Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Slope stability hazard management systems[*]

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Received July 12, 2007; revision accepted July 17, 2007

Abstract: Weather-related geo-hazards are a major concern for both natural slopes and man-made slopes and embankments. Government agencies and private companies are increasingly required to ensure that there is adequate protection of sloping surfaces in order that interaction with the climate does not produce instability. Superior theoretical formulations and computer tools are now available to address engineering design issues related to the near ground surface soil-atmospheric interactions. An example is given in this paper that illustrates the consequences of not paying adequate attention to the hazards of slope stability prior to the construction of a highway in South America. On the other hand, examples are given from Hong Kong and Mainland China where significant benefits are derived from putting in place a hazard slope stability management system. Some results from a hazard management slope stability study related to the railway system in Canada are also reported. The study took advantage of recent research on unsaturated soil behaviour and applied this information to real-time modelling of climatic conditions. The quantification of the water balance at the ground surface, and subsequent infiltration, is used as the primary tool for hazard level assessment. The suggested hazard model can be applied at either specific high risk locations or in a more general, broad-based manner over large areas. A more thorough understanding of unsaturated soil behaviour as it applies to near ground surface soils, along with the numerical computational power of the computer has made it possible for new approaches to be used in slope hazard management engineering.

Key words: Slope stability, Geo-hazards, Highway, Hazard, Slope stability management system
doi:10.1631/jzus.2007.A1695 **Document code:** A **CLC number:** TU4; X4

INTRODUCTION

Slope instability problems can be subdivided into two broad categories, namely, problems associated with the failure of natural slopes and failures associated with man-made slope (i.e., excavations or fills). There are a number of possible factors that can lead to the instability of a soil slope. However, in general, earthen slopes remain stable unless there are changes in the pore-water pressures in the soil comprising the slope. Changes in pore-water pressures are generally the result of water infiltration related the climatic conditions. Often it is the reduction in negative pore-water pressures in the upper 1 to 6 m that triggers slope instability (Zhang *et al*., 2004). The climatic conditions at a particular location produce a microclimatic condition that can result in the slope remaining stable with respect to time or becoming unstable with respect to time (Gitirana and Fredlund, 2003a; 2003b; 2005). In other words, the stability conditions are primarily controlled by the imposed climatic conditions. Consequently, slope instability problems become a “hazard” that needs to be managed through the application of sound engineering principles.

The consequences of slope instability can be costly and even result in the loss of many lives (Fell, 1994). Any slope failure can result in substantial costs for remediation while in regions of dense population or areas prone to high velocity landslide, the loss of life can be considerable. Therefore, governments and private agencies are increasingly asked to manage the “hazard” of slope instability.

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[*] The Zeng Guo-Xi Lecture, May 22, 2007

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This paper attempts to illustrate situations where the lack of slope management has turned out to be costly, and as well, show situations where substantial benefits have been accrued as a result of giving serious consideration to managing the "hazard" of slope instability. Advances in the theoretical understanding of unsaturated soils behaviour, along with numerical modelling techniques and the development of the digital computer (i.e., computer software and hardware), have made it possible to better address the interaction between climatic conditions and near ground surface soil behavior.

One does not need to travel far from Hangzhou, China to witness the benefits accrued from taking proactive action with regard to the back-slopes along highways. There are a number of excellent examples along the highway between Hangzhou and Nanjing (Fig.1). This example in Fig.1 also illustrates the individuality of each back-slope. In other words, it is likely that as much or more engineering design time will be required to address the design requirements associated with the highway back-slopes as will be required for the roadway substructure. It is also possible that final design of the back-slopes may need to await the excavation process. The final design can indeed be attractive to the traveler.

Fig.1 Example of a well-designed highway back-slope on the Hangzhou to Nanjing Highway, China

This paper can be subdivided into three main parts: first, an example is given showing the consequences of ignoring slope instability hazards when undertaking new road construction; second, two examples are given to show the benefits associated with paying strict attention to the hazard of slope instability; and third, an illustration is provided to show potential tools that are available for assessing the interaction between the climate and the soil. There are many examples that could be used to illustrate the contrast between having and not having an adequate slope hazard management system in place. The examples described in this paper are limited to those with which the author has had personal experience.

HIGHWAY EXPERIENCES IN ECUADOR

In 2002, the author was asked to deliver a keynote lecture to the Second Pan American Conference in Quayaquil, Ecuador on the Teaching Learning Process in Geotechnical Engineering (Fredlund, 2002a). Following the conference, some of the delegates to the conference were taken on a field trip to view a new highway that had been built from Quayaquil, Ecuador through the Andes to the border with Peru (Fredlund, 2002b; Fig.2). The highway had been constructed over the past few years and had subsequently been plagued with serious slope instability problems. The construction of the highway was undertaken with financial assistance from the World Bank.

Fig.2 Map of Ecuador showing the general location of a highway from Quayaquil, Ecuador through the Andes Mountains

The field trip commenced from Quayaquil, Ecuador, at sea level and quickly rose into the mountains to the south, reaching elevations in excess of 3657.6 m above seal level (Fig.3). The terrain was extremely rugged with much of surface soils on the mountainside consisting of weathered colluvium (Fig.4). The colluvium formed a mantle of material overlying the bedrock. Over the years the coluvium material has established an equilibrium condition between the soil on the mountainside and the generally encountered weather conditions in the region. The colluvium material exists near its angle of repose and remains relatively stable as long as extreme weather conditions are not encountered or unless the geometry of the mountainside is altered.

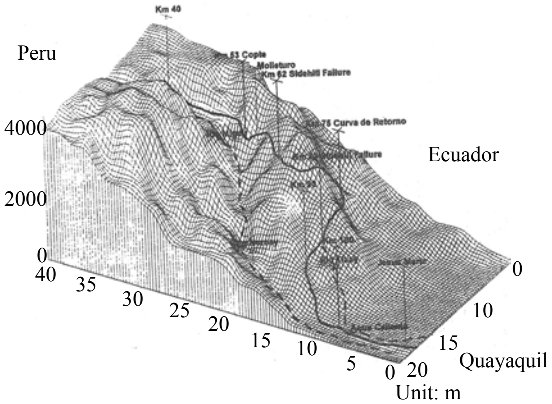


Fig.3 Topographic 'net' showing location of the highway from Quayaquil, Ecuador to Peru. Roadway rises from sea-level at Quayaquil, Ecuador to about 3657.6 m

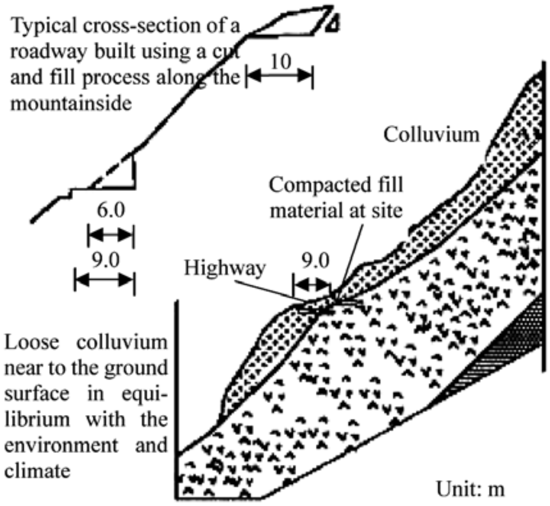


Fig.4 Illustration of how highway cut and fill is largely within unstable colluvium material at ground surface

The construction of a roadway along the mountainside involves cutting into the mountainside, thus producing an over-steepened back-slope. At the same time, fill is generally moved onto the above down-slope portion below the roadway. Both of the above-mentioned processes result in a disturbance to the delicate equilibrium of the mountainside. The colluvium materials exist at a factor of safety near to 1.0 and any change in the geometry of the slope and/or the water infiltration conditions will produce instability. As a result of the road construction project massive landslides were triggered both above and below the newly constructed road. Fig.5 illustrates the type of chain reaction landslides that were precipitated over the entire mountainside. Slope instability has been triggered over large portions of the new highway as a result of changing the ground surface geometry and subjecting the soils to new infiltration conditions (Fig.6).

