1999

Consideration of probability assessments relevant to hazard and risk for landslides

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Abstract

Probability of occurrence is the most important component of landslide hazard and risk and this paper outlines different approaches for its assessment. The reasons for the popularity of qualitative approaches are first outlined. Quantitative approaches can be best applied if the important influencing factors and issues are fully understood. Formal probabilistic approaches are often based on geotechnical models or on a combination of hydrological and geotechnical models. The paper also highlights the situations for which the performance function must be formulated in terms of lateral displacements rather than the conventional safety factor. Reference is then made to a procedure, based on observational data on lateral displacements, which may be used for quantitative assessment of probability and hazard of slow-moving landslides. Finally, the results of a quantitative probabilistic assessment for a landslide site (natural slope) are presented considering different scenarios and assumptions. The example highlights the changing magnitude of hazard before and after landsliding and the factors which influence this magnitude.

Keywords

landslides, assessments, risk, probability, consideration, hazard, relevant

Disciplines

Engineering | Science and Technology Studies

Publication Details

Chowdhury, R. N. & Flentje, P. N. (1999). Consideration of probability assessments relevant to hazard and risk for landslides. 8th International Conference on Applications of Statistics and Probability (ICASP8) (pp. 1-7). Australia:

Consideration of probability assessments relevant to hazard and risk for landslides

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ABSTRACT: Probability of occurrence is the most important component of landslide hazard and risk and this paper outlines different approaches for its assessment. The reasons for the popularity of qualitative approaches are first outlined. Quantitative approaches can be best applied if the important influencing factors and issues are fully understood. Formal probabilistic approaches are often based on geotechnical models or on a combination of hydrological and geotechnical models. The paper also highlights the situations for which the performance function must be formulated in terms of lateral displacements rather than the conventional safety factor. Reference is then made to a procedure, based on observational data on lateral displacements, which may be used for quantitative assessment of probability and hazard of slow-moving landslides. Finally, the results of a quantitative probabilistic assessment for a landslide site (natural slope) are presented considering different scenarios and assumptions. The example highlights the changing magnitude of hazard before and after landsliding and the factors which influence this magnitude.

1 INTRODUCTION

Decisions concerning the assessment and management of existing and potential landslides require consideration of probability, hazard, vulnerability and risk. A comprehensive discussion of proposed definitions of these terms with particular reference to landslides is outside the scope of this paper. It is important to note that the terms probability and hazard are often used interchangeably. While hazard also includes the magnitude (size) and intensity of an event, it is widely accepted that the probability of slope failure or landsliding is the predominant component of hazard. The term risk, on the other hand, should not be used in place of hazard because it includes both the probability and the consequences of failure or landsliding. Thus risk may be regarded as the intersection or product of the probability of landsliding, the vulnerability of elements at risk and the value of the elements which will suffer loss in the event of failure. This should include damage to or loss of property, amenity, environment, lives etc.

This paper will concentrate on issues concerned with the probability of occurrence and on methods for its assessment. Particular attention must be given to the temporal changes in probability.

After briefly discussing qualitative and quantitative approaches, the results of a quantitative analysis are presented in this paper.

For a landslide which moves a significant distance after the detachment of a soil/rock mass or if a debris flow occurs, the hazard and risk to the accumulation zone must also be considered. Once again it will be the product of probability, vulnerability and elements at risk but the estimated values of these quantities will, in general, be different for the accumulation zone than for the detachment zone.

From the above it is obvious that an estimate of the probability of occurrence of a landslide and/or a debris flow is of critical importance. Yet, as will become clear from the following sections, it is often quite difficult to estimate these probabilities.

One must also consider the estimated values of probability in comparison to the engineering planning and design objectives which may include the annual probability of failure based on the return period of influencing natural events such as rainstorm or earthquake.

