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Aspects of recent landslide research at the University of Wollongong

Abstract

This paper introduces the issues which are of critical importance to landslide hazard and risk assessment and management. These include understanding of probability and consequence, the separation of the role of site-dependent factors from that of influencing/triggering natural events and the factors influencing target levels of risk. The research completed at the University of Wollongong is then outlined. This includes the development of an observational approach based on monitoring of subsurface movements at individual sites and appropriate use of rainfall data in terms of the concept of annual rainfall percentage exceedance time (ARPET). Attention is then focused on current research including the development of a hazard-consequence matrix approach for risk assessment at individual sites. Another important research task concerns the development and assessment of magnitude - cumulative frequency relationships for landslides in the study area.

Keywords

aspects, wollongong, landslide, university, research, recent

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Aspects of Recent Landslide Research At the University of Wollongong

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ABSTRACT:

This paper introduces the issues which are of critical importance to landslide hazard and risk assessment and management. These include understanding of probability and consequence, the separation of the role of site-dependent factors from that of influencing/triggering natural events and the factors influencing target levels of risk. The research completed at the University of Wollongong is then outlined. This includes the development of an observational approach based on monitoring of subsurface movements at individual sites and appropriate use of rainfall data in terms of the concept of annual rainfall percentage exceedance time (ARPET). Attention is then focused on current research including the development of a hazard-consequence matrix approach for risk assessment at individual sites. Another important research task concerns the development and assessment of magnitude - cumulative frequency relationships for landslides in the study area.

1 INTRODUCTION

This paper is concerned with concepts of hazard and risk relevant to existing and potential areas of slope instability and landsliding. Aspects of research work being carried out at the University of Wollongong (state of New South Wales, Australia) are highlighted. Attention is drawn to recent developments reported by researchers and professionals working at other locations.

The scope, scale and methodology of landslide hazard and risk assessment can vary significantly depending on the aims and objectives. For example, the main aim may be to carry out a comprehensive regional study for planning and/or emergency management. In such cases, most of the effort would be devoted to the preparation of maps of hazard and/or risk. Such maps are now increasingly developed using computer-based techniques within the framework of a Geographical Information System (GIS).

Qualitative or semi-quantitative methods and techniques, generally used for such regional studies, include the following:

- Geomorphological analysis and stereo aerial photo interpretation
- Synthesis based on overlay of index maps (or parameter maps or state-of-nature maps) often with the use of weighting factors
- Statistical analyses, bivariate or multivariate.

The use of GIS-based methods has been discussed in some detail by Soeters and Van Westen (1996). A comprehensive review of the different assessment and mapping approaches, including those mentioned above, has been presented by Aleotti and Chowdhury (1999). The important role of GIS and the associated limitations and pitfalls under certain circumstances have been discussed briefly by Chowdhury (1999).

Instead of a regional study, the main aim of hazard and risk assessment may be to facilitate decision-making concerning new developments within urbanised sloping areas susceptible to landsliding. Alternatively, the main aim may be to facilitate the management of operations and medium to long-term developments for a railway or a highway passing through terrain susceptible to landsliding. In such cases, detailed assessment is necessary to identify and prioritise potential problem areas and individual sites and it is, therefore, useful to prepare maps on a relatively large scale (>1:10,000). The methods and techniques which may be used include the following in addition to those mentioned above:-

- Qualitative approach based on historical records and engineering judgement
- Observational approach based on surface and subsurface monitoring of sloping areas
- Hazard-consequence matrix framework
- Geotechnical modelling and deterministic and/or probabilistic analyses
- Analysis of data concerning influencing/triggering natural events such as rainstorms or earthquakes

2 CRITICAL ISSUES FOR ASSESSMENT AND MANAGEMENT OF LANDSLIDE HAZARD AND RISK

There are a number of important issues to be considered in carrying out studies for landslide hazard and risk assessment including the following:-

- Appropriate definitions of terms such as hazard, vulnerability and risk.
- Defining the categories or levels of each of the above in quantitative or qualitative terms
- Understanding and quantifying acceptable or tolerable levels of hazard and risk, and specifying target levels of risk for specific situations
- Understanding the relationship between magnitude (size) of landslides and their frequency
- Understanding the analysis of the relationship between the return periods of influencing/triggering events and the occurrence of landslides

Hazard of landsliding is dominated by probability but should also include the magnitude (size), velocity and travel distance. Predictions of size, velocity and travel distance are generally difficult to make and the term 'hazard' is often used interchangeably with 'probability'. While this is often useful especially for comparing similar types of landslides, it is an oversimplification which can be misleading for comparative assessment of different types of landslides. More importantly, the effects of such an oversimplification on decision-making require careful consideration.

