HAZARD OF LANDSLIDING DURING EARTHQUAKES - CRITICAL OVERVIEW OF ASSESSMENT METHODS

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SUMMARY

The paper presents an overview of the factors which need to be considered for assessment of landslide hazard under seismic conditions. The roles of limit equilibrium and sliding block analyses are explored and the amplification of ground motion due to local soil conditions and topography is emphasised. Reference is made to the ways in which failure probability under seismic conditions may be estimated so that account is taken of significant uncertainties. Innovative approaches allow relationships to be developed between observed probability of landsliding and calculated deformations. The paper concludes by emphasising the different approaches which may be used for seismically induced landslide hazard assessment.

INTRODUCTION

Landslides often cause significant damage and destruction to property and to the environment as well as loss of life. Within and near urban settlements, the adverse social impacts on communities are often as important as the adverse economic impacts. In order to properly manage sloping areas and associated physical developments, such as those for urbanisation and transportation infrastructure, it is important to develop rational and systematic approaches for landslide hazard and risk assessment. Such approaches facilitate long-term planning as well as minimisation and management of risk.

In recent years considerable attention has been focussed on landslide research related to hazard and risk assessment. Both qualitative and quantitative methods have been developed. Qualitative approaches require an understanding of the various factors which influence slope stability and the exercise of judgement based on available information, observation and experience. Quantitative or semi-quantitative approaches utilise analytical approaches based on appropriate geological/geotechnical models and/or detailed field observations and/or measurements. In both cases the final outcome may be expressed as descriptive categories of hazard or susceptibility such as very high, high, medium, low and very low.

The availability of GIS (Geographical Information Systems) has facilitated the development of powerful approaches for the generation of accurate maps describing different aspects of the physical environment such as topography, geology, existing landslides, existing land use, zoning of land for future development etc.

While this paper is not concerned with mapping of hazard it is important to mention that the use of GIS facilitates the updating of maps as additional information and more accurate data become available with observation and investigation. A GIS-based approach can also be a powerful tool for analysis and synthesis of data and therefore, for assessment of hazard and risk. Over the last decade, GIS-based landslide hazard assessment has received considerable attention from earth scientists and geotechnical engineers. However, relatively less attention has been given to assessment of hazard of landsliding during earthquakes. Good recent

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examples include studies associated with hazard mapping such as those from USA [Jibson et al, 1998, Keefer and Wang, 1998].

AIMS AND SCOPE

Assessment of hazard and risk requires a suitable framework and systematic approaches which lead to reliable and consistent outcomes. For example, the framework may be a hazard-consequence matrix approach such as the one recently proposed for rainfall-induced landsliding [Chit KoKo et al, 1999]. Risk is often considered to be a product of hazard and consequence. Hazard may be defined as the probability of landsliding and can be regarded as a product of landslide susceptibility of a site during a given earthquake and the seismic hazard associated with that site. The paper is concerned with factors affecting landslide susceptibility and the methods which may be used for assessing it. The assessment of seismic hazard associated with any region including the return periods of earthquakes is outside the scope of this paper. The aims of this paper include consideration of the following aspects of landslide susceptibility

- Amplification of ground motion due to local soil conditions and topography and reference to the sophisticated methods which are required for understanding and analysis of these effects
- The limit equilibrium concept for the calculation of static and 'dynamic' factors of safety
- The concept of critical or yield seismic acceleration for a given slope
- Calculated permanent displacement as an indicator of landslide susceptibility/hazard
- Sliding block approach for assumed compliant rather than rigid soil masses
- Importance of the correct failure mechanism for calculating permanent displacements
- Importance of uncertainties for the assessment of hazard
- Probabilistic approach and the role of reliability analysis in updating seismic landslide hazard

HAZARD ASSESSMENT BASED ON LIMIT EQUILIBRIUM ANALYSIS

Earthquake shaking of a slope reduces its factor of safety and, depending on a number of factors, permanent deformations may be caused. These factors include the intensity and duration of shaking, the type of slope (e.g. natural slope, embankment, earth dam, waste containment fill), the slope geometry, its geotechnical characteristics (shear strength, deformation response), local geological details and existing pore water pressures due to seepage, impounded water or other conditions.

Based on the concept of limit equilibrium the factor of safety F may be evaluated under static conditions for translational or rotational failure mechanisms. Many methods are now available for slopes with potential failure surfaces of arbitrary shape and it is not necessary to assume a planar or a circular shape. The static factor of safety is used in combination with the critical seismic coefficient to calculate permanent slope deformations using a sliding block analysis which is considered in the following sections of this paper.