Probability or hazard values may be used in a number of ways as discussed below

(a) the values may be used to generate or develop landslide hazard maps which is

often facilitated by the use of a Geographic Information System (GIS)

(b) the values may be used directly to compare or rank different landslide sites or sloping sites which are considered to have the potential for landsliding under certain circumstances.

(c) the probability or hazard values may be used to calculate risk and then ranking carried out in terms of risk.

(d) probability values may be used in a cost-benefit analysis to compare different management options in terms of expected total cost.

(e) Following from this is the use of probability values in an event-tree approach, which allows consideration of different scenarios involving events, consequences and management options.

The probability values to be used in each of these applications may be determined in several different ways:

(a) values based primarily on judgement. In the absence of detailed geotechnical investigation and reliable data on the important parameters it will be necessary to rely on historical data on the occurrence and recurrence of slope failures, relevant experience in the particular region, engineering judgement and independent expert opinion.

(b) values based on the interpretation from return periods of initiating/ influencing/triggering events

(c) values based on the calculations carried out within the framework of geotechnical models .

(d) values based on calculations carried out in the context of hydrological and geotechnical models

Often qualitative terms are used and, for example, the probability or hazard maybe described in one of the following categories: Very high, high, medium, low and very low. Hazard maps may be developed showing the spatial distribution of these categories and there has to be an explanation about the meaning of each of these categories. Often it is argued that each descriptive term should be replaced by a numerical value or a range of values. This may be desirable not only from the point of view of better communication with other professionals and with the users of the maps but also for the carrying out of other types of study referred to above, each of which requires numerical values of probability. Care should, however, be taken to justify the numbers and to emphasise that the basic approach used has been a qualitative one and not a quantitative or semi-quantitative one.

2 JUSTIFICATION OF QUALITATIVE APPROACHES OF HAZARD ASSESSMENT

Conventional geotechnical analysis of slopes based on appropriate geological models and proven computational techniques enable the determination of a factor of safety for a slope corresponding to a set of geotechnical parameters including shear strength and pore water pressure. Using the same models within a probabilistic framework, the probability of failure of a slope can be calculated corresponding to assumed probability distributions of the random variables representing the relevant geotechnical parameters. Such detailed calculations, deterministic or probabilistic, can be justified where the ranges of values of the most important parameters and their variabilities have been established with a sufficient degree of confidence. In other cases, one may have to resort to indicative calculations and sensitivity analyses using typical assumed values of parameters. Even so, it is necessary to have a good idea of the potential failure mechanisms and the corresponding geotechnical models.

However, landslides are generally complex and often detailed geotechnical investigation and testing have not been carried out. Moreover, conventional geotechnical analysis does not include some important aspects of particular types of landslides. For example, some marginally stable sloping masses undergo periodic or intermittent movement following rainfall events. However, these movements may range from extremely slow to slow and in between these episodes, the slope mass is at rest or stable. Going from the particular to the general, conventional geotechnical analysis can not be relied upon to predict or even explain the dynamics of landslides and debris-flows.

Considering these facts, one can see why qualitative hazard assessment approaches have been very popular and why the progress towards the development of quantitative or even semi-quantitative approaches has been rather slow. Reviews have been presented recently by Aleotti & Chowdhury (1998) and Chowdhury (1998).

Important factors and issues relevant to quantitative assessments are considered below.