Another aspect of hazard concerns the separation of the role of site-dependent factors from that of influencing/triggering natural events. It would be more logical to use a term such as 'susceptibility' to denote the probability of landsliding based on factors such as geomorphology, local geology and geotechnical parameters. Susceptibility should, where appropriate, be combined with the probabilities of influencing/triggering events. For example, rainfall events may have significant influence on the pore water pressure and, therefore, the probability of assumed pore water pressure values should be used in arriving at the probability of landsliding. The latter would then be a product of (a) susceptibility (b) the probability of the rainstorm with a given return period occurring with the project life and (c) the probability that if such a rainstorm event occurs, it will result in the assumed pore water pressures.

Risk includes hazard of landsliding as well as the consequences. In order to consider the consequences of landsliding it is necessary to consider the elements at risk and their value. These assessments should include damage to property and the environment and the loss of or injury to human life. In order to consider the elements at risk, it is important to distinguish between the detachment zone and the accumulation zone. The hazard varies spatially and will, in general, be different in the two types of zones. The importance of assessing velocity and travel distance is again highlighted. Having considered the elements at risk, it is necessary to consider the vulnerability of these elements to damage and destruction. Again this would apply in different ways to property, environment and human life.

Consideration of target levels of risk or tolerable/acceptable levels is very important. However, the determination of these levels or values involves complex issues such as individual versus societal acceptance and voluntary versus involuntary risk acceptance.

Beyond such issues is the relationship between frequency, consequence and risk acceptance. The less frequent an event, the greater is likely to be its magnitude and, therefore, the more damaging are its consequences. Lower values of acceptable failure probability are generally associated with relatively higher consequence events and vice versa. A probability - consequence diagram was proposed by Whitman (1984) and researchers as well as practitioners continue to refer to this diagram showing generally accepted risk levels (combinations of probability and corresponding consequence in (a) dollars and (b) human lives) for typical engineering and other projects/applications. It also

shows two lines representing bounds for 'accepted' and 'marginally accepted' risk respectively. The subject of acceptable risk has also been discussed by Fell (1994), IUGS (1997) and Aleotti and Chowdhury (1999). Further consideration of this issue is outside the scope of this paper.

3 RECENT RESEARCH STUDIES AT THE UNIVERSITY OF WOLLONGONG

3.1 Background to Slope Stability Problems

The purpose of this section is to outline recently completed work at the University of Wollongong. The primary aim of the initial studies was to identify the major influencing factors for slope instability in the urbanised hilly areas of this city and to develop effective methods of assessment and management of these areas. Landslides also impact the operation of highways and the railway line from Sydney to Wollongong and, therefore, research concerning better prediction and management methods has a high priority for the concerned government agencies.

During preliminary work, existing maps of geology and landslides were found to be outdated and, in parts, inaccurate. A hazard zoning scheme had been developed by HN Bowman, a geologist, in 1971 and the relevant maps showing these zones have been available for reference to the City Council as well as to members of the public. However, the limitations of these zoning maps became increasingly obvious. Therefore, from time to time since 1971, the City Council also commissioned detailed reports or studies for some individual residential suburbs of the City of Greater Wollongong.

Bowman's 1971 maps and the detailed studies carried out since then have facilitated decision-making by the City Council on applications for the development of new residential subdivisions in the hilly suburbs or for the development of individual blocks of land in existing hilly suburbs. It was recognised that the perception of hazard could change with time for any sloping area. In particular, reassessment of suitability for development became necessary even for existing subdivisions when more accurate and new information about slope instability or about geological and geotechnical details became available.

Significant community concerns about urban landslip have been recognised over the last 30 years. During rainfall years, the local media have publicised these concerns but the issues were not canvassed actively in the intervening years. Concerns were not limited to landslide damage to houses, potential or actual. Affected suburbs could lose in terms of property values whether particular houses were damaged by landslip or not. Lack of availability of insurance against landslip compounded the problem. There has also been unwillingness on the part of some property owners to report damage to houses for fear of loss of property values. Such a practice, the full extent of which has not been established, hinders research workers as the observational evidence remains incomplete.

The City Council has also been concerned about issues of liability for decisions concerning development in hilly areas. There has been an increasing tendency for owners (of property affected by landslip or by decisions about land with suspected or presumed susceptibility to landslip) to go for or to contemplate litigation against others including, of course, the City Council. Consequently, increasing emphasis has been placed on the need for development applications to include geotechnical reports prepared by qualified consultants.

