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Geotechnical risk map of a railway in a slide prone region

Dinis da Gama, C.
Geotechnical Center, IST, Lisbon, Portugal

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ABSTRACT:
Train traffic safety and track maintenance programs require appropriate planning methods for the transportation companies. One of the main concerns in their activity is due to landslides that may occur in hilly regions, turning essential the prediction of the occurrence of those phenomena. The paper describes an example regarding the development of geotechnical risk maps to quantify landslide susceptibility and presents an application of such a process, in conjunction with a continuous real-time rain monitoring system, aimed to implement the tele-management of a section of the Portuguese railways network.

1. INTRODUCTION

The growing use of reliability analysis and probabilistic methods in Geotechnics is a trend that is associated with the need for accuracy required in most engineering projects.

The available methods are well known for both deterministic and probabilistic geotechnical applications and their reliability is sometimes questionable, mainly due to input quality and output contents. For accurate applications, engineers must understand the nature of uncertainty and error, reflecting the lack of information on soil and rock properties, as well as the degree of belief in the numerical data supplied to modelling and design.

Using probabilities on the states of nature rather than on observations may lead to serious mistakes, as the distinction between trend and the spatial error is a human choice, not a property of nature.

On the other hand, ground's geotechnical properties must not be estimated from small scale samples, as well as from insufficient number of tests, being easier generally to estimate mean values well, but underestimating uncertainty or being overconfident in safety evaluations.

Another difficulty for most engineers is related with the interpretation of results on failure probabilities, much greater than the understanding the meaning of conventional safety factors and that a calculated probability is normally a lower bound evaluation, because it can fail to incorporate certain factors that are ignored in the analysis.

In fact, the concept of probability is not a property of the world but a state of mind, so the current challenges to the profession are to make use of probabilistic methods in practice and to improve our investigations and analyses so that its field application is confirmed by other observation means.

The purpose of this paper is to contribute for filling the gap between those aspects, through an example of railway tele-management by the use of a probabilistic analysis of slope stability assisted by a continuous rain monitoring system.

2. PROBABILISTIC APPROACHES TO SLOPE STABILITY

One of the earliest probabilistic approaches to the design of slopes is the one proposed by Coates [1] where the so-called generalized cost of slope failure is given by means of the expression:

$$C_g = C_o + P_c (R + D) \qquad (1)$$

where C_o is the initial cost of slope excavation and construction, P_c is the probability of slope collapse, D and R are the costs of damage and slope reconstruction, respectively. The variation of C_g with slope angle is depicted in Fig. 1, leading to the definition of optimum slope angle, which corresponds to a minimum generalized cost.

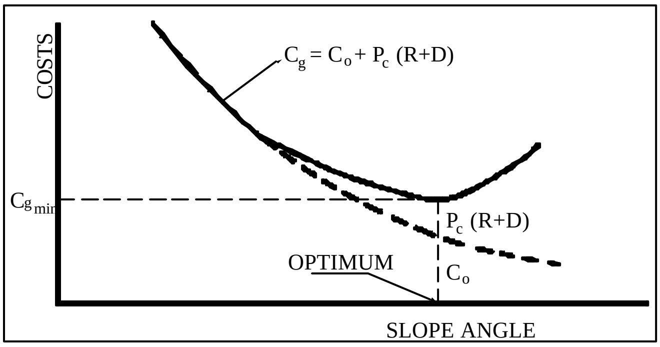

Fig.1. Slope generalized cost vs. slope angle, showing the criterion to find its optimum value (after Coates [1])

An increasing number of probability and reliability oriented methods of slope stability has been published, demonstrating the need for more accurate solutions reflecting reality, as well as leading to engineering decision criteria (Dinis da Gama, [2]).

A recent review of the subject was conducted by Baecher & Christian [3], providing valuable insights in the methodology and applications of reliability and probabilistic analysis to practical problems such as slope stability, offshore structures, dams, open pit mines, etc.