3 INFLUENCING FACTORS AND IMPORTANT ISSUES

It is widely recognized that the important influencing factors for landsliding at a sloping site include geology, geomorphology, hydrology and geotechnical details. Often landslides are caused or triggered by natural events such as rainstorms or earthquakes. It is, therefore, important to have reliable knowledge of the frequency and magnitude of different events in each category. These are very significant and complex tasks requiring reliable historical data which have to be carefully analysed. Moreover, there must be field validation of any proposed relationship between a natural event such as a rainstorm and the occurrence of landslides in an area. There is no universal law or precise cause-effect relationship and each region may exhibit a different response to a natural event of given magnitude. Variation of rainfall with time can be a critical factor and therefore magnitude can not be considered as in the case of a sudden and short event such as an earthquake shock. Cumulative rainfall for different antecedent periods, depending on the type of landsliding, is often very important. There are different types of uncertainties concerning earthquake-induced events. Historical records may be very limited and, therefore, magnitude -frequency relationships are not easy to establish either on a deterministic or a probabilistic basis. Moreover there is often considerable uncertainty in understanding the performance of slopes during earthquakes and, therefore, in the development of appropriate geotechnical models. Often landslides are caused, directly or indirectly, by human action. To put it in a different way, human action is at least a significant contributor to the occurrence of slope instability. Deforestation, development of land for urbanisation, the establishment of roads and railways and other infrastructure are important contributors to both the short-term and long-term development of instability. The concepts, which underpin the long-term effects, have now been fully established by researchers but such effects are not widely appreciated by developers, the general public and even by the engineering planning and design professionals

Previous history of landsliding or slope movement is of critical importance in determining how a sloping area may perform in the future. Historical information is often limited and yet, it is possible to recognise the boundaries of ancient or old landslides especially from aerial photographs. Inactive landslides must be distinguished from active ones, which may exhibit continual or intermittent movement recognisable from visual observation. However, in some cases the movements are extremely slow to very slow and can only be recognised if monitoring is carried out with subsurface instrumentation such as inclinometers

As stated earlier, in addition to the hazard of slope failure or detachment, it is necessary to assess the hazard of a debris flow occurring and its travel distance. These assessments are important for estimating the total area which may be affected, the details of elements at risk and the total risk. Remedial or preventive measures may have been installed at a landslide site or in an area with no previous history of landsliding. The assessment of future hazard of landsliding must take into consideration the performance with time of such measures over the design life of the project

3 FORMAL PROBABILISTIC APPROACH

3.1 *Based on Geotechnical Models*

Based on a geotechnical model involving the conventional factor of safety, denoted by F, as a performance function, the conditional probability of failure based on the assumed distributions of individual random variables and the values of parameters regarded as constants, is defined as

$$p_f = P[F < 1]$$

Alternatively, one may define a safety margin as the excess stabilising moment or force over the driving moment or force and this excess may be denoted by SM. Then the conditional probability of failure is

$$p_f = P[SM < 1]$$

These are to be regarded as conditional probabilities if the mean values of the random variables and, in particular, those of the shear strength parameters and the pore water pressure are not accurate or can not be regarded as constants. Any of these values may be associated with a given probability, which must then be multiplied with the probability p_f to estimate the failure probability P_f.

Unfortunately, it is often not recognised that these p_f values are conditional probabilities and

thus the interpretation of hazard may be misleading. For example, an average value of the pore pressure ratio $r_u = 0.35$ may be considered appropriate for a slope considering a rainstorm with a given return period and for a given project design life. It is then necessary to estimate the probability that such a storm will occur at least once during the design life of the project. It is also necessary to estimate the probability that a value of $r_u = 0.35$ will correspond to this storm at the given site. This is explained in a later section of this paper with an illustrative example.

3.2 *Based on Hydrological Model and simple Geotechnical Model*

Many landslides occur as a consequence of rise in the pore water pressure following prolonged or intense rainfall as was also considered in the above example. Therefore, the probability of failure may be defined in terms of groundwater levels. Wu and Abdel-Latif (1994) considered the spatial variation of groundwater levels based on infiltration through the unsaturated zone and drainage by gravity through the saturated zone. A simplified groundwater profile was assumed in order to develop a lumped parameter hydrological model as part of a methodology for prediction and mapping of landslide hazard. Also a better estimate of the groundwater flow was obtained by using a finite-difference solution in the saturated zone. They defined the probability of failure as follows

$$p_f = P\,[\,H_w > H_c\,]$$

Where H_w is the groundwater level at the point of interest and H_c is the critical groundwater level required to cause failure. Infinite slope analyses were carried out to estimate the critical groundwater levels at different locations. Clearly this simple, one-dimensional approach will not be applicable to landslides involving deep-seated, non-planar slip surfaces and complex geology. Their model is most relevant to shallow translational landslides. Even so, it is important to realise that a hydrological model requires a great deal of information including the spatial variability of different parameters and especially the ground permeability. In the absence of detailed subsurface information, the use of such models may be unjustified

For the probability calculations, uncertainties about the input parameters to the infiltration and slope stability model were considered after incorporating data from published sources, site investigation, field observation and landslide inventories.

