operation and maintenance

For low cost roads typical of developing countries only a few percent of the budget may be allocated to feasibility and design which includes research and preventive measures(e.g, 3% feasibility and design, 97% construction). Such resource allocation would not be sufficient for proper assessment and management of potential landslide problems. Increasing the budget for feasibility and design to about 10% of the total may be necessary for road construction in problematic terrain. (Hearn, 2011).Even in developed countries, isolated landslides on minor urban roads may require investment of millions of dollars. Referring to minor roads in the Wollongong region of New South Wales, Tobin (2012) estimated AUD 2.7 million for a proactive response to remediate three rockfall hazards and 4 landslide hazards on Mt. Keira Road. These amounts are in accord with estimates, based on research, of historical expenditure since 1950 on landslide remediation and management to which reference was made in the first section of this paper.

3.2 UNCERTAINTIES IN LANDSLIDE RISK MANAGEMENT

Both qualitative and quantitative approaches to assessment, design and management of slopes and landslide areas require collection, organization and analysis of relevant information. It is inevitable that these processes can be subject to significant uncertainty.

Challenges posed by uncertainties and reliability approaches to assessment of urban slope stability have been discussed previously by Chowdhury et al (2010, 2012), Chowdhury and Flentje (2011) and Chowdhury and Bhattacharya (2011).

Broadly speaking, uncertainty types are:

- Natural Variability
- Systematic uncertainty or error
- Modelling uncertainty

However, it is also useful to consider uncertainty in separate categories, each with components of variability and systematic error.

- Geotechnical parameter uncertainty
- Geological uncertainty
- Hydrological uncertainty,
- Uncertainty related to historical data
- Uncertainty of triggering events including temporal

3.3 DEFINING CONDITIONS FOR CATASTROPHIC LANDSLIDING

Conventional methods of analysis seek to define and deal with 'failure' or unsuccessful performance which is then regarded as the indicator .for landslide occurrence. Within a probabilistic framework the focus changes to defining and estimating 'the probability of failure'. However, the definition of failure or landslide occurrence may include a wide range of slope displacements. Therefore; an important challenge is to define 'catastrophic failure' or catastrophic landslide. Despite the availability of powerful tools such as limit equilibrium and finite element methods, amongst others, the assessment of potential for catastrophic landsliding has received little attention. The following suggestions may facilitate relevant research:

(a) One important step forward would be to compute the rate at which the factor of safety of a slope decreases with time when approaching critical equilibrium Research should enable definition of threshold rate of change of factor of safety for catastrophic landsliding. Within a stress deformation analysis framework, the rate of increase in critical displacement would be a corresponding indicator. Research would also be required to define a critical triggering event for catastrophic landsliding. For rainfall induced landsliding, for instance, this means establishing, from historical records the relevant intensity-duration relationships which might cause catastrophic landsliding (for either site specific or regional events).

(b) Another step forward might be to track the rate of decrease of factor of safety on a number of potential slip surfaces and not just the critical slip surface. Under certain conditions, the factor of safety may reach critical levels on multiple slip surfaces leading to 'catastrophic landsliding'. It is reasonable to assume that such conditions develop during exceptional rainfall events. Research would be required to determine what constitutes an exceptional rainfall event in the specific area or region.

(c) Moreover, other factors which may contribute to 'catastrophic landsliding' must be identified and their magnitude assessed on a qualitative or quantitative basis. These might include the potential for

- Soil erosion including internal erosion
- Progressive spatial expansion of a failure zone
- Static or dynamic liquefaction.

4 REGIONAL LANDSLIDE HAZARD ASSESSMENT

4.1 KEY ELEMENTS

Regional landslide management studies are typically carried out within the framework of a Geographical Information System (GIS). Such approaches also facilitate planning for geohazards especially in urban areas (Gibson and Chowdhury, 2009). There are several fundamental elements of using a GIS based approach. These include: (a) digital elevation model (DEM) which represents the topography of the study area in three dimensions, (b) geo-referenced aerial or satellite based imagery, (c) a comprehensive inventory of existing landslides including reactivations, (d) relevant data sets relating to the main influencing factors of the study area such as geology, soils, vegetation, cadastre, land use, assets, boreholes and other relevant factors, (e) selection of GIS software, and (f) modeling and simulation techniques.