For seismic or dynamic conditions, a pseudo-static analysis is often performed considering a horizontal inertia force to represent the effect of an earthquake. (However, other directions of the inertia force may be assumed). The seismic acceleration a_h may be considered as the product of a seismic coefficient k and the gravitational acceleration g.

The dynamic (pseudo-static) safety factor which may be considered as indicator of landslide hazard, is related to the static safety factor. For simple failure modes (e.g infinite slope analysis or planar slip surface) the relationship is explicit. For slip surfaces of arbitrary shape, appropriate limit equilibrium models may be used to obtain the relationship numerically. As an example, consider a planar slip surface in a simple slope of height H, inclination α and the soil or rock shear strength parameters c and ϕ. The relationship, considering a horizontal inertia force, is:-

$$F_{dy} = \frac{F - a_h \tan\phi}{a_h \cot\beta + 1} \tag{1}$$

in which β is the inclination of the slip surface.

The relationship appears to be independent of cohesion c, slope height H and the unit weight γ of the slope materials. However, the influence of these is included in F.

There is, of course, a significant uncertainty associated with the pseudo-static approach because the applicable ground motion is replaced by a constant acceleration and because it is difficult to select the appropriate value of the seismic acceleration a_h or the coefficient k. Consequently, the use of the dynamic (pseudo-static) factor of safety F_{dy} to represent landslide hazard is generally not considered to be reliable.

Changes may occur in the shear strength of the slope materials (e.g. strain-softening, generation of excess pore water pressures) during an earthquake and these effects are not considered in such simple analyses. In particular, saturated cohesionless soils of loose to medium relative density may develop significant excess pore water pressures during earthquake shaking leading to reduction in shear strength. In some cases, liquefaction of a cohesionless soil layer may take place under such conditions. Even slopes which primarily comprise of cohesive materials may contain thin lenses of saturated cohesionless soil and, therefore, the importance of seismically induced excess pore water pressures and of liquefaction in hazard assessment should be highlighted. This remains true even if one adopts more comprehensive methods of slope response analysis such as the sliding block approach [Newmark, 1965] or finite-element, boundary element or finite-difference approaches.

AMPLIFICATION OF GROUND MOTION

An important task for earthquake response analysis is the assessment of the amplification of ground motion. Depending on the local soil conditions and the topography of an area the seismic ground acceleration may be amplified. If the amplification factor is A the horizontal acceleration to be used for pseudo-static analysis within a limit equilibrium framework is Aa_h. In other works the seismic coefficient to be used is Ak.

The influence of local soil conditions (including the depths and stiffnesses of various soil layers) has been recognised for several decades and a simple, one-dimensional approach was incorporated in the well-known computer program SHAKE, developed at the University of California at Berkeley. In contrast, the effect of topographical shape on the amplification of ground motion is not well known. Therefore, this important factor may be ignored in the assessment of landslide hazard. As an example, several landslides in the coastal bluffs of the Pacific Palisades due to the 1994 Northridge earthquake have been attributed to topographic amplification. Severe damage to houses on the top of the bluff was concentrated within about 50 metres (one slope height) of the slope crest. Response analyses using 2D visco-elastic frequency domain GCTB (Generalised Consistent Transmitting Broundaries) analyses was able to explain the spatial distribution of the damage and the topographic amplication was estimated to be between 52 and 76% [Ashford and Sitar, 1998].

Based on observations, it has also been suggested that the response of a slope is also influenced by the direction of wave propagation and wave inclination relative to a slope. During the 1989 Loma Prieta earthquake, for example, massive failures occured on spurs from ridges but there was no failure associated with nearby cliffs. There are many instances in different parts of the world of landslides occurring with greater frequency on one side of a ridge or valley relative to the other side. Analyses may significantly underestimate amplifications observed in the field “which mostly range from 2 to 10 and up to as much as 30” [Ashford et al, 1997]. Yet topographic amplification may in some cases be offset by reduced site amplification and other effects as was found from analyses concerned with inclined shear waves in a steep coastal bluff [Ashford and Sitar, 1997].

A brief review of other approaches such as the finite difference, finite element and boundary element methods for the analysis of topographic amplification has been given elsewhere [Tabesh and Chowdhury, 1997]. Results for example cases of homogeneous and non-homogeneous escarpment using the finite difference program FLAC, for time-domain analysis, have also been presented [Chowdhury and Tabesh, 1998]. It has been shown that the presence of a valley has little effect on the deformation response of an otherwise level area. On the other hand the presence of a mountain results in significant amplification of the displacement response.