To incorporate the uncertainties, the above equation is modified as follows

$$p_f = [N\,H_w > H_c]$$

in which

$$N = N_1 \text{ x } N_2 \text{ x } N_3 \text{ x } \quad N_i$$

Where N_1, N_2, N_3 ....N_i are random variables representing individual uncertainties and the model error

The use of a hydrological model for groundwater levels has also been presented by Van Westen and Terlien (1975). They referred briefly to the availability of one-, two- and three-dimensional models but adopted a two-dimensional, two soil-layer model, which calculates groundwater levels on a daily basis in layers with different hydrological properties. The model was applied to different values of slope angle, slope length, thickness of upper layer (ash), and saturated hydraulic conductivity. The maximum groundwater levels for each of the ground profiles were calculated for a 20 year period. Magnitude- frequency curves were then developed and profiles linked to maps using the engineering-geological database and the topographic information. Groundwater maps were derived for different return periods.

Both Wu and Abdel-Latif(1994) and Van Westen and Terlien(1995) refer to the use of a GIS system to construct landslide hazard maps based on the calculated failure probabilities. The former identified areas with values $p<0.01$,0.1.... etc and updated the computed hazard based on Bayes' theorem, computed values having been compared with the results of landslide inventory in which landslides are identified from aerial photos and site inspection.

Van Westen and Terlien(1995) recognised the limitations of a one-dimensional (infinite-slope) model but referred to its suitability for direct use within a GIS environment. The slope stability calculation can be made for each pixel. This can not be done if any two-dimensional slope stability model is used. In that case a number of profiles from a digital terrain model (DTM) and other parameter maps are exported outside the GIS to external slope stability models. The major disadvantages are the need for (a) data conversion, (b) interpolation of the values of the safety factor or probability of failure and (c) linking them back to geomorphological units.

4 CONSIDERATION OF HAZARD BASED ON DISPLACEMENTS

As stated earlier, there are many landslide masses, which may move very slowly and only intermittently. Yet the cumulative movements may, in time, cause sufficient damage to important structures and especially to residential houses in hilly urban areas. The impact of such movements may also be critical to the performance of infrastructure such as railway lines. Therefore, the definition of the probability of failure must be based on a variable representing lateral movement of the ground or of the sloping mass rather than a ratio of forces or moments. Denoting the lateral movement by D and the critical or threshold value, exceeding which would lead to non-performance or failure, by x. Then the conditional probability of failure may be defined as

$$p_f = P[D > x]$$

Using such an approach is a consequence of the recognition of the potential for destruction or damage or non-performance of even limited cumulative movement undergone by landslides which, most of the time, may be moving very slowly indeed. Often attention is given only to the probability of sudden or catastrophic failure and thus the hazard associated with less spectacular landslides is ignored. Such an approach is obviously flawed and it can have adverse economic and social consequences in urban areas. Slow moving landslides can also pose a threat to life. Potential for train derailment is an obvious example.