Fig.5 Example of numerous, multiple slope failures triggered above and below the newly constructed highway in Ecuador

Fig.6 Another example of almost continuous slope instability triggered by changing geometric and environmental conditions along the highway in Ecuador

Fig.7 shows a location where an attempt was made to improve the alignment of the road by reducing the sharpness of a curve along the highway. The result was the initiation of a large block slide involving a substantial depth of colluvium from the mountainside. A subsequent soils investigation at the site showed that the remedial retaining wall was not anchored into the intact bedrock materials.

The consequence of using switch-backs on the mountain side under these conditions is clearly illustrated in Fig.8. Slope instability on the up-slope portion of one roadway creates instability that intersects with instability on the next switch-back. It is easy to see how most of the mountainside can become unstable. At the particular location shown in Fig.8, it was decided to place gunite on the entire surface to prevent moisture from entering at the ground surface. Fig.9 illustrates the difficulties associated with attempting to place gunite on a surface that may be 45° or greater from the horizontal. The handling of the pressurized gunite hoses on such a steep surface is a challenge to the contractor. It is also a challenge to place gunite over a relatively loose colluvium surface. It was necessary to first place a wire mesh over the surface which was then anchored to the underlying soil. Then gunite was sprayed over the wire mesh. A small retaining wall was also constructed at the toe of the slope. There is no guarantee that the solution will prove to be a long-term solution. Also, the solution is very much a trial and error solution with little engineering design involved.

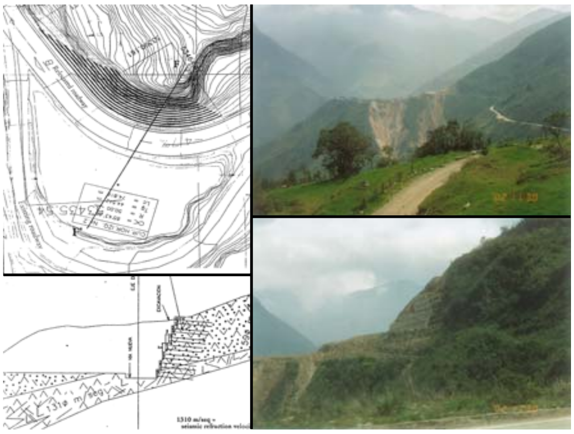


Fig.7 Example of a major landslide triggered by attempting to improve alignment along the highway in Ecuador. Photos in the right showing that the relocation of the switch-back creates major instability

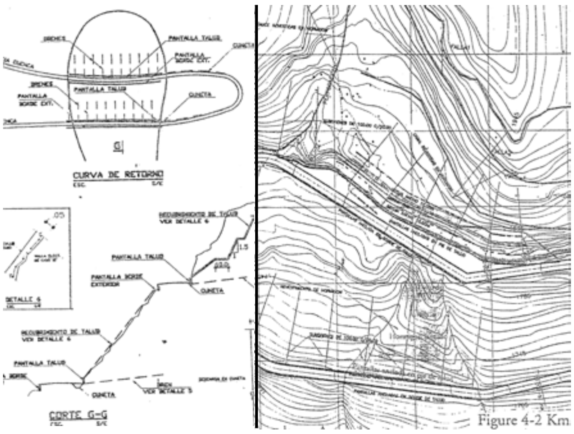


Fig.8 Example of mountainside instability triggered through the use of 'switch-backs' along the Ecuador highway. Switch-backs placed on extremely steep slopes can produce instability for the entire mountainside

In 2003, the World Bank called for an engineering study to provide viable solutions for the previously constructed highway in the Andes Mountains. It was suggested that the engineering study and remedial work would cost in the order of $50 million (USD). Engineering studies can be undertaken following the initiation of major landslide problems; however, it would be much better to put the money towards engineering studies prior to the construction of the highway. All too often the emphasis is placed on building a roadway while little attention is given to the back-slopes and down-slopes associated with the roadway.

Unsaturated soil mechanics and water balance studies have much to contribute to a more in-depth understanding of slope instability "hazards". Unfortunately, this expertise was not pursued prior to the construction of the highway. Lives were lost as a result of mass movements of material into the valley below (Fig.10), and great inconvenience and maintenance expense were encountered over a period of many years.

Fig.9 Use of anchored mesh and gunite to reduce infiltration of water and maintain stability on the back-slopes of the highway in Ecuador. Placing gunite on the back-slope consisting of residual soil

Fig.10 Large debris flows set off into the valley leading to endangerment of farming residents

The author is not suggesting that the engineering solutions to the slope instability problems encountered at this site are simple. On the contrary, the problems are extremely complex and challenging but the geotechnical engineer needs to be given an opportunity to apply his skills to generate a superior slope hazard management system. As shown later in this paper, there are places in the world where significant success has been achieved in addressing slope instability problems within the context of a slope hazard management system.

The slope instability problems associated with highway construction in mountainous regions (or hillside conditions) are by no means restricted to one country. Disastrous situations have been repeated in many countries where major highway projects have been undertaken without ample regard for the interaction between the environmental conditions and the geology and soil conditions. There are numerous examples that could be cited from countries such as Vietnam and the other Indo-China countries.

SLOPE STABILITY MANAGEMENT IN HONG KONG

Hong Kong has had many years of experience with managing difficult slope stability conditions (Fig.11). The geology of Hong Kong shows that there are two primary residual soil types that cover Hong Kong Island, Kowloon and the New Territories, namely, decomposed granite and decomposed rhyolite (volcanic) (Leach and Herbert, 1982). These materials show the greatest weathering near ground surface, decreasing to an essentially unweathered material at depth. The water table is often at considerable depth (i.e., 10 to 30 m), located just above the unweathered bedrock. Consequently, most of the soil profile is in an unsaturated soil state. There are also areas in Hong Kong where the surface material consists of a colluvium layer.