4.2 LANDSLIDE INVENTORY

It is important to develop a landslide inventory and to prepare of maps showing the distribution of existing landslides. A comprehensive landslide inventory should have several fields of information in order to capture the history of instability, the size of landslide and information on geological and geotechnical details. Landslide maps should identify different landslide categories such as slides, debris flows and rockfalls.

4.3 LANDSLIDE SUSCEPTIBILITY, HAZARD AND RISK

GIS-based approaches are used for the development of maps of landslide susceptibility and hazard. In general, there will be significant differences between the distribution and relative susceptibility and relative hazard of different landslide categories. There are several elements in modeling and simulation using a GIS-based approach. These include a digital elevation model(DEM) representing the topography of the study area in three dimensions, a comprehensive landslide inventory ,and data-sets relating to the main influencing factors such as geology, soils, vegetation, cadastre, land use ,assets, boreholes. The DEM is generally used to derive elements of topography such as slope inclination, slope aspect, slope curvature and drainage. Brief references will be made to the methodology for assessment of risk

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

Topographical details such as slope inclination, slope aspect, slope curvature and drainage can be derived from the DEM. Recently, 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 the data provides high resolution contemporary digital elevation models (DEMs). Prior to the advent of this technology, DEMs were typically derived from 10 to 50 year old photogrammetric contour datasets. Increasingly, ALS datasets are also being collected in tandem with high resolution geo-referenced imagery.

4.5 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 both for site-specific and 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 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. Continuous monitoring data supplied in real-time via the web is also of tremendous value to asset and risk management operations.

5 REGIONAL CASE STUDY, WOLLONGONG REGION

The University of Wollongong Landslide Research Team (UOW-LRT) has been involved in this long-term research project for several decades. 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 have been described in detail elsewhere (e.g. Flentje 2009) and 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).

5.1 WOLLONGONG 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, andSlides) including 480 slides. Amongst the 426 landslides within the Susceptibility Model Area, approximate landslide volume has been estimated for 378 of these sites. The average volume is 21800 m3 and the maximum 720,000 m3.

5.2 KNOWLEDGE-BASED MODELING OF LANDSLIDE SUSCEPTIBILITY (DATA MINING)

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).

5.3 SUSCEPTIBILITY OUTCOMES

The Susceptibility classification that has been developed for Wollongong thus far relates to 'slide' category landslides only. Susceptibility zones (Fig.1) have been classified as (a) high susceptibility with 8.12% of this area subject to landslides and containing 60.3% of the known landslide population, (b) moderate susceptibility with 4.12% of this area subject to landslides (contains 32.3% of known landslides), (c) low susceptibility with 0.85% of area subject to landslides (contains 3.3% of known landslides), and (d) very low susceptibility with 0.09% of the area subject to landsliding (contains 4.1% of known landslides) and yet representing 70.9% of the study area. The high susceptibility zone extends over 23 square km. Furthermore, the model also identifies over 130 square km as having a very low susceptibility to landsliding. Each landslide is identified as such and does not therefore comprise part of any susceptibility zone.

A useful method has been developed for quantitative interpretation of the scale of susceptibility and hazard from 'High' to 'Very Low' as discussed elsewhere (Chowdhury and Flentje, 2011). This methodology can be developed further to take into consideration the spatial and temporal variability within the study area.

5.3.1 HAZARD ASSESSMENT

The 'Slide' category Susceptibility maps described above have been enhanced with additional detail regarding landslide volume, frequency and travel distance. This information appears as unique landslide site labels for each site and with text boxes appearing on the map sheet frame outlining the distributions and averages of these values for each of the individual hazard zones. With these additional details, the maps can be regarded as 'Slide' category Hazard maps (Figure 2). On these maps, the Susceptibility and Hazard zones have the same boundaries.