CRITICAL SEISMIC COEFFICIENT

The critical or yield acceleration is that which reduces the factor of safety of a slope to unity (F = 1) consistent with a condition of critical equilibrium. The critical seismic coefficient k_c is the corresponding proportion of gravitational acceleration. It is related to the static factor of safety F, the relationship depending on the shape of the slip surface i.e. the failure mechanism. Thus k_c is an indirect measure of the stability of a slope under static conditions.

An explicit relationship can be derived for a simple planar shape of slip surface, the location of which is known. For example, translational landsliding for long natural slopes is often analysed using a one-dimensional 'infinite slope' approach. (The assumptions are that the slip surface is approximately parallel to the ground surface and that the sliding layer is of shallow depth). The equation for the critical seismic coefficient can be written in the form

$$k_c = (F-1)\frac{\tan\beta}{1+\tan\beta\tan\phi} \tag{2}$$

The above relationship is also valid for a plane wedge failure mechanism with plane slip surface passing through the toe and having a known inclination β. Recently numerical solutions for minimum value of k_c have been derived for a simple slope considering (i) a plane failure mechanism passing through the toe for which the optimum inclination θ is not known in advance and (ii) a log spiral failure mechanism passing through the toe [Cressplani et al, 1996]. The ratio of k_c (plane) to k_c (log spiral) was found to be always greater than 1 and, as critical equilibrium for a given slope is reached (F approaching 1), the ratio increases to infinity. The assumption of a plane failure mechanism for a simple slope, therefore, leads to an underestimation of displacements as will become clear from the next section.

ESTIMATING PERMANENT DEFORMATIONS

An approach originally proposed by Newmark and based on the analogy of a block sliding down an inclined plane has proved to be a very important and versatile tool for estimating permanent displacements of slopes. It has been used successfully for assessments concerning both man-made and natural slopes [Newmark, 1965]. It is a one-dimensional dynamic analysis based on the assumption that the potential sliding mass behaves as a rigid body.

The acceleration of a rigid block moving on an inclined plane of inclination β may be expressed in the following form:

$$a = \frac{\cos(\phi-\beta)}{\cos\phi}[k(t)-kc]g \tag{3}$$

in which k(t) represents the applied acceleration-time history and ϕ is the friction angle relevant to the interface between the rigid block and the inclined plane. This simple equation has been successfully applied to slopes with different translational and rotational failure mechanisms. Double integration of the equation is, of course, required to calculate the deformations.

Since some soils suffer a loss in shear strength during earthquake shaking, it has been suggested that k_c and factor of safety F also be considered functions of time during an earthquake

$$k_c = k_c\,(t)$$

$$F = F\,(t) \tag{4}$$

The sliding block model has been extended into a more comprehensive method by adopting an iteractive, incremental time-step procedure during the limit equilibrium analyses and during the numerical integration of the basic equation of motion [Chowdhury 1995]. For strain-softening soils and for soils which are susceptible to increase in excess pore pressure during earthquake shaking, a conventional sliding block model (constant k_c) would seriously underestimate the permanent deformations.

The comprehensive approach enables analyses to be carried out in terms of effective stress and leads to reliable estimates of the factor of safety, critical seismic coefficient and permanent deformation at the end of an earthquake represented by the selected acceleration-time history.

The assumption of a potential sliding mass as a rigid body is quite acceptable for rock slopes and slopes of relatively stiff soil. According to a study dealing with a modified Newmark model for compliant slopes [Kramer and Smith, 1997], the conventual analysis (rigid body assumption) provides good estimates of the permanent displacements of relatively thin or stiff failure masses but tends to overestimate deformations of thick and/or soft failure masses. For landfills this overestimate may be a factor of 2. Landsliding is most often associated with natural slopes and, therefore, overestimation of deformations based on the rigid block model is unlikely to be significant.

To facilitate large numbers of analyses associated with regional hazard mapping, empirical regression equations have been developed by researchers for particular regions. Thus double integration can be avoided and the numerical process is simplified considerably. For example, the Newmark displacement D_N (cm) has been expressed as a function of Arias intensity I_a and the critical seismic acceleration a_c [Jibson, 1993; Jibson and Keefer 1993] as follows:

$$\log D_N = 1.46 \log I_a - 6.642\, a_c + 1.546 \qquad (5)$$

The Arias Intensity has been related to earthquake magnitude M and source distance R [Wilson and Keefer 1985] as follows:

$$\log I_a = M - 2 \log R - 4.1 \qquad (6)$$

Arias intensity is a single numerical measure of an acceleration time record calculated by integrating the squared acceleration values. A term 'seismic destructiveness potential factor' has also been defined by the ratio of the Arias intensity Ia and the square of the number of zero crossings per second of the accelerogram

$$P_D = \frac{I_a}{v_0^2} = \frac{\pi}{2g} \frac{\int_0^{to} a^2(t)dt}{v_0^2} \qquad (7)$$