Fig.11 Development of Hong Kong on extremely steep, mountainous conditions has created a history of slope instability problems

For many years, numerous lives were lost each year as a result of slope failures. Often the people killed were living in forbidden areas and little was done to try and change their living practices. In 1972, a major landslide occurred on Hong Kong Island. The landslide is referred to as the Po Shan Road landslide and an aerial view of the landslide after failure immediately is shown in Fig.12. This landslide became a turning point in the attitude of the people of Hong Kong to the management of slope hazards. Seventy-eight people were killed as a result of the Po Shan Road landslide but it was also clear that the death toll could have been much greater had not the warnings to

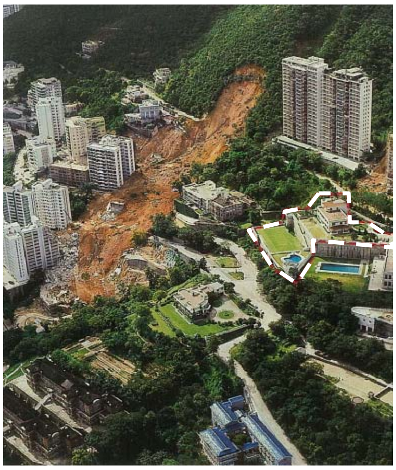


Fig.12 The Po Shan Road landslide of 1972 killed 78 people but subsequently led to the formation of an effective hazard management system

evacuate been heeded. Many of the people killed were wealthy, high profile person in Hong Kong. The cry went out through the publishing of many words saying, "If you allow people to build and live along the mountainside, then the engineers must be able to ensure that the slopes will remain stable".

The outcry for accountability and a superior hazard management system for Hong Kong resulted in the collection of many geotechnical engineers that were to focus on addressing the slope instability problems in Hong Kong. But first, all further development was suspended in the "mid-level" mountainside region of Hong Kong Island. The landslide site was thoroughly studied and a remediation plan was put in place. The repaired slope focused on the collection of surface water and the minimization of infiltration into the underlying soil. Fig.13 shows the Po Shan Road landslide site following remediation. The site remains to this day as a stark reminder of the awesome potential for destruction as a result of mass movement.

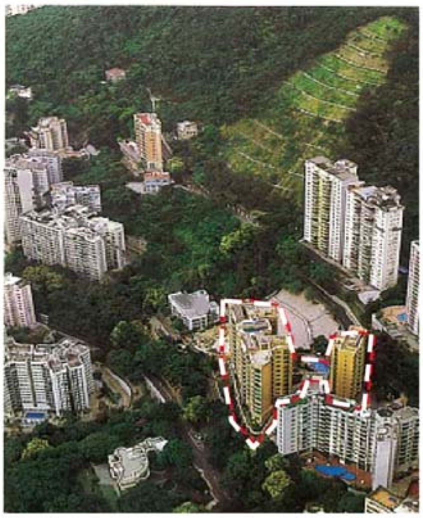


Fig.13 The scar remains from the repair of the Po Shan Road landslide of 1972

The GCO (Government Control Office) was formed and later changed to the GEO (Geotechnical Engineering Office) (Brand, 1982; 1985). This office eventually grew to in excess of 500 engineers and personnel devoted to the management of slope instability problems in Hong Kong. Considerable money was ear-marked for research into a better understanding of the mechanisms contributing to slope instability (Anderson, 1983). An array of dipping rain gauges was installed on the mountainsides around the Hong Kong region (Fig.14). The rain gauges reported rainfall intensities through a solar-driven telephone network on an hourly basis. The results were compiled on a central computer system thereby providing an hourly contouring of rainfall intensities throughout Hong Kong. The locations of the rain gauges are shown in Fig.15. The system of rain gauges provides important information related to the assessment of water balance at the ground surface.

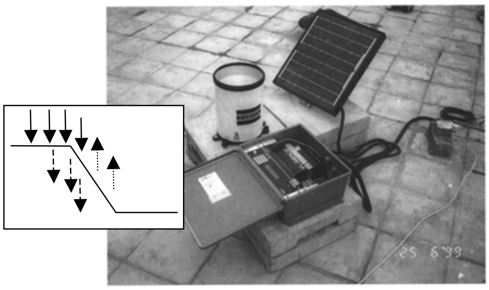


Fig.14 Solar powered rain gauges report to a central computer on an hourly basis. Water balance at ground surface becomes the key to analyzing the stability of a slope. Precipitation: measured; Evaporation: computed using soil-atmosphere model

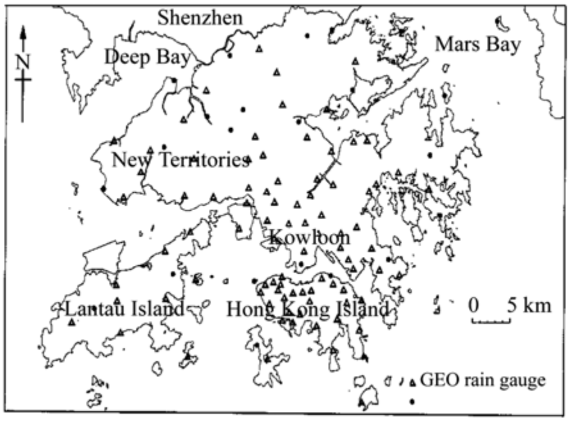


Fig.15 Location of rain gauges placed throughout Hong Kong. Contour maps of precipitation can be plotted on an hourly basis

Several universities around the world became involved in experimental, theoretical and analytical research studies. The Government of Hong Kong also embarked on his own research programs. The author became involved first as a consultant to Fugro, Hong Kong (Fredlund, 1981; Sweeney and Robertson, 1979), and later through research contracts with GEO, Government of Hong Kong. The research programs that the author became involved with were directed towards: first, a better understanding of the shear strength of residual soils with negative pore-water pressures (i.e., matric suction); second, the measurement of negative pore-water pressures in the field; third, studying how to take matric suction into account in a slope stability analysis; and fourth, modelling of the infiltration of rainwater into unsaturated soil slopes.

In the early 1980s, the author took part in a study that involved the measurement of in situ matric suctions inside a 23 m deep caisson in decomposed granite on Hong Kong Island (Sweeney, 1982). The caisson was about 1 m in diameter and had port-holes in the side walls every metre throughout its depth. Matric suction readings were taken on approximately a monthly basis over a period of several years. The results from the year 1980 are shown in Fig.16. The matric suction readings followed a similar pattern over a period of several years and revealed much about suction changes near to the ground surface in these types of soils. First, matric suction changed significantly in the upper 5 m, particularly during the typhoon rainy season; Second, in the zone between 5 and about 20 m, matric suctions readings stayed approximately constant the year around; Third, below about 20 m the groundwater level was seen to change significantly in response to rainfall conditions. While other soil conditions may exhibit behaviours that are different than those observed at this site, the measured results provide important information on infiltration into decomposed granite and residual soils. The measurements assisted in understanding how natural slopes utilize negative pore-water pressures near the ground surface to maintain stable conditions.