On both the Susceptibility and Hazard maps, each landslide site is identified and labeled with its own unique Site Reference Code. On the Hazard maps, the label for each landslide also includes its volume (m3). Landslide Frequency has been calculated from the total number of landslide occurrences within a zone including all reactivations (see Table 1). The specific landslide frequency for each landslide appears as the third label for each landslide. The average annual landslide frequency has been determined for all landslides within each Hazard Zone. The average distribution of landslide frequency between the years 1880 to 2006, and for the period 1950 to 2006 is shown in Table 1. The shorter period is based on more complete data and is considered to be more reliable. An indicative annual probability of landsliding for each hazard zone should be based on a number of selected factors including this frequency data and expert judgment.

The 'profile angle' appears as the fourth label for each landslide site. This profile angle has been determined by digitizing a point mid way along the rear main scarp and at the toe and querying the elevation at each of these points using a 2m DEM elevation grid. The profile angle of known landslides is important as it has implications for landslide mobility. It is also very useful to consider the distribution of the profile angles (the average is 17o) and this is also featured in one text box.

Table1 Zones of landslide frequency and volume based on the Landslide Inventory.

Hazard Description	Landslide Annual Average Frequency (1880 - 2006)	Landslide Annual Average Frequency (1950 - 2006)	Maximum Landslide Volume (m^3)	Average Landslide Volume (m^3)
Very Low	0.0098	0.0165	36,300	3,500
Low	0.0102	0.0172	4,700	1,450
Moderate	0.0125	0.0221	45,000	5,700
High	0.0144	0.0247	720,000	28,700

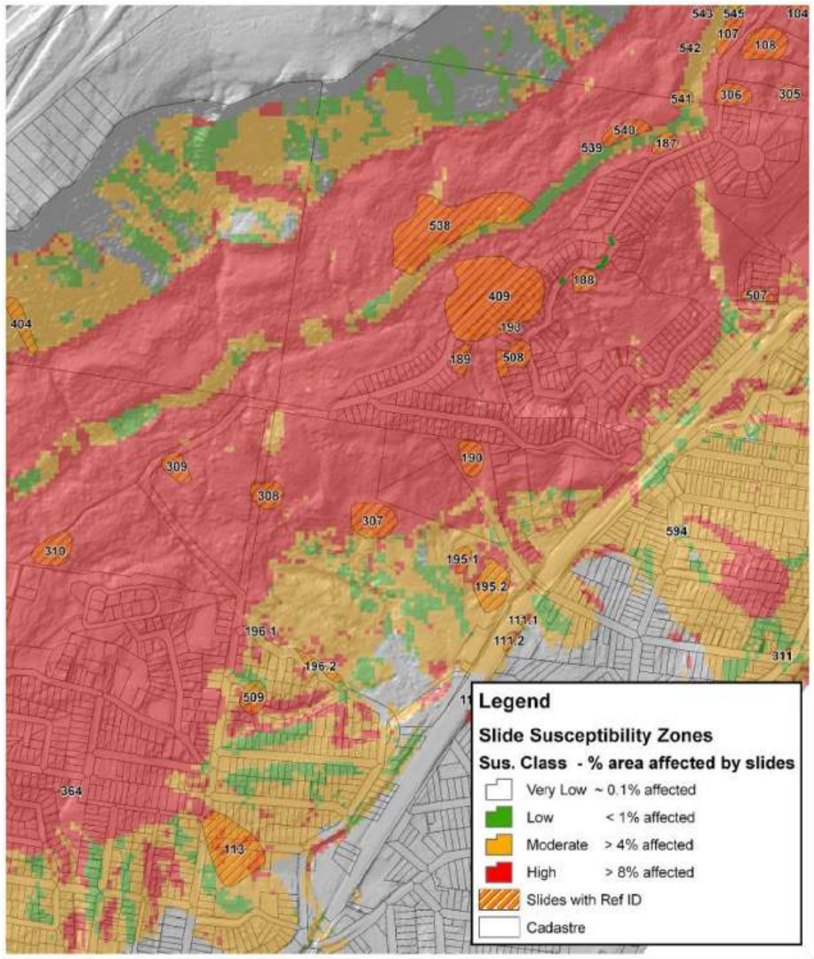

Figure 1. Segment of Landslide Inventory and Susceptibility Zoning Map, Wollongong Local Government Area, New South Wales, Australia.