In this process it became obvious that there was an urgent need not only for more accurate maps of geology and landslides but also for appropriate definitions of terms such as susceptibility, hazard, vulnerability and risk and, within an appropriate framework, classification of landslide hazard and/or risk into several grades or categories.

Damage affecting the highways and the railways line has continued to occur although millions of dollars have been spent on upgrading and on preventive/remedial measures against landslip. The occurrence of an embankment failure-mudflow at Coledale in 1988, which caused the loss of two lives, has highlighted the need for better methods of hazard risk assessment and management.

Against this background, research at the University of Wollongong has covered a number of areas as outlined below.

3.2 Development of Databases

Geological and geotechnical information about the area of study was compiled from a number of sources including mining companies, government agencies and geotechnical consultants. Valuable information on major geological discontinuities became available from detailed subsurface investigations carried out over decades on behalf of government agencies or private industry. A major effort was then devoted to the development of a landslide database.

The main requirements for such a database include (a) A unique site reference code (b) nature and history of slope instability (c) whether a first time occurrence or a renewal of landslide movement and the dates of occurrence/recurrence (d) uncertainties concerning boundaries, dates etc (e) size, location and relevant details such as type of movement (classification and basis for it) and velocity of movement (again the basis of velocity classification) (f) any remedial or preventive measures installed and the related performance (g) geotechnical parameter from any previous site investigation and/or from back analyses.

Further details of the developed geotechnical database of 328 sites, each with 60 primary fields of information are given by Chowdhury and Flentje (1998).

3.3 GIS - based Maps of Geology and Existing Landslides

Maps were prepared for the northern suburbs of the City of Greater Wollongong as these suburbs include significant areas of landsliding. A modern, computer-based approach was used for the development of these maps within the framework of a Geographical Information System (GIS). In addition to preparing maps of geology, all the landslides which could be recognised from visual observation or from aerial photographs were mapped. A scale of 1:4000 was used for these maps and it is important for development of hazard assessment approaches to note that topographic maps of the area with 2 m contour interval are also available for this region on a 1:4000 scale. This scale is very convenient for desktop studies and for detailed assessment of individual subdivisions within any suburb.

An important aspect of the task of preparation of these maps was their validation including direct field checking. Considerable effort was devoted to field work for geology and for inspection of existing landslide areas and locating their boundaries.

3.4 Subsurface Monitoring

A number of sites have inclinometers and piezometers installed. These instruments are owned and/or operated by different organisations who provided access to the University for monitoring these sites. This new data has been combined with data from previous monitoring (where available) for a study of progressive lateral or shear movements of individual landslides.

This data can be used as part of the proposed 'observational approach' for landslide hazard assessment. Such an approach is different in concept from the well-known 'observational method in soil mechanics' which was developed and promoted so ably by eminent professionals such as Casagrande, Terzaghi and Peck. That well known approach involves the updating of geotechnical design during construction based on the observed magnitude of selected stress or deformation parameters. On the other hand the Chowdhury & Flentje approach is concerned primarily with the assessment of temporal frequency of landslide events (significant episodes of accelerated lateral movement) related to causative natural events such as rainstorms.

There are 50 inclinometers over 23 sites listed in the geotechnical database. In comparison, the number of piezometers is small. Therefore, it has not been possible to use piezometer data as extensively or effectively as the inclinometer data. Consequently, the analysis of rainfall data in relation to the performance of individual areas and slopes has been given a great deal of emphasis.

3.5 Rainfall Analyses

Data from several rainfall stations is available over many decades on a daily basis. Studies by other research workers and geotechnical consultants have suggested that prolonged periods of heavy rainfall

produce most of the landsliding in the study area. This applies especially to most of the deep-seated and slow-moving landslides which are characteristic of the study area. Relatively superficial slope instability, including debris-flows, may, however, be triggered by short duration high intensity rainstorms. Such occurrences are relatively rare and are of relatively small size.

In order to establish the magnitude of cumulative antecedent rainfall which might be most likely to cause or trigger instability, different periods of antecedent rainfall were considered (7 days, 1 month, 2 months, 3 months).

Cumulative plots of rainfall versus time were developed for each of these periods.

3.6 *ARPET Concept/Approach*

A methodology was developed to determine from the rainfall curves the values of ARPET (antecedent rainfall percentage exceedance time) over two specified historical periods, 20 years or 110 years. For each historical period different values are obviously obtained for each period of cumulative antecedent rainfall selected (eg. 1 month, 2 month, 3 month). Each ARPET value can be interpreted as a probability of particular cumulative rainfall assuming a selected antecedent period of rainfall and considering a selected historical period of rainfall data.

