Geotechnical analysis of slopes and landslides - achievements and challenges

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Publication Details
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Abstract
This paper is concerned with the major achievements in geotechnical slope analysis and the challenges for further advancement in the 21st century. New developments of great value have occurred over the past few decades for carrying out both site-specific and regional studies. These include advanced limit equilibrium methods, sophisticated stress deformation analysis, seismic analyses, applications of GIS, probabilistic approaches, advanced geological modeling (2D and 3D) and knowledge-based methods of predicted performance and decision-making. Outcomes of slope analysis are enhanced by advances in observational methods including real-time or continuous field monitoring of slope performance. One of the challenges is to further understand the causes and mechanisms of failure in order to minimize future losses through efficient hazard and risk management of which slope analysis is a vital part. Climate change will present long-term challenges associated with more unfavorable conditions for slope stability. Innovative engineering solutions will be required for better risk management. In turn, such solutions will require substantial progress in slope analysis in the context of multidisciplinary studies.

Keywords
analysis, geotechnical, slopes, landslides, achievements, challenges

Publication Details

This conference paper is available at Research Online: http://ro.uow.edu.au/eispapers/1736
Geotechnical analysis of slopes and landslides - achievements and challenges

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ABSTRACT: This paper is concerned with the major achievements in geotechnical slope analysis and the challenges for further advancement in the 21st century. New developments of great value have occurred over the past few decades for carrying out both site-specific and regional studies. These include advanced limit equilibrium methods, sophisticated stress deformation analysis, seismic analyses, applications of GIS, probabilistic approaches, advanced geological modeling (2D and 3D) and knowledge-based methods of predicted performance and decision-making. Outcomes of slope analysis are enhanced by advances in observational methods including real-time or continuous field monitoring of slope performance. One of the challenges is to further understand the causes and mechanisms of failure in order to minimize future losses through efficient hazard and risk management of which slope analysis is a vital part. Climate change will present long-term challenges associated with more unfavorable conditions for slope stability. Innovative engineering solutions will be required for better risk management. In turn, such solutions will require substantial progress in slope analysis in the context of multidisciplinary studies.

KEYWORDS: Slope Stability, Landslides, Pore-water Pressure, Probabilistic Analysis, Observational Approach, Risk Management

1 INTRODUCTION AND OVERVIEW

Advances in geomechanics and engineering geology have led to a variety of methods for designing, assessing and managing natural slopes, embankments and excavated slopes. While new and sophisticated methods of geotechnical analysis have been developed, steady improvement of conventional methods continues to occur. Moreover, new perspectives concerning slope reliability can be gained by using methods within a probabilistic framework. It is important to distinguish between regional and site-specific studies and, in each case, to consider carefully the requirements, suitability and limitations of qualitative and quantitative approaches (Chowdhury and Flentje, 2008).

The development of geotechnical analysis for slopes of soil and rock has progressed as a consequence of improvement in the knowledge of basic geotechnical concepts and an understanding of the causes, processes and mechanisms associated with slope failures. Pore-water pressure often plays an important role in slope stability and it may determine how the factor of safety varies spatially and over time. The effective stress principle is fundamental to an understanding of the short-term and long-term behavior of soil and rock slopes in which pore-water pressure develops as a consequence of water infiltration and seepage. Rainfall-induced slope failures occur generally, but not always, in saturated soils. Such failures are caused by the increase of pore-water pressures to critical values. Back-analyses of rainfall-induced slope failures enable the estimation of critical pore-water pressures. Concepts related to “excess” pore-water pressure are particularly important for behavior of soil slopes under undrained or partially drained conditions. It is of particular interest to study the stability of constructed or excavated slopes immediately after construction and to understand the changes in stability of submerged slopes during drawdown, complete or partial (Chowdhury et al, 2010).