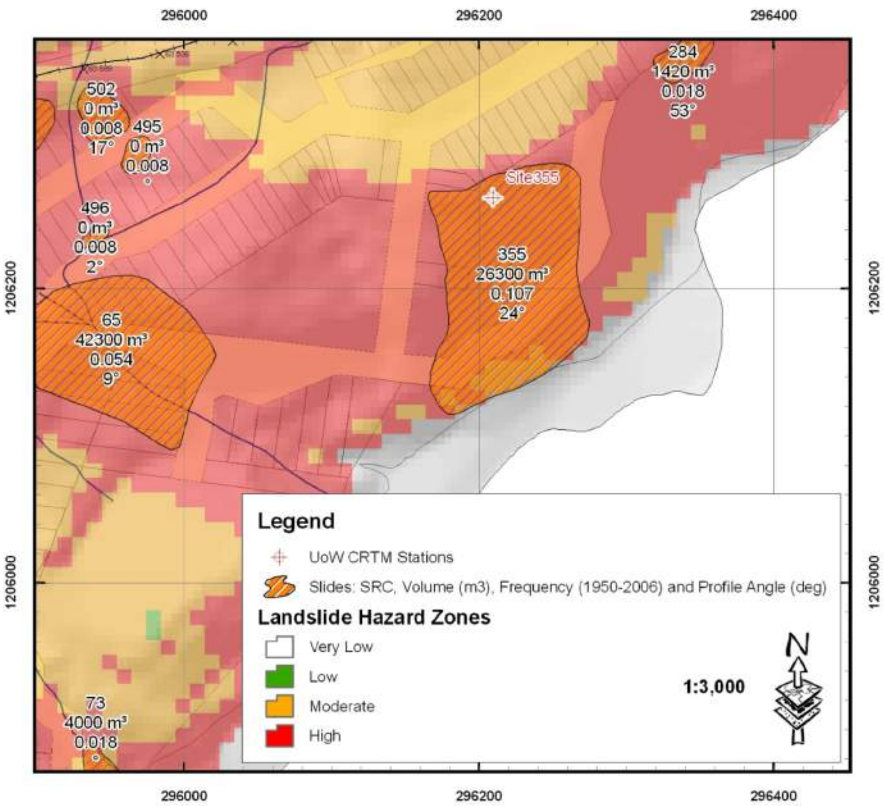

Figure 2. Segment of the Landslide Hazard Map.