The ARPET values may be considered in relation to curves of lateral/subsurface shear movement magnitude versus time. Many of the large deep-seated landslides exhibit episodic and variable rates of movement. From such curves, events of 'failure' were identified as episodes of accelerated movement or sustained values of peak movement. Other recorded observational evidence such as surface disruptions may also be used to help identify these 'failure' events. Once identified, such occurrences can then be plotted on the ARPET curves. By superimposing the movement-time curves and the antecedent-rainfall time curves, the most appropriate period of antecedent rainfall (and, therefore, the appropriate ARPET curve) can be identified. (Flentje and Chowdhury, 1999)

In order to have a basis for future landslide hazard assessment which requires a probability of occurrence, the ARPET value itself may be used as the probability. While appropriate to rainfall-induced slow-moving landslides in the study area, extension of such an approach to other areas and to other types of landslides must be considered on the basis of individual circumstances and evidence.

3.7 *Hazard Ranking*

An important advantage of developing a comprehensive landslide database including the history of each landslide is that the frequency of occurrence of all the landslides can be compared. This has been used as a basis for ranking, in order of probability or hazard, all the 328 landslides. Moreover, another definition of hazard was also used for an alternative ranking. In this approach the volume in cubic metres of each landslide was evaluated and the product of the frequency (assumed as the probability) and the logarithm of volume was calculated as the hazard. The hazard ranking was then carried out for all the 328 landslides. Both approaches were found to be remarkably consistent with the known records of historical impact of landslide damage (houses destroyed or damaged) although, as can be expected, the detailed results from each approach were different for some of the sites.

The ARPET approach may be used as an alternative for the assessment of the probability and hence the hazard of landsliding for all those sites which are properly instrumented for monitoring of subsurface shear movement and for which such data has been collected. Thus hazard ranking can be carried out on a rational basis using this observational approach. Again, the results were found to be consistent with the alternative approaches as well as with the evidence of actual historical impact of landsliding.

4 CURRENT RESEARCH AT THE UNIVERSITY OF WOLLONGONG

In this section aspects of current research at the University of Wollongong are outlined.

4.1 *Hazard-Consequence Matrix Approach (HCMA)*

Qualitative approaches for direct assessment of landslide risk of individual sites are increasingly being replaced by approaches which assess hazard separately from the elements at risk and the consequences of landsliding on those elements. The elements at risk should include property, human safety and environmental safety. Consequences would include damage to property or the environment and injury to and loss of life. A number of hazard-consequence matrix approaches have been developed in Australia by individual agencies for their internal use. There has, however, been very little published work in this area. For instance the Roads and Traffic Authority (RTA) in the state of New South Wales considers five grades of instability from very high to very low and five grades of consequence from very low to very high. The matrix then defines five grades of 'Risk Rating' from the highest at 1 to the lowest at 5. Again the New South Wales Railway Services Authority (RSA) considers four grades of 'probability of event affecting the track in the short-term (12 months) from high to very low and four grades of 'consequence of the event affecting the track' from extreme to minor.

The trend toward a matrix approach is highlighted by the development of an Australia New Zealand Standard for Risk Management which is for general application across a variety of applications (AS/NZS 4360:1995). It was developed with the objective of providing a generic framework for identification, analysis, assessment, treatment and monitoring of risk. It is not specific to landsliding and, in fact, there is no direct reference to natural hazards in general or to landslides in particular. Consequently, there is an urgent need for the development of a comprehensive matrix approach for landslide risk assessment.

Current research of the University of Wollongong has focussed on the development of field inspection data sheets which are comprehensive and which lead to consistent assessments. Separate hazard assessment sheets are being developed for natural slopes, embankments and side fills, rock cuttings and soil cuttings. For consequence assessment separate sheets are being developed for different applications such as railways, roads, buildings, sewer and telecommunication lines, human injury and fatality etc.

This work also involves more specific and precise definitions of different grades of hazard or of consequence. For example, 'very high' probability of occurrence is defined as an event which occurs within 5 years, i.e., an annual probability of 0.2 years. Thus a scale is developed which includes probability varying from 0.0002 to 0.2. A scoring method is also included in which very low probability corresponds to a score of less than 40 and a very high to a score of greater than 100 with several intermediate values between these boundaries. This approach is found to be a significant improvement on arbitrary or imprecise definitions of grades of hazard used by others. Similar detailed work has been done concerning definitions of grades of consequences. Where possible, quantitative measures are used to supplement or amplify qualitative descriptions of consequence.