The above approach requires the development of an expression, analytical or empirical, for the performance function D in terms of basic geotechnical parameters such as soil cohesion, angle of internal friction, pore water pressure, coefficient of lateral stress, elastic modulus, Poisson's ratio etc. Simple analytical modeling of deformations may not be feasible for natural slopes and a computer based finite-element or finite-difference solution may be required. However if a slope is supported by a retaining wall (with or without anchors) or if the slope is in a cutting supported by a retaining structure, both sophisticated or relatively simple solutions may be used. An innovative approach, not requiring the above type of formulation, but based instead on observational measurements is discussed below

5 OBSERVATIONAL APPROACH RELEVANT TO ESTIMATION OF HAZARD ----SLOW-MOVING LANDSLIDES

In recent work at the University of Wollongong (Chowdhury & Flentje 1998, Flentje & Chowdhury 1999) innovative procedures have been developed to assess the hazard of landsliding in areas where intermittent movements are known to be often very slow. The development and use of a comprehensive database enabled the assessment of average annual frequency from historical records of landsliding. In the next stage the data from monitoring of instrumented sites was examined carefully. This inclinometer data was studied in conjunction with the rainfall data. Several antecedent periods were considered to determine cumulative rainfall. The annual percentage exceedance time (ARPET) of these rainfalls was calculated.

In this way the ARPET values corresponding to "failure" episodes of any particular landslide could be determined and such values may be taken to indicate the probability or hazard associated with that landslide based primarily on an observational approach of lateral movement and the correspondence of such movement to a particular antecedent period of rainfall. This approach has been validated for the Greater Wollongong area of New South Wales, Australia. Further application of this approach to currently stable areas is the subject of continuing research.

6 EXAMPLE OF QUANTITATIVE HAZARD ASSESSMENT

This example pertaining to a natural slope will enable consideration of quantitative hazard assessment using some formal probabilistic procedures. It also brings into clear focus the fact that landslide hazard is not constant and often varies significantly with time. For reasons of confidentialities the site of the slope failure is referred to here only as "Site MK". A landslide at this site was first observed in December 1984 although significant movement may have occurred over a period of several months. The landslide mass was approximately 150 metres long, 75 metres wide and 10 metres deep with an approximate volume of 85000m^3 and an average slope angle of 9.7°. For several months after the failure, the sliding mass was moving at velocities as high as 110mm per day. Although the toe of the landslide was 65 metres from the nearest road, that road was closed in January 1985 and remained closed for several years. Catastrophic failure of the landslide

mass had not taken place when management options were considered seriously in 1989 (Chowdhury 1989). As part of the investigation it was decided to assess probabilities of failure on a quantitative or formal basis. The work included survey monitoring, analysis of rainfall data, review of data on shear strength and laboratory tests on samples of soil from the slip surface.

Conventional slope stability analyses were carried out and, in addition, simple probabilistic calculations were also carried out.

After a review of the data from careful monitoring of surface movement, it was concluded that the landslide had not stabilised. Moreover, acceleration of movements could be expected in the event of a major rainfall and there had been no such rainfall from 1985 and 1989. A significant correlation was found between cumulative rainfall (10, 15 or 20 days) and velocity, quite independent of time. Two piezometers were installed but no pore water pressure was recorded by either.

The average value of residual friction angle was interpreted from back analysis to be $\phi'_r = 10^o$. The average mobilised shear strength at failure was interpreted from back-analysis to be about $\phi' = 13^o$. A wide range of values between 8° and 18° was obtained for φ′r values based on the results of direct shear tests. However, the back-calculated values were considered to be realistic and reliable. No information could be gained from back analyses about the spatial variability of the peak or residual shear strength.

Although the slide was translational and back analyses with the "infinite slope" model would have provided reasonable results, appropriate two-dimensional models were used to carry out many of the slope stability calculations.

The initial failure was attributed to seepage of water associated with ponding caused by a farm dam. This dam had been removed when initial remedial action was taken after the landslide. While there were no significant pore pressures recorded at the slip surface, there was clearly a direct correlation between rainfall and continuing part-failure movement. It was demonstrated with example calculations that even a small and temporary rise in pore pressure on the slip surface could provide sufficient energy for the mass to move. Similarly, if the water level in tension cracks rises by a fraction of a metre, sufficient energy for movement is provided for the sloping mass.