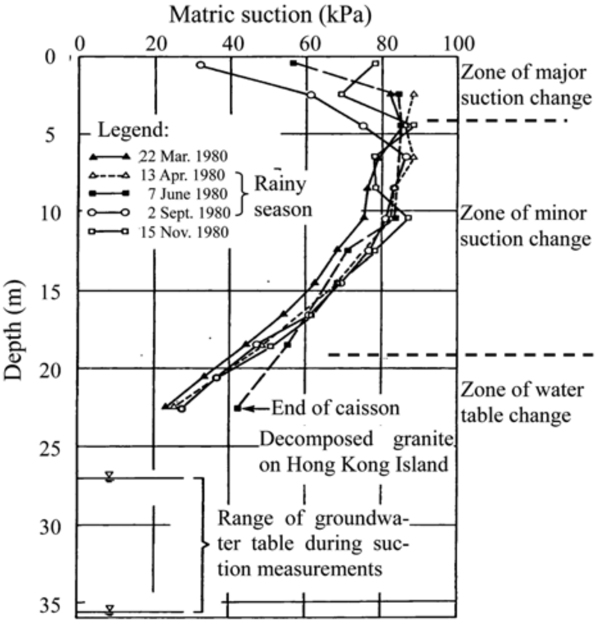


Fig.16 Measurements of matric suction along a deep, cased hole in decomposed granite on Hong Kong Island

The maximum in situ matric suctions measured in the decomposed granitic soils in Hong Kong were about 90 kPa. An analytical study was conducted to assess the significance of matric suctions of this magnitude on the computed factor of safety (Rahardjo and Fredlund, 1991). Matric suction values can be converted to an equivalent cohesion component and used in the calculation of the factor of safety of typical slopes (Fredlund, 1981; Fredlund and Rahardjo, 1993). Fig.17 illustrates that matric suctions of as little as 50 kPa can increase the computed factor of safety by about 60% on a 2:1 slope. The effect is even more significant on steeper slopes and matric suctions of 100 kPa could more than double the computed factor of safety of a slope. The results illustrate how matric suctions can contribute significantly to the stability of a slope. Further numerical studies have assisted in better understanding the temporal and/or permanent nature of in situ matric suctions in the soil (Kasim *et al*., 1998).

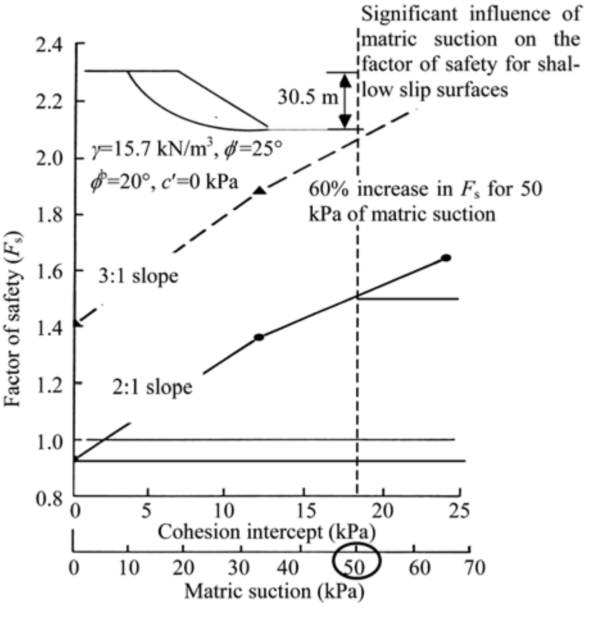


Fig.17 Illustration of the importance of matric suction in increasing the factor of safety of steep slopes

Even if matric suction values are not directly taken into account in slope stability assessment, their effect can be indirectly taken into consideration through proposed engineering designs. For example, preparing the soil surface in such a way that there is a reduction in infiltration can greatly assist in maintaining the stability of a slope (Fig.18). Numerous measures have been put in place in Hong Kong to minimize the infiltration of rainwater into a slope. A mixture of decomposed granite, flyash and cement, referred to as "chunam", has been used to cover exposed back-slopes along roadways and building sites (Fig.19). Each slope has a small plaque placed on its surface for identification purposes (Fig.20). A complete performance record along with photographs and descriptions of the soil conditions are maintained by GEO for each slope in Hong Kong. This is an extensive undertaking that has confirmed the high importance placed on maintaining the stability of all slopes in Hong Kong.

Public pressure has encouraged government engineers to consider "greener", more environmentally pleasing solutions. A variety of "mat" materials that can sustain vegetative growth on steep slopes have been studied and brought into practice (Fig.21). These engineered designs appear more pleasing but it is important to remember that the water infiltration characteristics of the slope have also been altered. Modifications to the surface design need to be studied to ensure that the slopes will be able to maintain an adequate factor of safety under extreme rainfall conditions. The dense population conditions in Hong Kong have forced careful design considerations for all slope surfaces. These conditions are quite different from those encountered in sparsely populated areas. However, the Government of Hong Kong has clearly led the way in demonstrating a "will" to provide high level slope stability hazard management. The emphasis on individually engineered designs and an environmentally pleasing solution can be observed at many sites. Fig.22 shows a back-slope along the road-

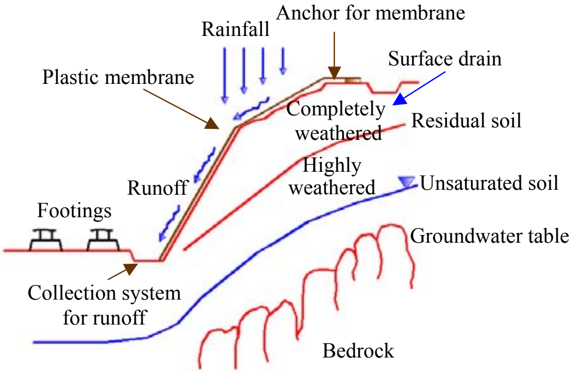


Fig.18 Illustration of how controlling infiltration of moisture on the slope assists in maintaining stability. "Control of Infiltration" through use of Geomembranes is common in many parts of the world

Fig.20 Identification plaques placed on the surface of a slope to assist the public in participation in slope management. Each slope is photographed from a variety of angles and has an identifying label. Performance data is stored in a large database

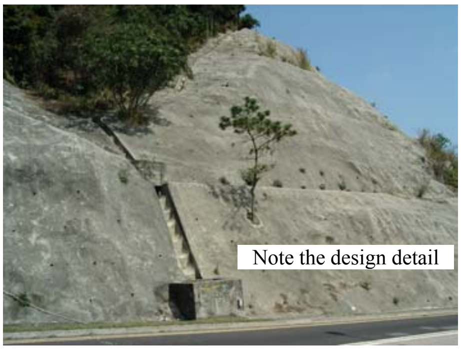


Fig.19 Illustration of the use of "chunam" to reduce infiltration of moisture on slopes in Hong Kong. Slopes in Hong Kong are generally covered with Chunam (i.e., mixture of decomposed granite, flyash and cement) to reduce surface infiltration by 90%

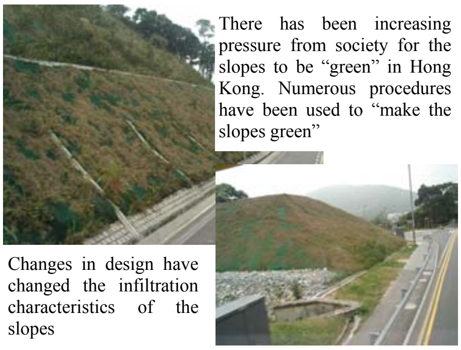


Fig.21 Use of more environmentally-friendly green growing meshes placed on sloping surfaces in Hong Kong

Fig.22 Example of a recent, environmentally-friendly designed back-slope in Hong Kong

way to the new airport in Hong Kong. The interceptor ditch along the crest of the slope is another one of the important details of design.