Methods of analysis developed for saturated slopes of soil and rock can be extended to slopes comprising unsaturated soil zones as well. However, the relevant shear strength equation (different from that applicable to saturated soils) must used. In unsaturated soils, rainfall-triggered failures are a consequence of the elimination of negative pore-water pressures (soil suctions). Thus it is necessary to estimate the distribution of suctions (negative pore pressures) within unsaturated soil zones.

Understanding the regional context of a site in terms of topography, geology, groundwater flow and geomorphology is important. Knowledge about the location,
character, types, distribution and behavior of landslides in a regional context can be very valuable. The development of comprehensive databases including a landslide inventory is most desirable if not essential especially for the assessment of slope stability in a regional context. It is important to study the occurrence and spatial distribution of first-time slope failures as well as reactivated landslides (Flentje and Chowdhury, 2005a; Reeves and West, 2009). A successful knowledge-based approach for assessment of landslide susceptibility and hazard has been described by Flentje (2009).

Dealing with seismic slope stability requires consideration of slope behavior under cyclic loading conditions. It is important to estimate the decrease in the factor of safety of a slope or an earth structure as a consequence of a design seismic event. For earth dams and other major earth slopes, it is also important to estimate the cumulative permanent deformation which might result as a consequence of a design seismic event. Analyses after an earthquake can be based on the actual recorded earthquake ground motion if such data are available. Moreover, geotechnical engineers have the task of assessing the likelihood of liquefaction occurring within deposits of loose saturated sand or zones or pockets of such sand within cohesive soil deposits such as clays.

While analysis is important, its role should not be considered in isolation. Therefore it is necessary to highlight the importance of an observational approach. In particular, the monitoring of slope movement and subsurface pore-water pressures can be critically important. Monitoring of slope performance is often part and parcel of an important geotechnical project such as an earth dam, a reinforced embankment or major excavation. However, it is also desirable to monitor the performance of natural slopes in urban areas because of the adverse economic and safety consequences of urban landslides. Analysis of data from such monitoring can help validate concepts concerning causes and mechanisms of landsliding and facilitate decisions concerning remedial measures and warning systems (Flentje and Chowdhury, 2006).

2 DETERMINISTIC METHODS OF ANALYSIS

2.1 Limit Equilibrium and Stress deformation Approaches

Broadly the deterministic methods can be categorized as limit equilibrium methods and stress-deformation methods. Starting from simple and approximate limit equilibrium methods based on simplifying assumptions, several advanced and relatively rigorous methods have been developed. Advanced methods are versatile, enabling the analysis of a slope with complex geometry, formed in an anisotropic, non-homogeneous or reinforced earth mass, assuming either linear or non-linear stress-deformation characteristics. The history of slope formation can also be taken into consideration. Two-dimensional (2D) limit equilibrium analyses are, of course, the most widely used. However, considerable progress has been made in the development and use of three-dimensional (3D) analyses. Post failure behavior including the dynamics, mobility and travel distance of landslides is often associated with significant uncertainties (Chowdhury, 1980; Chowdhury et al, 2010).

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

2.2 Analysis of Progressive Failure

Progressive failure of natural slopes, embankment dams and excavated slopes is a consequence of non-uniform stress and strain distribution and the strain-softening behavior of earth masses. Thus shear strength of a soil element, or the shear resistance along a discontinuity within a soil or rock mass, may decrease from a peak to a residual value with increasing strain or increasing deformation. Analysis and simulation of progressive failure requires that strain-softening behavior be taken into consideration within the context of changing stress or strain fields. This may be done by using advanced stress-deformation approaches. (See, for instance, Richards, 1982; Potts et al, 1990; Sitar et al, 2005) Other approaches which may also be used include initial stress approach and shear-band approach and the reader will find an overview of several methods with references and relevant details in Chowdhury et al (2010).