Analysis showed that an average pore water pressure ration $r_u = 0.25$ would have been operative based on a $\phi'_r = 10^o$. Although, at the time of investigation, the pore pressure was close to zero, it could increase following a heavy rainstorm especially if the drainage conditions within the sliding mass deteriorated with time. A rainstorm event with either a 30 year return period or a 100 year return period and a 30 year design life were considered to be appropriate for the assessments. An average value of pore water pressure ratio of $r_u = 0.2$ was considered appropriate for evaluating the probabilities of failure and the management options.

The following were the results of calculations considered to be appropriate for the different phases of the site.

(a) Before construction of farm dam and assuming the mean and coefficient of variation of (tanφ) as (tan 13°) and 10% respectively

$\bar{F} = 1.34$, $\sigma_F = 0.133$, and $p_f = 0.06\%$

(b) After construction of the farm dam and assuming $r_u = 0.2$

$\bar{F} = 1.05$, $\sigma_F = 0.095$, $p_f = 28.1\%$

(c) Post-failure conditions

(i) No pore water pressure

$\bar{F} = 1.02$, $\sigma_F = 0.079$, $p_f = 40\%$

(ii) Design value of $r_u = 0.2$

$\bar{F} = 0.82$, $p_f = 99.8\%$

(d) Calculated probability of failure for project life

(i) Consider 1 in 100 year rainfall event and project life of 30 years. The probability that such a rainfall will occur at least once during the project life is given by Poisson's distribution as $p_{r1} = 0.222$.

The probability of failure with some surface stripping of the slope surface as a stabilisation measure and with design value of pore water pressure $r_u = 0$ was calculated as

$p_f = 36.6\%$

The conditional probability that a 1 in 100 year storm will lead to an average pore pressure ratio of $r_u = 0.2$ was assumed as

$p_{ru} = 1$

Combining all these values, the probability of failure for the project life was calculated as

$P_f = 8.1\%$

(ii) Consider that 1 in 30 year rainfall event is related to the design value of r_u = 0.2. In this case Poisson's distribution gives

$p_{r2} = 0.37$

Assuming that the probability of a value r_u = 0.2 occurring approaches 1

$p_{ru} = 1$

Again $p_f = 36.6\%$

Combining these probabilities the failure probability during the project life is

$P_f = 13.5\%$

(iii) 1 in 30 year event and considering no stripping of the slope for stabilisation

$p_f = 99.8\%$

$P_f = 37\%$

(iv) Consider 1 in 30 year rainstorm event but assume that subsurface drainage has been installed. As a result of such drainage the probability of r_u = 0.2 occurring is only p_{ru} = 0.05. then the values of P_f are reduced in cases (i) and (ii) as follows

Case (i) $P_f = 0.40\%$

Case (ii) $P_f = 0.67\%$

It is also interesting to note that if fully effective drainage is assumed, r_u = 0 and the probability of failure will be independent of rainfall during the project life. Thus direct calculations may be made based on r_u = 0 and these yield

$P_f = p_f = 0.66\%$

This value is close to the values obtained above

7 DISCUSSION AND CONCLUSIONS

In this paper attention has been drawn to the variety of factors that must be considered for assessing landslide hazard and risk. The assessment of probability of failure or non-performance is the most important task and, in this paper, attention has been drawn to both qualitative and formal quantitative procedures. The fact that probability and hazard change with time has been emphasised. Moreover, the objectives of the assessment, the performance functions and the design specifications must be considered. Attention has been drawn to assessment of probability or hazard based on deformations either through the formulation of an appropriate performance function in terms of deformations or through observational approaches and analysis of the data concerning influencing events such as rainstorms.

In order to illustrate the formal or quantitative assessments of probability and hazard, results of an analysis for a natural slope have been presented. From these results the importance of design objectives and management options becomes clear. The hazard of landslide reactivation may vary by more than an order of magnitude depending on the remedial/preventive measures adopted and the corresponding assumptions made concerning, for instance, the extent of increase of pore water pressure within the project life

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