The displacement of a rigid block on a horizontal plane is a function of P_D and the critical seismic coefficient k_c. For a slope with given geometry and a specified failure mechanism an appropriate correction factor can then be applied [Cressplani et al, 1998]. Based on 310 earthquake records the authors obtained two regression equations for permanent deformation of a rigid block with confidence levels of 50% and 90% respectively denoted as s_{50} and $s_{90.}$ This approach highlighted several aspects of permanent deformation analysis. Firstly displacements associated with a plane failure mechanism are constant along the plane but those associated with a curved failure mechanism vary significantly along the slip surface. Secondly, the critical seismic coefficient for a rotational failure mechanism is smaller than that for a plane failure mechanism. Consequently the displacements corresponding to a rotational failure mechanism are greater than those for a plane failure mechanism. Thirdly displacement ratio, s(curved)/s(plane), can be even greater than the corresponding k_c ratio.

ROLE OF PROBABILISTIC ANALYSIS

Numerous Uncertainties

Assessment of seismic landslide hazard involves a number of uncertainties. These include:

- spatial and temporal variability of geotechnical parameters
- Uncertain failure mechanisms and the assumptions associated with geotechnical models

- Systematic uncertainty due to limited data from site investigation and due to the choice of site investigation and testing methods

- Uncertainties associated with the ground motion including site and topographical amplification effects

In view of these uncertainties accurate prediction of slope performance on a deterministic basis is generally difficult. It is, therefore, desirable to carry out probabilistic analysis in which the geotechnical parameters are treated as distributions rather than as constants. The probability of failure would then be an indicator of landslide susceptibility/hazard. It could be defined on the basis of the dynamic factor of safety

$$p_f = [F_{dy} < 1] \tag{8}$$

It could alternatively be defined on the basis of the permanent deformation s exceeding a specified value s_1.

$$p_f = P[s > s_1] \tag{9}$$

The estimation of these probabilities can be facilitated by adopting appropriate limit equilibrium and sliding block models. A convenient and simplified approach for deformation-based probabilities of failure would be to use one of the regression equations for deformation as the performance function, if such an equation is available.

Probability of Failure Based on Observation and Calculated Values

An innovative definition of the probability of failure which combines observed failures and calculated values of deformation has recently been used for the preparation of digital probabilistic seismic landslide hazard maps [Jibson et al, 1998]. Calculated displacements of all the cells (the study area was divided into 10m x 10m cells) were compared with the inventory of landslides triggered by the Northridge earthquake. The full range of calculated displacements for all cells was separated into different displacement categories (e.g. 1-2cm, 2-3cm, 3-4cm etc.). Cells with a particular displacement category were identified and of these some were landslide source areas. The probability of failure was then defined as the proportion of landslide cells in that displacement category. As might be expected, the probability of failure showed a monotonic increase with the displacement up to a limit. The shape of the curve (landslide failure probability plotted against displacement category) reflected the brittle nature of most failures (typical of the region considered), the curve flattening out at about 15cm deformation with no further increase in the failure probability.

The generated curve was used for producing seismic landslide hazard maps showing spatial variation of landslide probability. The curve could be used for any set of ground-shaking conditions but recalibration would be required if it was used for a different region.

The ‘infinite slope’ model was used as a basis for calculating the permanent displacements primarily because of convenience in carrying out GIS-based mapping tasks. However, the inherent uncertainties and limitations of this choice must be recognised. In the previous section, the importance of the correct failure mechanism has been emphasised. A curved failure mechanism may lead to deformations significantly greater than a plane failure mechanism.

There are, of course, considerable difficulties in predicting or anticipating the right failure mechanisms and their spatial variability in the region of interest. Moreover, technology has not yet developed to the stage where a two-dimensional analysis procedure could be integrated with a GIS-based approach in a regional hazard assessment task.

In conclusion, it is wise to be fully aware of the implications of an infinite-slope assumption and the fact that the hazard may be significantly underestimated. Therefore, one should be prepared to carry out detailed additional studies for specific areas identified after the regional study has produced a complete picture based on initial assumptions.