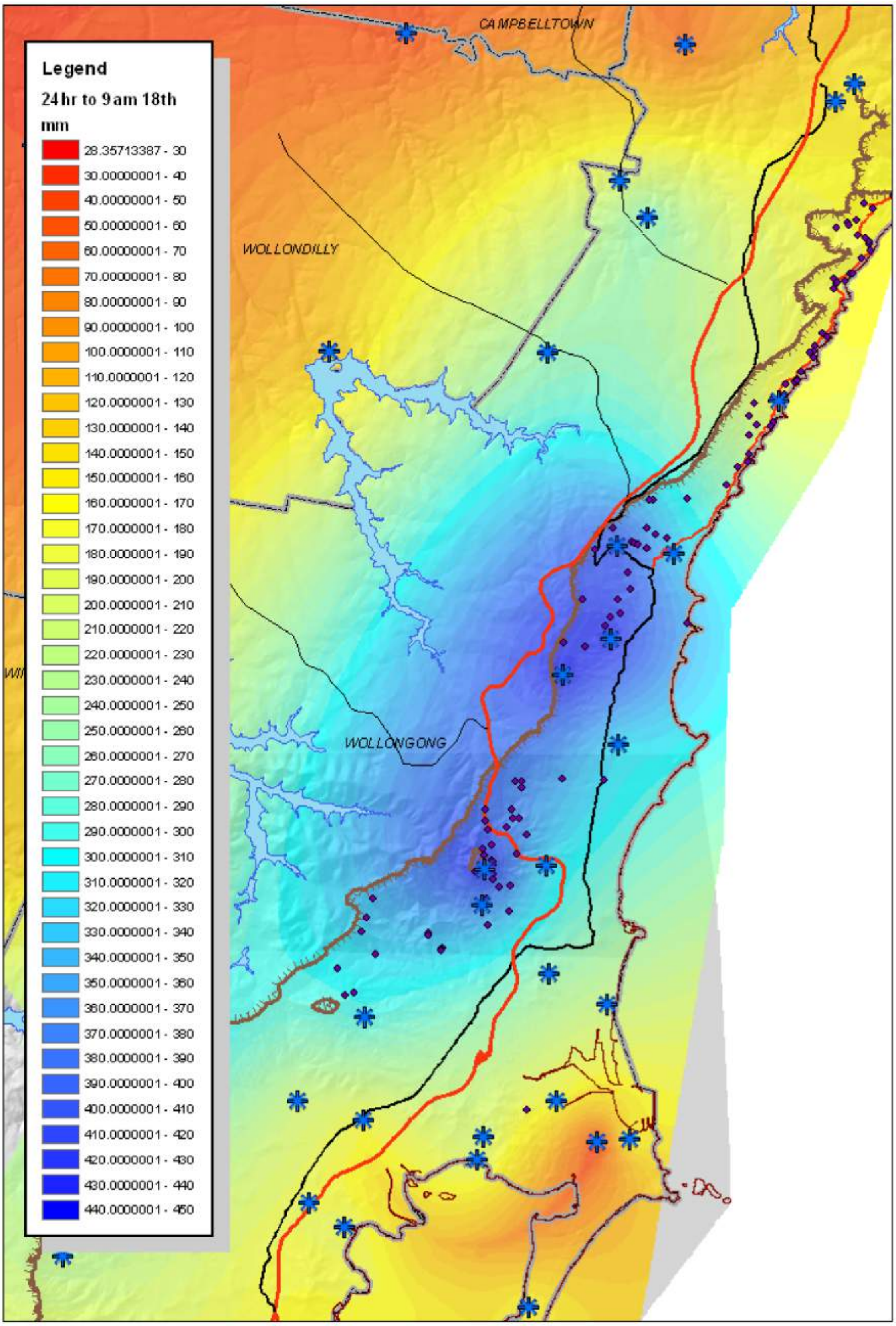

Figure 3 Rainfall distribution (24hrs to 0900hrs 18th August) during the August 1998