POTENTIAL LEVEE MANAGEMENT ALONG YANGZTE RIVER, CHINA

Levees have been constructed along the banks of the Yangtze River throughout the history of China. The purpose of the levees was to contain the rising water levels of the Yangtze River during flood season, thereby protecting the surrounding farmland, farmers and other residents. Fig.23 shows a typical Class I levee to the east of the city of Jingzhou near Wuhan, China. The soil strata associated with a considerable number of cross-sections has been identified through subsurface investigation studies. Fig.24 shows a typical cross-section through the levee system.

The stability of the levees is somewhat influenced by rainfall conditions but the more significant factor affecting levee stability is the raising and lowering of the water in the river. The most severe instability condition along the levees will likely arise from sustained high water levels. This situation is somewhat different than the previous examples mentioned in that slope instability is related to a changing boundary “water head” as opposed to a changing boundary “moisture flux”.

Over the past few years, Golder Associates (and the author) have become involved in a hazard management study of the dyke or levee system near Wuhan. The project was funded in part by the World Bank (Nippon Technologies Industries, 2005a; 2005b; 2006). The main study to-date has involved the identification of the main hazard components and the definition of an optimal “decision making” methodology for the Yangtze River dyke and Sihu Basin flood operations.

The main function of the proposed computer modelling system was to provide an estimation of the probability of potential failure of the Yangtze River dykes using numerical models and information collected in real-time. A modelling system for this situation can be defined as a mathematical representation of a physical system that includes the simulation of various processes that might lead to dyke failure. The physical system involves a description of the geometry, stratigraphy and soil properties. The processes of primary concern involve the seepage of water into the dykes and potential mass movements that may result. The numerical models are intended to integrate deterministic model formulations, accept probabilistic and deterministic model inputs, and produce estimates of probability of dyke failure (Fig.25). The decision making methodology consisted of various numerical models that would be able to simulate the identified potential hazards that might cause dyke failure. The primary hazards were identified as: (i) seepage and piping, (ii) shoreline and dyke toe ero-

Fig.23 Typical dyke built along the banks of the Yangtze River near Wuhan, China

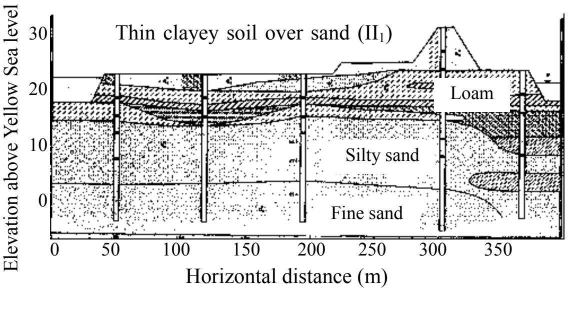


Fig.24 Geological cross-section of double-layered structure (II_1) based on borehole results, identifying the stratigraphy and soil conditions at a selected location

sion, (iii) dyke and foundation slope instability, (iv) seepage at hydraulic structures, (v) effects of animals and (vi) overtopping (Table 1). The probability of potential dyke failure can be computed for each type of hazard. The individual probabilities of failure are then combined to give an "overall probability of failure" in accordance with the following equation:

$$P=1-(1-P_1)(1-P_2)(1-P_3)(1-P_4)(1-P_5)(1-P_6), \quad (1)$$

where P is overall probability of dyke failure, P_1~P_6 are probability of failure due to seepage and piping across the dyke, shoreline and dyke toe erosion, dyke and foundation slope instability, seepage at hydraulic structures, effect of animals, and overtopping, respectively.

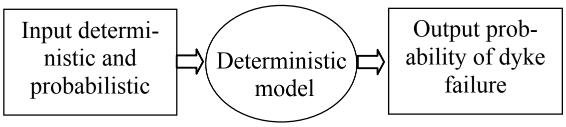
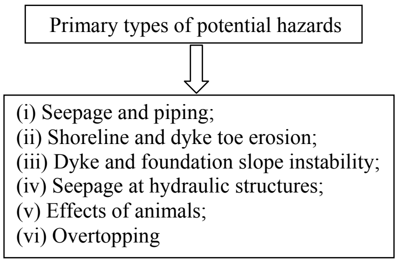
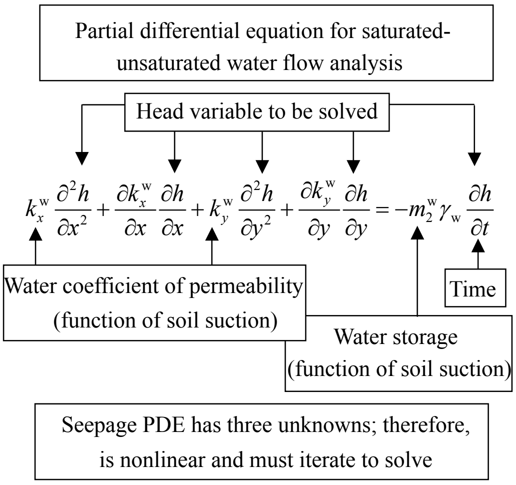


Fig.25 Relationship between deterministic and probabilistic modelling

Table 1 Primary types of potential dyke hazards





$$k_x^{\mathrm{w}}\frac{\partial^2 h}{\partial x^2}+\frac{\partial k_x^{\mathrm{w}}}{\partial x}\frac{\partial h}{\partial x}+k_y^{\mathrm{w}}\frac{\partial^2 h}{\partial y^2}+\frac{\partial k_y^{\mathrm{w}}}{\partial y}\frac{\partial h}{\partial y}=-m_2^{\mathrm{w}}\gamma_{\mathrm{w}}\frac{\partial h}{\partial t}$$

Fig.26 Partial differential equation (PDE) for 2D saturated-unsaturated seepage modelling

The most basic process to be modelled involves the seepage of water into the dyke on a transient (i.e., real-time) basis. The hazard model for the seepage and piping hazard follows the form shown in Table 2. The general, 2D, partial differential equation (PDE) for modelling seepage through saturated-unsaturated soil systems can be written as shown in Fig.26. As the analysis proceeds, the assessment of the likelihood of failure is computed based on comparison of predicted flow velocities and hydraulic gradients at exit points along the dyke surface to limiting values.

Modelling seepage through saturated-unsaturated soil systems means that highly nonlinear PDEs must be repeatedly solved while marching forward in time. The modeller desires to be confident that the computer software can continuously converge and also converge to the correct solution. One of the most powerful techniques developed to-date to accomplish this goal has been the adaptive mesh refinement technique where the finite element grid is up-dated following every iteration in order to meet the criteria for convergence (Fig.27; SoilVision Systems Ltd., 2003). This means that convergence difficulties are made the responsibility of the mathematical solver

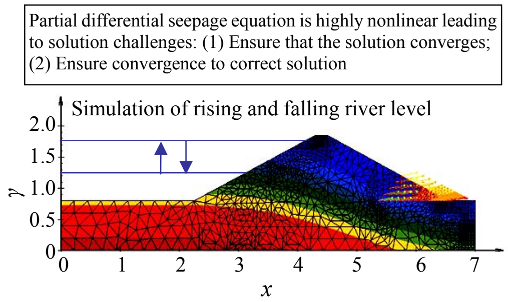
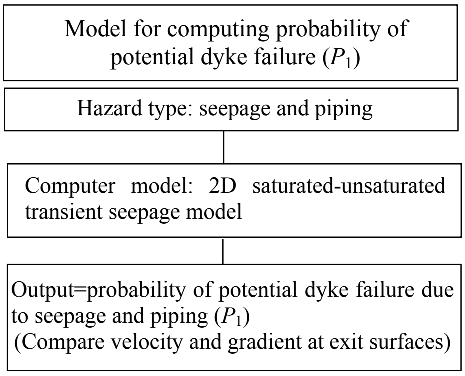


Fig.27 Transient boundary conditions requiring an adaptive mesh to ensure convergence of the solution

Table 2 Model for computing the probability of dyke failure due to seepage and piping (P_1)



and moved away from the responsibility of the geotechnical engineer (Fredlund, 2006).