Increase of Existing Landslide Hazard Due to Earthquakes

How one may estimate earthquake-related increase in landslide hazard of a site with known prior failure probability has been considered in a different way [Christian and Urzua, 199]. The reliability index β of a slope is defined

$$\beta = \frac{E[F]-1}{\sigma_F} \tag{10}$$

The probability of failure is related to β, the relationship depending on the probability distribution of F. Knowing p_f and assuming a reasonable value for σ_F , the expected value of F can be determined. Next one may use the appropriate relationship between F_{dy} and F and once the expected value of F_{dy} is found, the corresponding values of reliability index and probability of failure can be calculated under dynamic (psuedo-static conditions) for values of acceleration a_h and amplification factor A relevant to the site. The authors obtained a curve showing the relationship of p_f to the product A a_h (amplified acceleration). They also considered the earthquake recurrence rate for a given site (for which detailed data were available) to obtain the overall (combined) landslide probability, including earthquakes of different return periods at the site, based on a numerical integration procedure. The authors concluded that, for a reasonable range of parameters, the increase in probability of landsliding was 10 to 20% above the pre-existing probability. This was less than the assumed uncertainty associated with the pre-existing landslide (σ_F = 30%). The authors were trying to explain how some significant landslide sites do not fail during earthquakes whereas both major and minor failures due to earthquakes at many sites do occur frequently.

One must, of course, be careful in interpreting this type of conclusion too narrowly. This may lead to generalisation which is not warranted. Although the analysis process is systematic and elegant, it appears to be associated with a circular argument. The initial failure probability is assumed on the basis of observation/historical data whereas the probability associated with earthquakes is based partly on the assumed value under static conditions and partly on a calculation process and using a plane failure mechanism. It would be interesting to research the issue by using a systematic and consistent calculation process for both static and seismic calculations and considering the curved failure mechanism which may be more appropriate.

CONCLUSIONS

Either qualitative or quantitative approaches may be developed for landslide hazard assessment under seismic conditions. For important regional studies a combination of qualitative, semi-quantitative and quantitative methods may actually be used. For example, in a recent regional study [Keefer and Wang, 1998] slopes steeper than 25° were analysed using empirical criteria (degree of weathering, strength of cementation, spacing and openness of rock discontinuities and presence and/or seepage of water. Slopes with inclination between 5° and 25°, generally mantled by colluvium, were assessed from limit equilibrium and sliding block analyses. Susceptibility ratings used were associated with these displacements (High susceptibility >100 cms, Medium susceptibility (10cm - 100cm) and Low susceptibility (0 - 10cm)). Slopes with inclinations less than 5° were assessed for lateral spreading type of slope instability associated with liquefaction failure. Moreover, existing landslides were considered separately and given a rating of very high although it was recognised that this may be conservative especially for inactive landslide areas.

The emerging trend is to use deformation analysis and not just limit equilibrium analysis under dynamic conditions. Experience has shown that estimated sliding block deformations correlate much better with performance (or non-performance) of slopes during earthquakes than do dynamic (pseudo static) factors of safety. The availability of GIS has facilitated mapping as well as the whole process of hazard assessment. However, it has encouraged the widespread use of the 'infinite slope' model as a basis for calculating the factors of safety as well as sliding block deformations. This approach may be valid in some regional studies but can lead to significant underestimates of deformations where more complex failure mechanisms are involved. This is one of the most important areas for future research and development. As has been emphasised in this paper, a curved failure mechanism leads to deformations of significantly higher magnitude in comparison to a plane failure mechanism.

There is a need to consider the effect of local soil conditions and topography on the amplification of ground motion. While site amplification is often evaluated in geotechnical earthquake engineering, there is little evidence from the literature of taking amplification into account in slope stability problems. Yet there is evidence from the field observations that some landslides occurred primarily as a consequence of topographic and/or site amplification.

Uncertainties of different types are associated with deterministic analyses and there is an increasing trend towards the use of probabilistic methods. Aside from formal probabilistic approaches, observed failure probabilities can also be evaluated. Reference is made to innovative approaches for (i) determining the relationship between observed landslide probability and calculated deformations (ii) increase in the failure probability of a site with a known prior probability.

In conclusion, methods for assessment of landslide hazard are still developing and improvements are required for qualitative as well as quantitative hazard assessments. For both types of assessments, there is need to identify and evaluate all types of effects. Some effects are currently not considered at all or not considered fully. For quantitative assessments, the choice of correct failure mechanism is an important area for development. Also it is necessary to develop methods to enable 2D analysis techniques to be implemented within the framework of a GIS-based approach.

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