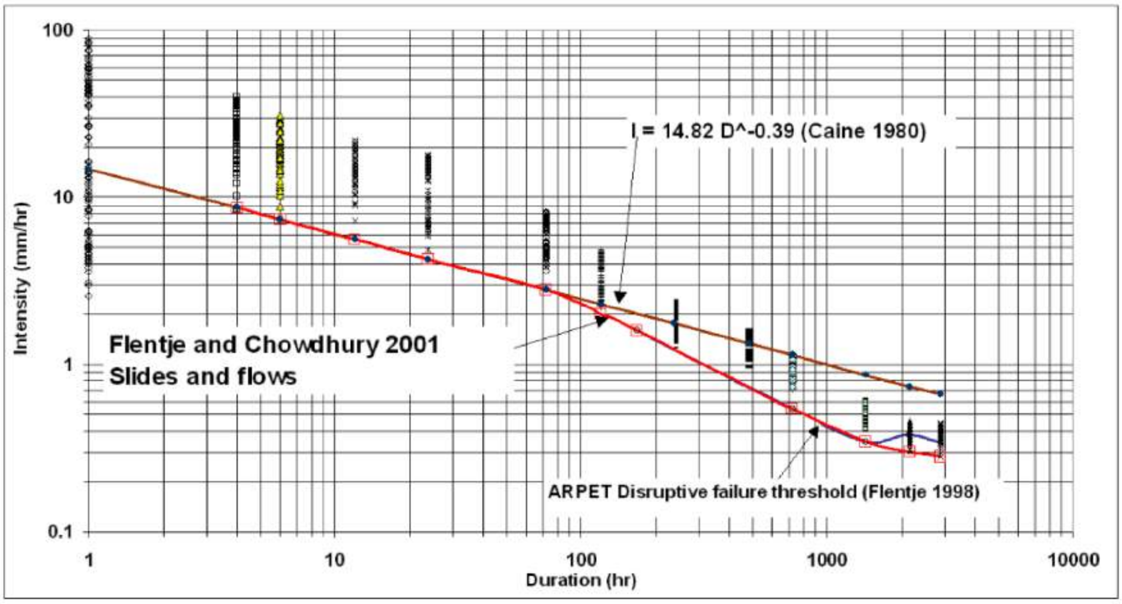

Figure 4 Summary rainfall Intensity and Duration for all 142 landslide sites during the August 1998 rainfall event combined with ARPET thresholds for the longer durations. The lower bound envelope from the August 1998 event (Flentje and Chowdhury 2001) is compared with Caine, 1980.

6 RAINFALL THRESHOLDS FOR TRIGGERING OF LANDSLIDES

The UOW-LRT has been researching rainfall distribution, landslide occurrence and monitored displacements for over 15 years. By August 1998 sufficient data had been collected such that qualitative predictions of widespread landsliding could be made during the exceptional rainfall event from the 15th to 19th August 1998.

Prior to this event, correlations were based on manual landslide inclinometer monitoring records and daily rainfall data from the Australian Bureau of Meteorology. Cumulative rainfall values were calculated for different antecedent periods varying from 3 days up to 120 days. By comparing these values in relation to the monitored landslide displacements in the field it was possible to estimate the approximate thresholds. Initially, this data was analyzed using a proposed concept of Antecedent Rainfall Percentage Exceedance Time (ARPET).

Two developments resulted from the Aug 1998 event. Firstly, the UOW- LRT analyzed in great detail the spatial and temporal distribution of rainfall and landslides during the August 1998 event itself (Figures 3 and 4).

Secondly, the UOW-LRT in collaboration with industry partners commenced the establishment of a network of field monitoring stations for real-time continuous monitoring of rainfall, pore water pressures and surface and subsurface landslide displacements.

Plotting rainfall intensity versus duration was found to be very useful for making interpretations concerning rainfall triggering thresholds and for comparison with research from other sources internationally. It was also found useful to superimpose relevant annual rainfall recurrence curves which have been well established in the hydrological discipline (ARR, 1998). Two interpretations of the regional threshold (lower bound) for landsliding are shown in Figs 4 and 5. Note that there are two separate curves in Fig 5, the lower one for 'warning' and the upper curve for 'alarm'. The lower curve indicates the highest rainfall below which no landslide movement has been detected.

The current goal of the UOW-LRT is to develop threshold curves for specified magnitudes of movement. This research is now feasible because of the data being collected at the network of continuous monitoring stations. An example of thresholds based on a record of continuous data is shown in Figure 6.

Landslide assessment and management in the Wollongong region of New South Wales has been a focus of research over the last two decades and includes the following key elements

This section will deal with the Outcomes of susceptibility and hazard zoning for an urban area, the Illawarra region within the state of New South Wales, Australia. This section will also explain how the relative susceptibility and hazard of different zones may be quantified using the available historical data of landslide occurrence.

6.1 OBSERVATIONAL APPROACH

A modern observational approach includes the setting up of monitoring stations which may include rainfall stations, inclinometers, piezometers and extensometers. Site-specific monitoring helps understand and manage individual landslides and to develop early warning systems. Observation and monitoring also facilitate the understanding of widespread landsliding (multiple occurrences of instability) after a heavy rainfall or another external event. Continuous or near-real-time monitoring of rainfall, pore water pressure and landslide displacement has been carried out at a number of sites in the study area. The data can be