The probabilistic component is largely applied through variations in the soil properties. It was suggested that grain size distribution curves be used to assess the coefficient of variability of the materials involved. The saturated coefficients of permeability for a soil may be measured in the laboratory but values can also be estimated from the grain size distribution curves. It is also possible to estimate the soil-water characteristic curves and subsequently, the unsaturated soil properties from the grain size distribution curves. Fig.28 shows a band of grain size distribution curves from sands found below the levees near Wuhan. It is each individual grain size distribution curve that is analyzed for the estimation of saturated-unsaturated soil properties.

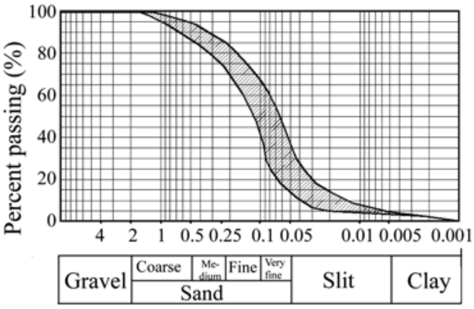


Fig.28 Collection of grain size distribution curves that can form the basis for a probabilistic analysis for the saturated coefficient of permeability and the soil-water characteristic curve

The hazard model for dyke and slope instability follows the form shown in Table 3. It was suggested that the factor of safety of the dyke slopes be computed using a dynamic programming method (DPM), where the location of the critical slip surface and the corresponding factor of safety are determined through use of an optimization technique (Fig.29; Pham and Fredlund, 2003). The assessment of the likelihood of failure is based on the computed mean factor of safety (F_{ms}) as well as the distribution of factor of safety (F_s) determined as part of the probabilistic analysis. Fig.30 shows two types of frequency distributions that might be computed for a particular slope depending upon the variability of the soil properties. For the example shown, one slope has F_{ms} 1.2 while the other has F_{ms} 1.5. It is easy to conclude that the slope with F_{ms} 1.5 must be the safest slope until the probability of failure P_f of each slope is investigated. Now the slope with F_{ms} 1.2 has the lowest P_f (i.e., 2.3%) while the slope with F_{ms} 1.5 has a higher P_f (i.e., 16%). Consequently, it is important to use F_{ms} and P_f when assessing dyke slope stability.

The hazard model related to seepage around hydraulic structures should be 3D in character due to the complexities common to the geometry and stratigraphy associated with these structures (Table 4). The probability of potential dyke failure will be assessed

Table 3 Model for computing the probability of dyke failure due to slope instability (P_3)

Model for computing probability of potential dyke failure (P_3)

Hazard type: dyke and foundation slope instability

Computer model: 2D limit equilibrium methods of slices

Output=probability of potential dyke failure due to slope instability (P_3)
(Compare factor of safety and probability of failure distributions)

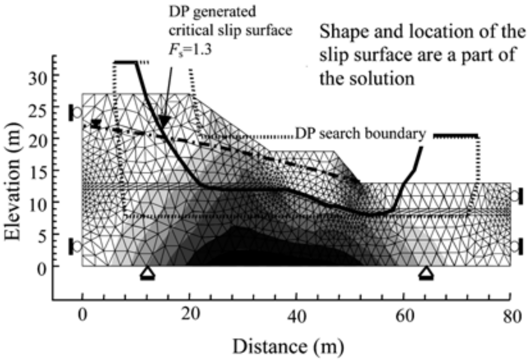


Fig.29 Example of a slope stability analysis performed using the dynamic programming method

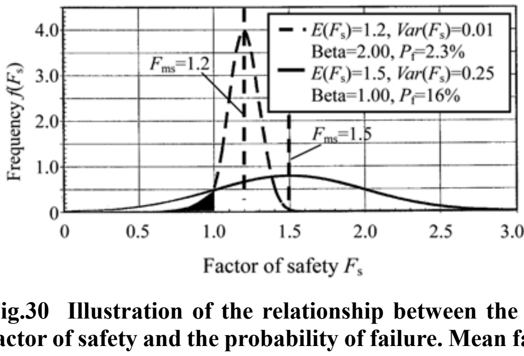
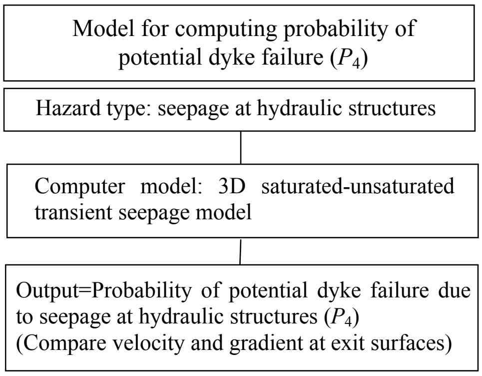


Fig.30 Illustration of the relationship between the mean factor of safety and the probability of failure. Mean factors of safety and the distribution of factors of safety both assist in assessing potential instability

Table 4 Model for computing the probability of dyke failure due to seepage at hydraulic structures (P_4)



through comparison of predicted flow velocities and exit gradients to limiting values.

The feasibility design for the dykes along the Yangtze River also involved the development of an expert system. The primary role of the expert system was to allow the estimation potential failure of the Yangtze River dykes through use of expert knowledge, historical and real-time information. The expert system relies strongly on the experience of engineers and operators who have been involved with the design, construction, monitoring and maintenance of the dykes over a number of years.

In other words, two independent approaches are being used to estimate the impact of flood conditions. One approach is quite empirical and is based on historical information, available data and statistical correlation of significant identifiable factors. The other approach is mainly analytical (i.e., numerical) modelling and involved a fairly detailed evaluation of site-specific information that may vary temporally and spatially. Each of these approaches are independent but should be supportive one of the other.

A risk matrix was developed comprised of one index that represented a measure of probability of failure and another index that represented a measure of severity of the consequence of failure. The output of flood risk was expressed using numeric values and a color scheme.

POTENTIAL SLOPE MANAGEMENT SYSTEM FOR RAILWAYS IN CANADA

Weather-related geo-hazards are a major concern for the railway industry in Canada (Fig.31). The financial losses that result from derailments and delays amount to millions of dollars every year (Transportation Safety Board of Canada, 1994; 2001). The assessment and management of geo-hazards is a difficult problem that involves complex coupled phenomena and numerous soil and weather related parameters. Loss of suction in the subgrade below the railroad can result in the derailment of the train (Sattler *et al.*, 1989) (Fig.32).

Fig.31 Railway embankments in Canada stretch for thousands of kilometres with failures often producing derailments. Role of soil mechanics in slope stability risk assessment along railway

Fig.32 Typical minor railcar derailment due to a bearing capacity failure caused by a loss of soil suction

The theories of unsaturated soil mechanics can be used to develop a hazard slope instability framework for infrastructure elements such as a railway system (Fredlund, 2006). More specifically, estimations of the soil-water characteristic curve (SWCC), can be used as an indicator of the present hazard level (Fredlund, 1999; 2002c).