Of the many historical landslides in which progressive failure is known to have played an important part, perhaps the most widely studied is the catastrophic Vajont slide which occurred in Italy in 1964. The causes and mechanisms have not been fully explained by any one study and there are still uncertainties concerning both the statics and dynamics of the slide. Simulation of progressive failure on the basis of an initial stress approach is discussed fully elsewhere (Chowdhury et al, 2010). An alternative approach based on limit equilibrium and the assumption of high artesian pore-water pressures was proposed by Hendron and Patton (1985).

2.3 Seismic Slope Analysis

For earthquake analysis, a pseudo-static method of limit equilibrium analysis is used in which the effect of earthquake shaking is simulated by a lateral force which is a product of the gravitational force and a seismic coef-
A probabilistic approach should not be seen simply as the replacement of a calculated ‘factor of safety’ as a performance index by a calculated ‘probability of failure’. It is important to consider the broader perspective and greater insight offered by adopting a probabilistic framework (Chowdhury, 1984; 1988). It enables a better analysis of observational data and enables the modeling of the reliability of a system. Updating of reliability on the basis of observation becomes feasible and innovative approaches can be used for the modeling of progressive failure probability (Chowdhury, 1992) and for back-analysis of failed slopes. Other innovative applications of a probabilistic approach with pertinent details and references are discussed by Chowdhury et al (2010).

An interesting approach for probabilistic seismic landslide analysis which incorporates the traditional infinite slope limit equilibrium model as well as the rigid-block displacement model has been demonstrated by Jibson et al (1998; 2000).

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

Although the adoption of a probabilistic approach by the geotechnical profession was initially a slow process, the considerable benefits in doing so are now increasingly recognized. Often there are difficulties in applying a quantitative probabilistic approach because data concerning one or more key parameters are insufficient or lacking in quality. In such cases, a subjective approach, based on expert judgment may be used. However, such an exercise should be used with caution and with full recognition of its inherent limitations.

In this regard it is pertinent to refer to a recent paper (Silva et al., 2008) where the development of empirical non-linear relationships between the factor of safety F and annual probability of failure pF is outlined. Slope stability problems are classified into one of four types, category I to category IV, depending on a number of factors such as the extent of investigation, the reliability of shear strength data and the quality of engineering including construction supervision. For each category, there is a different empirical curve relating factor of safety to probability of failure.

Adopting such an approach may prove useful in particular cases where a lot of previous experience is available. On the other hand, such an approach discourages the consideration of each problem as unique and inhibits an understanding of the components of uncertainty and their relative influence on the results. For example, in problems of natural slope stability, variability of pore-water pressure, spatial and temporal, is often a significant source of uncertainty. Such variability can not be fully understood on the basis of a simplistic empirical approach.

3 PROBABILISTIC APPROACHES AND SIMULATION OF PROGRESSIVE FAILURE

The importance of uncertainties in geotechnical engineering and engineering geology is now widely understood. There are systematic uncertainties related to the estimation of geotechnical parameters because of the limits to the extent and quality of investigation and testing. It is also necessary to consider the natural variability of parameters, both spatial and temporal. For example, one frequently encounters spatial variability of shear strength parameters and pore-water pressures in natural slopes. Consequently there are limitations to the conventional deterministic methods of analysis and the calculated factor of safety, often designated by F, may not be a true reflection of the reliability of a slope. New approaches within the framework of statistics and probability have, therefore, been developed. Estimation of the probability of failure, often designated by pF, is feasible when the probability distribution of each significant geotechnical parameter is taken into consideration. There are, of course, other uncertainties which must be included in a probabilistic analysis such as statistical uncertainty, bias and geotechnical model uncertainty.
4 GEOTECHNICAL SLOPE ANALYSIS IN A REGIONAL CONTEXT

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

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

Spatial and temporal variability of triggering factors such as rainfall have a marked influence on the occurrence and distribution of landslides in a region (Flentje, 2009; Flentje and Chowdhury, 2005b).