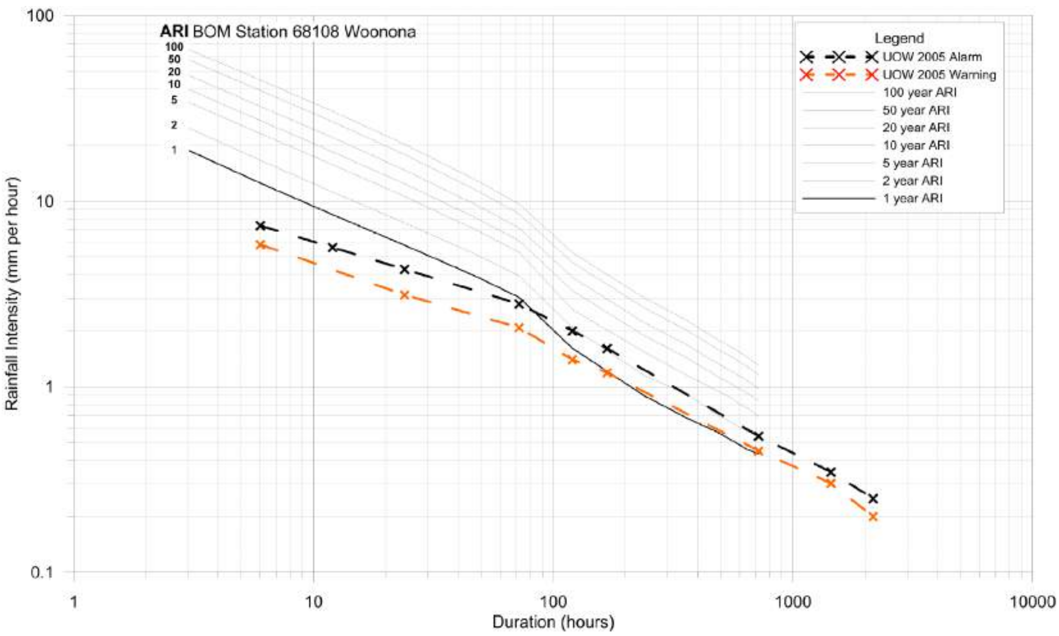

Figure 5. Regional rainfall threshold curves (lower bound) based on all monitoring records to 2004.

accessed via the web in real time. This part of the research has been described in other publications but is excluded here due to space limitations. Data from landslide monitoring (periodic as well as continuous) enables the updating of landslide susceptibility, hazard and risk. In particular, continuous monitoring data can facilitate early warning risk management and mitigation of impacts.

6.2 LANDSLIDE-TRIGGERING RAINFALL THRESHOLDS.

Detailed analysis of rainfall magnitude and frequency is necessary for understanding rainfall thresholds for occurrence of landsliding. This can be done on a site-specific basis as well as a regional basis. There are, of course, advantages and disadvantages in each case .Examples will be provided of spatial and temporal distributions of rainfall during a period of very heavy rainfall.

6.3 MITIGATION OF LANDSLIDE IMPACTS AND/ OR POTENTIAL DISASTERS

The above strategies play a significant role in understanding and managing landslide risk The management of landslides and mitigation of their impacts can also benefit in a significant way from these approaches. However, observational approaches greatly enhance the strategic management of landslides during every major phase such as prevention, remediation, early warning and recovery. Each project has its own specific requirements and a strategic approach must be flexible to accommodate individual project aims and goals. More importantly future challenges must be considered carefully developed new or expanded strategies for landslide research and management.

7 DISCUSSION AND CONCLUSIONS

The focus of this per has been on mitigation of landslide impacts with particular reference to rainfall-triggered landslides. Reference has been made to main categories of landslides, the context of their occurrence and the range and significance of their impact which depends on a variety of factors such as magnitude, velocity and travel distance as well as the elements at risk. Understanding of failure progression is necessary for more accurate analysis of slopes and landslides especially in strain-softening soils. After an initial landslide occurs, considerable spatial expansion may occur by processes of progression or retrogression. Such spatial development is not to be confused with post-failure movement (travel) of a landslide Significant and continuing economic impact of landslides needs to be appreciated in order that more resources become available for research, design and preventive management. Recent research has enabled a much better understanding of rainfall –triggered landsliding in unsaturated soils in comparison to landsliding in saturated soils. The key aspects are covered in this paper. Improved knowledge of failure mechanisms and processes can lead to better methods of analysis and more effective early warning systems.

In this paper attention is given to the need to define ‘catastrophic failure’ or catastrophic landsliding’. Some ideas are proposed including assessment and tracking of rate of decrease of factor of safety with time under particular conditions which might include a particular triggering agent.