A concise description of a suggested weather-related geo-hazards assessment model will be described. Deterministic and probabilistic aspects of the model have been developed within a "Decision Analysis" framework (Ang and Tang, 1984; Harr, 1987; Applied Decision Analysis LLC, 1998). The deterministic core of the model consists of a 2D slope stability analysis combined with a 2D saturated-unsaturated seepage analysis that computes changes in pore-water pressures in the soil as a result of imposed weather conditions (SoilVision Systems Ltd., 2003). Weather conditions interact with the ground through the flow of liquid water, water vapour, and heat. The overall stability of the embankment was assessed using the DPM, combined with a finite element based stress analysis (Yamagami and Ueta, 1988; Pham and Fredlund, 2003). Consequently, the soil system is ultimately represented by a series of PDEs (PDEs), satisfying conservation of mass and momentum (Gitirana and Fredlund, 2003a; 2003b). A discrete stochastic analysis can be implemented within the proposed framework.

Several unsaturated soil property functions are required as input data for the system of PDEs (SoilVision Systems Ltd., 1996). The hydraulic conductivity (i.e., coefficient of permeability), water storage, thermal conductivity, shear strength, and other unsaturated soil properties are all nonlinear functions that are related to the SWCC (Sillers and Fredlund, 2001). The theoretical model provides a means whereby it is possible to quantitatively assess the stability of an embankment based on real-time weather conditions. The methodology can be applied in a general, system wide manner or more specifically to a particular site that may be deemed to be at risk (Fig.33). This paper will primarily describe the application of the hazard model to a particular site.

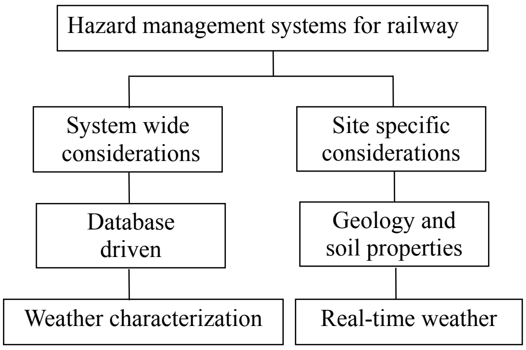


Fig.33 Flowchart to separate local site hazard management and system wide hazard management

Soil-water characteristic curve as a hazard gauge

Embankment hazards are strongly related to the reduction in matric suction within the embankment (Fig.34). The matric suction in the soil varies according to the amount of water stored within the embankment. Changes in the amount of water within the soil are related to the weather conditions and soil properties. The relationship between the amount of water being stored in the soil and soil suction can be described by the soil-water characteristic curve (SWCC) (Fig.35) (Fredlund and Xing, 1994). The SWCC is actually a hysteretic relationship with one curve describing drying conditions and another curve describing wetting conditions. SWCC can be defined using the following primary variables; namely, air-entry value, residual suction, residual degree of saturation S_{res}, and the saturated water content (Gitirana and Fredlund, 2003a; 2003b).

Fig.36 makes use of an analogy to explain the concept of water storage in a soil and the weather hazard slope instability model. According to this analogy, the soil comprising an embankment can be

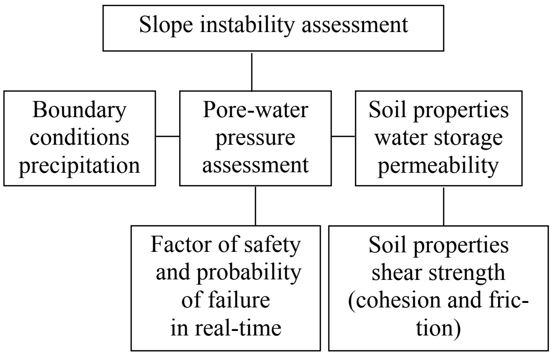


Fig.34 Relationship of the boundary conditions and soil properties to the assessment of slope stability

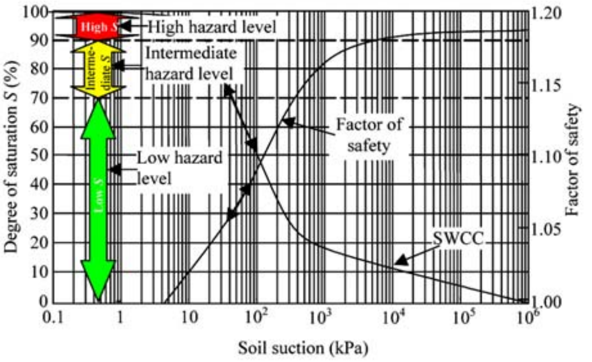


Fig.35 Use of a SWCC as a "water storage" gauge correlated to embankment hazard level

viewed as a ‘water tank’. The SWCC works as a gauge that indicates the water level within the ‘water tank’ (Fig.37). The water level is lowered through evaporation, evapo-transpiration, and downward seepage and is raised through infiltration from rainfall and snowmelt. The embankment factor of safety, F_s, and the embankment hazard level vary according to the amount of water in storage. A low water level corresponds to a lower level of hazard (i.e., higher F_s), while higher water levels produce potential for a high level of hazard (i.e., lower F_s). The model for the assessment of potential embankment instability is based on the ‘water tank’ concept and the computed factor of safety.

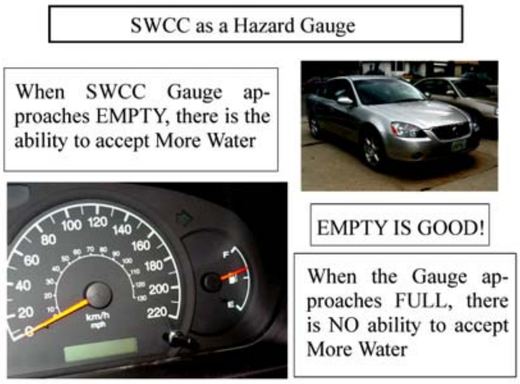


Fig.36 Comparison of the SWCC as a hazard gauge and the gas gauge in a car

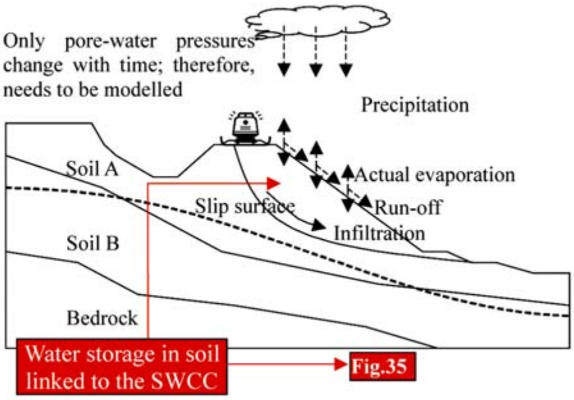


Fig.37 Concept of “water storage” in the soil used as a hazard gauge

Weather hazard model for embankment instability

The weather hazard model is based on the solution of a series of PDEs governing the thermo-hydro-mechanical behaviour of the saturated-unsaturated soil system (SoilVision Systems Ltd., 2003). Appropriate boundary conditions are required to account for evaporation, precipitation, and runoff. It is environmental factors that affect the overall stability of an embankment. The shear strength of the soil within the embankment changes in response to the moisture flux at the soil-atmosphere boundary. In order to determine the moisture flux and changes in pore-water pressure in the soil, PDEs governing the flow of water must be combined with appropriate boundary conditions and solved for the period of time under consideration (i.e., real-time simulation) (Gitirana and Fredlund, 2005). The PDE governing the flow of heat must also be solved since the amount of liquid water and water vapour flow depends on temperature which largely controls the energy available at ground surface for evaporation. Special conditions must also be satisfied to determine the amount of run-off from the sloping surface and the actual evaporation (Penman, 1948; Wilson *et al.*, 1994; 1997). Total stresses remain essentially constant with time and can be computed by “switching on gravity” and computing the stress state at all points. The shear stress acting along any potential slip surface is also obtained through solving the PDEs governing static equilibrium of forces.