This context is important for understanding the uncertainties in the development of critical pore-water pressures. Consequently, it helps in the estimation of rainfall threshold for on-set of landsliding. Regional and local factors both would have a strong influence on the combinations of rainfall magnitude and duration leading to critical conditions (Flentje and Chowdhury, 2001; Murray, 2001).

Since earthquakes trigger many landslides which can have a devastating impact, it is important to understand the causative and influencing factors. The occurrence, reach, volume and distribution of earthquake-induced landslides are related to earthquake magnitude and other regional factors. Among the important studies published on regional seismically-induced landsliding are those by Keefer (1984), Rodriguez et al (1999) and Keefer (2007).

5 GEOGRAPHICAL INFORMATION SYSTEMS (GIS) AND OTHER POWERFUL TOOLS

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

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

The linking of multiple datasets representing different influencing factors for slope stability is a powerful basis for hazard assessment. Knowledge-based approaches require spatial databases, advanced geological and geotechnical models as well as GIS. Such approaches are very powerful for assessment of landslide susceptibility, hazard and risk as well as for decision-making under a wide variety of scenarios.

Meeting future challenges will require continued efforts for understanding changes in landslide hazard over time caused by different factors including potential climate change. Regional modeling of geohazards change will therefore be an important task for geoscientists and geotechnical engineers. Consequently, 3D geological models have been discussed by a number of authors such as Rees et al (2009) who envisage that such models should be the basis for 4D process modeling in which temporal changes and factors can be taken into consideration. They refer, in particular, to time-series data concerning precipitation, groundwater, sea level and temperature. Such data, if and when available, can be integrated with 3D spatial modeling.

6 CHOICE BETWEEN CONVENTIONAL AND ADVANCED METHODS OF ANALYSIS

The choice amongst limit equilibrium methods depends on the type of slope (e.g., soil, rock), the shape of the slip surface (e.g., planar, multi-planar, circular, non-circular) and other aspects. Even so, more than one method may be suitable and many available software packages do include several alternative methods and options. Similarly there are several sophisticated methods of analysis for determining stresses and deformations and there is a corresponding choice of software packages.

The use of one or more limit equilibrium methods is sufficient in most slope problems where the aim is to determine the safety factor of the slope as the main performance indicator. Moreover, one of these methods can serve as a useful geotechnical basis for probabilistic modeling and analysis. On the other hand, if slope deformations need to be calculated and if detailed knowledge of stress and strain distributions is important, the use of advanced stress–deformation methods is desirable and, in fact, may be necessary. However, the required input data must be available and, in fact, the monitoring of deformations in the field would be desirable in order to validate the results based on the input data. Using a finite element solution simply to calculate the factor of safety offers little or no advantage over a limit equilibrium approach.
Slope analysis cannot be considered in isolation since a good understanding of site conditions and field performance is essential. Thus 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 within a region after a significant triggering factor such as a rainfall event (Flentje and Chowdhury, 2005b; Flentje and Chowdhury, 2006; Flentje et al., 2007; Flentje, 2009). Most importantly, observational approaches help in the back-analyses of slope failures and landslides. From the beginning of soil mechanics as a discipline, back-analyses have been very useful in understanding the mobilization of shear strength, the development of stresses and deformations and several other aspects of slope behavior. Whether considering new or existing slopes or the strengthening of slopes, a well designed program of observation and monitoring can be useful for validating geotechnical analyses. Moreover, data for slope analysis, such as pore-water pressure and shear strength can be updated as more observational data become available. The availability of real-time data will contribute to more accurate assessments and to more accurate back-analyses. Consequently, real-time monitoring will lead to further advancement in the understanding of slope behavior.

8 EMERGING CHALLENGES

First and foremost we must consider the challenge of the increasing numbers of slope failures and their increasingly adverse consequences. These trends have developed in spite of significant progress in our understanding of natural processes and in spite of the successful development of experimental, analytical and design tools.

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

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

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

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

9 CONCLUSIONS

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

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

REFERENCES