Field trials have been carried out by two professionals, one experienced in landslide work and the other with little such experience. These independent assessments were carried out on the basis of the new proposed system as well as on the basis of existing approaches developed by others. On the basis of such comparisons, the new approaches have been validated and, where necessary, further improvements and refinements have been carried out.

4.2 Relationship Between Volume of Landslides and Their Frequency

The external project partners of the research at the University of Wollongong include the Wollongong City Council (WCC) at the local level, the Railway Services Authority of New South Wales (RSA) at the State level and the Australian Geological Survey Organisation (AGSO) at the national level. As part of their Cities Project, AGSO have carried out a landslide risk study for the city of Cairns in North Queensland, the main output being a series of risk maps. The methodology used by AGSO includes, as a basis, the relationship between magnitude (volume) and frequency of major types of landslides. One of the current aspects of joint work between the University of Wollongong and AGSO is the preparation of risk maps for the Wollongong area. It is proposed to combine techniques previously used by the University (synthesis based on important factors such as geology,

geomorphology, slope inclination and existing landslides) and by AGSO (volume-frequency relationships). Consequently, the landslide database at the University is now being used to study the volume-frequency relationships.

While researchers working in the area of natural hazards have used magnitude-frequency relationships for many years, few geotechnical engineers have developed or used such relationships. Seismologists and some earthquake engineers are aware of the Gutenberg-Richter relationship between the number N of earthquakes exceeding a particular magnitude M in a specific region in the form

$$\log N = A + BM$$

As M is measured on a logarithmic scale, this relationship is a straight line on a log-log scale. References, dating back to 1970 and 1983, to similar statistical relationships for rockfalls and rock avalanches have been cited by Hungr et al (1999). However, there is no conceptual or other reason to expect that landslides will plot along a straight line on such a scale. The latter also developed similar statistical relationships for rock falls and rock slides in a region of British Columbia, Canada. In Australia Moon et al (1996) also found a linear, statistical relationship between rockfalls per year and rockfall size on a railway cutting made in 1946 and requiring assessment for stabilisation works against rockfalls in 1994. It is not clear that Moon et al (1996) plotted the cumulative frequency of events exceeding a given magnitude. Thus their approach may not be comparable to that of Hungr et al (1999). It is interesting to note that Moon et al (1996) proposed a future extension to their probabilistic model which would include time as a parameter and also rainstorms of different intensity. This reference to a more realistic model was based on a recognition of the fact that the failure mechanisms were process-dependent and time dependent.

In a subsequent paper (Moon, 1997), similar form of size-frequency relationships were assumed for consideration of the probability of rapid landslides at Roxborough Gorge, New Zealand with a view to assessing the risk of serious landsliding including the formation of a landslide dam. Detailed data for such a form of relationship was obviously not available and, therefore, the assumed relationships were considered only on the basis of inference and judgement.

In contrast to the above, the database developed at the University of Wollongong provides an opportunity to determine volume-frequency relationships based on real data. An example of a recently developed relationship is presented as Fig 1 which also shows the histogram of landslide volumes from which the cumulative frequency-volume curve was developed considering 477 landslide events recorded in the Wollongong study area after 1950.

There are a number of uncertainties concerning the development of these relationships and these include (a) whether to combine different types of landslides or to separate them into different categories (b) the varying frequency with which data have been collected over the historical period (c) whether the total volume of landsliding during major storms should be considered or only the volumes of individual landslides (d) lack of data on rockfalls along the top of the escarpment (vertical cliff line) (e) non-inclusion of rockfalls along the highways and along the railway line in the landslide database which was developed primarily for the urban areas and for major landslide events along the transportation corridors (f) non-reporting or censoring of landslide data with small volumes ($<1000\text{m}^3$).

5 CONCLUDING REMARKS

The major aims of landslide research should include rational and comprehensive methods for the assessment of hazard and risk. For such assessment, development of accurate databases and reliable maps within a GIS-framework is necessary. Moreover, procedures are required for detailed assessment of individual areas or sites. It is necessary to progress from qualitative to quantitative assessments using systematic methods and approaches. In this paper, details have been given of research successfully completed at the University of Wollongong in recent years. Attention has then

been invited to the current research which includes the development of hazard -consequence matrix approaches and the establishment of cumulative frequency - magnitude (size) relationships for landslides.

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