The weather hazard model incorporates the influence of ground surface moisture fluxes on the stability of an embankment in accordance with the flowchart presented in Fig.38. An essential component of the model is the Dynamic Programming algorithm associated with the slope stability analysis.

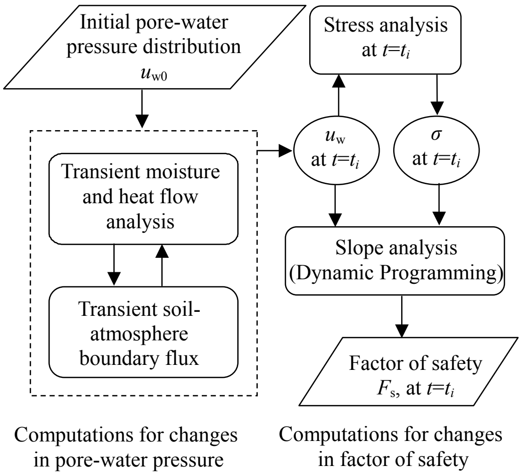


Fig.38 Relationship between changes in (negative) pore-water pressure in a slope and the assessment of the stability of a slope

The algorithm is used to determine the shape and location of the critical slip surface and the corresponding factor of safety F_s. This process can march forward in time on a real-time basis.

The weather hazard model considers uncertainties related to soil properties and weather conditions through appropriate frequency or probabilistic analyses (Rosenblueth, 1975). The probabilistic model consists of sampling the frequency distribution of the variables considered as uncertain.

Unsaturated soil property assessment

The unsaturated soil properties found in the PDEs describing hydro-thermo-mechanical behaviour of the soil can all be estimated from SWCC (Fredlund and Xing, 1994; Fredlund, 2002c). The water hydraulic conductivity curve is obtained from the saturated coefficient of permeability and integration along the SWCC (Fredlund *et al.*, 1994; 1996). The water storage modulus is obtained through differentiation of the SWCC (Fig.39). The SWCC can in turn be estimated from the grain size distribution curve as illustrated in Fig.40 (Fredlund *et al.*, 2002). The above procedures involve estimation techniques but have a sound theoretical basis and provide the weather hazard model within a deterministic and probabilistic framework.

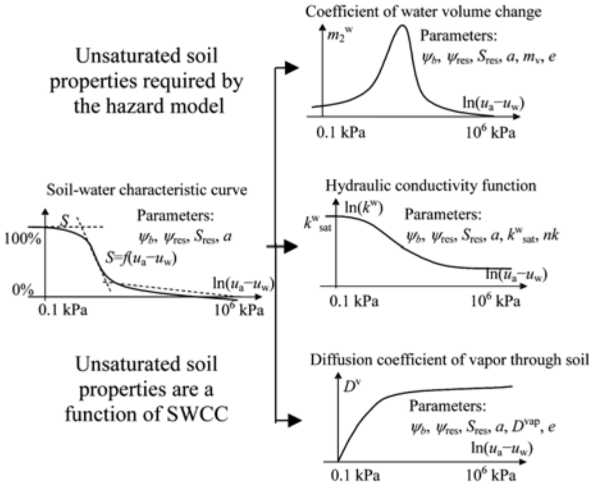


Fig.39 Unsaturated soil property function can be computed from the saturated soil properties and the SWCC

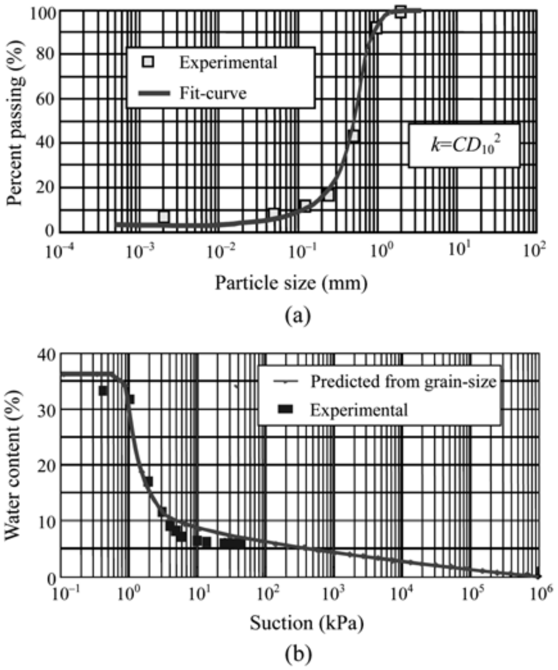


Fig.40 Use of the grain size distribution curve (a) for the estimation of the SWCC (Fredlund *et al.*, 1996) (b)

CONCLUSION

Several examples have been described that involve potential slope stability hazards. In each case, there has been an attempt to utilize the most recent theoretical finding of unsaturated soil mechanics and the quantification of flux boundary conditions in order to develop a hazard slope stability model. The ability of the engineer to address hazard assessment situations has also been greatly enhanced as a result of advances in computational tools. It is the responsibility of engineers to take advantage of all available technologies in order to provide the public with the best possible system for slope stability hazard management.

Some of the specific conclusions that arise from the author's experiences are as follows:

(1) Improved hazard management modelling systems are available for the assessment of potential instability of natural and man-made systems.

(2) Most slope stability hazard situations involve combining the modelling of water seepage with a slope stability analysis. Both of these processes can be addressed through the solution of appropriate PDEs.

(3) The climatic conditions (i.e., precipitation, evaporation and evapo-transpiration) become the primary driving mechanism for changes in the factor of safety of a slope.

(4) Slope hazard modelling systems can be for-

mulated on a deterministic basis and then extended to include a probabilistic framework.

(5) Slope stability hazard management systems need to be designed for conditions most relevant to the problem at-hand.

ACKNOWLEDGEMENT

The author would like to thank many persons who have provided an opportunity for involvement in the study of interesting slope stability problems. Following are just a few of the persons; namely, the Organizing Committee of the Second Pan American Conference on Teaching Learning Process of the Geotechnical Engineering; Fugro Consultants, Hong Kong; Geotechnical Engineering Office, Government of Hong Kong; Nippon Technologies Industries Ltd., Golder Associates Ltd., the World Bank, and the Yangtze River Authority, China; Canadian Pacific Railways, Canada; and NSERC, Government of Canada.

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