Methods used and the outcomes achieved in the preparation of zoning maps for landslide susceptibility and hazard have been outlined in brief. Quantitative interpretation of different susceptibility and zoning classes such as ‘high’, ‘moderate’ , ‘low’ and ‘very low’ has been discussed elsewhere (Chowdhury and Flentje,2011) .

Aspects of research concerning the development of rainfall thresholds for landsliding have been presented. Monitoring of real-time slope displacements and pore pressures has been covered in previous publications but not included here due to space limitations.

A 'warning' or 'alarm' system may be based on rainfall intensity-duration plots supplemented by continuous monitoring.

There are continuing challenges such as (i) trying to use the continuous pore pressure data from monitoring to greater advantage and (ii) trying to 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.

Landslides will, over time display a continuum of movement magnitudes and rates in response to the environmental factors that affect the site. One of the lesson from the case studies in the study area is that even very low magnitude landslide displacements may be unacceptable in certain situations. For example the disruption of traffic on a major highway or railway line can have enormous economic and safety consequences.

Research into the effects of climate change and, in particular its implications for geotechnical engineering are urgently needed. 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.

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.

8 REFERENCES

ARR, (1988). Australian Rainfall and Runoff. Institution of Engineers, Australia

Caine, N. (1980). The rainfall intensity: duration control of shallow landslides and debris flows. Geografiska Annaler. Series A. Physical Geography, 62(1/2), 23-27. Retrieved from http://www.jstor.org/stable/520449?origin=crossref doi:10.2307/520449

Chowdhury, R., & Bhattacharya, G. (2011). Reliability analysis of strain-softening slopes. Paper presented at the 13th international conference of IACMAG, Melbourne, Australia (Vol. 2, pp. 1169-1174).

Chowdhury, R., & Flentje, P. (2008). Strategic Approaches for the Management of Risk. Paper presented at Geomechanics, Theme Paper, Proc. 12 IACMAG conference, Goa, India, CD-ROM (pp. 3031-3042).

Chowdhury, R., & Flentje, P. (2011). Practical Reliability Approach to Urban Slope Stability. Paper presented at the 11th Int. Conf. on Application of Statistics and Probability in Civil Engineering, ETH, Zurich, Switzerland (pp. 1-4).

Chowdhury, R., Flentje, P., & Bhattacharya, G. (2010). Geotechnical Slope Analysis : CRC Press, Balkema, Taylor and Francis Group.

Flentje, P. (2009). Landslide inventory development and landslide susceptibility zoning in the Wollongong City Council Local Government Area. Unpublished Report to Industry Partners-Wollongong City Council, RailCorp and the Roads and Traffic Authority, University of Wollongong, Australia, 73.

Flentje, P., Stirling, D., Science, C. R., Management, E., Vail, M., & 3-8, C. J. (2007). Landslide Susceptibility and Hazard derived from a Landslide Inventory using Data Mining – An Australian Case Study. Paper presented at the First North American Landslide Conference, Landslides and Society: Integrated Science, Engineering, Management, and Mitigation, Vail, Colorado June 3-8, 2007. CD, Paper number 17823-024 (pp. 1-10).

Gibson, A. D., & Chowdhury, R. (2009) Planning and geohazards. In M. G. Culshaw, H. J. Reeves, I. Jefferson, & T. W. Spink (Eds.), Engineering geology for tomorrow's cities (pp. 113-123). London: Engineering Geology Special Publication.

Hearn, G. J. (2011). Slope Engineering for Mountain Roads. London: Geological Society, Engineering Geology, Special Publication.

Palamakumbure, D., Stirling, D., Flentje, P., & Chowdhury, R. (2013). ArcGIS v.10 Landslide Susceptibility Data Mining add-in tool integrating data mining and GIS techniques to model landslide susceptibility. Paper submitted, XII IAEG Congress, Torino, Sept, 2014.

Quinlan, R. (1993). C 4.5: Programs for Machine Learning. San Mateo, CA: Morgan.

Tobin, P. R. (2012). Manage slope instability hazards affecting local roads within the city of Wollongong. Australian Geomechanics Journal, 47, 53-58