The main purpose is to evaluate stability of systems rather than a single component is attained through the use of several tools (such as logic trees, expert elicitations, detailed reliability assessments and simulations) under the condition of minimizing time and effort required for interaction between system experts and those experienced in reliability studies.

After emphasizing the need for management commitment, Baecher & Christian suggest a combined use of reliability and observational approaches to deal with complex geotechnical problems.

3. PROBLEM CHARACTERIZATION

The case study to be described in this article deals with the request presented by Refer, the Portuguese railway company, who wish to create a framework for decision making on the rail track maintenance priorities and also for improving traffic safety. The means to develop such a program is based on the development of geotechnical risk maps regarding the stability of slopes adjacent to their lines.

As a first step to implement this project, a pilot study of a section with 10 km length was proposed for investigation. For this purpose, the railway link between Santarem and Vale de Santarem was selected, which first location dates back to 1841.

The region is limited at East by the river Tejo and at West by the hills of Santarem, so the railway has been confronted with many slope slides in the past, some of which caused damage to train operations.

Geologically, the hills are formed by Pliocenic formations with limestone at the top and a series of horizontal alternate layers of sandstones and overconsolidated silty clays, sometimes mixed together in a complex layers (Coelho, [4]).

An extensive collection of technical reports were available for reviewing, including the design of complex retaining structures built at the Santarem slope, as Fig. 2 shows.

Fig. 2. Slide prevention workings built at the Santarem slope, with railway and Tejo river at the right side

The main criterion used to develop the risk mapping aim was the division of the 10 km line in homogeneous sectors for slope stability analysis. Under this concept a total of 11 sectors were created, as Fig. 3 depicts.

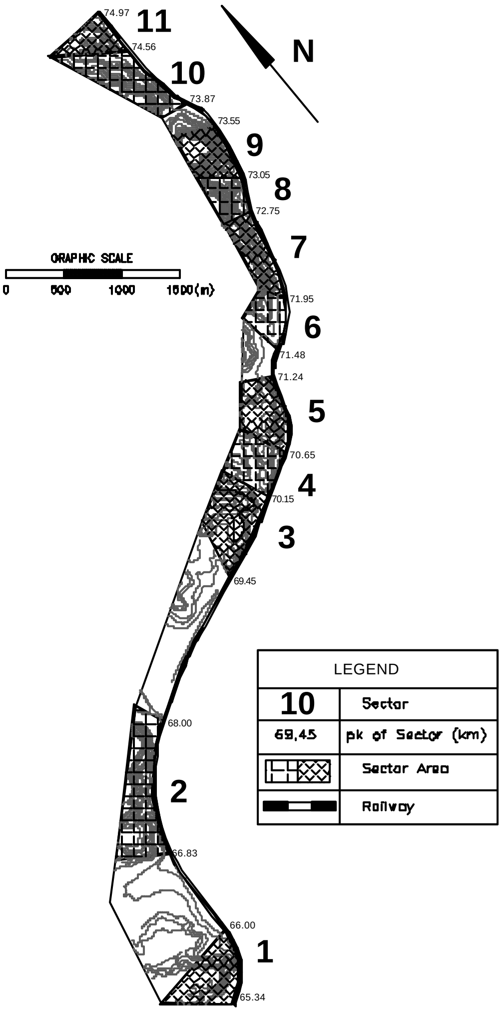

Fig. 3. Plan view of the 11 sectors in which the railway segment was divided

For each sector the most critical slope was defined and their main parameters were established in terms of topographic data, laboratory testing (direct shear, permeability and porosity), as well as information taken from backanalysis studies conducted on previous slides in the region. An addition source of data was the intense geotechnical monitoring that exists in the Santarem slopes, involving piezometry, and drainage, anchor load cells, extensometers, etc., for a period of more than 20 years.

Therefore, a matrix of 11 x 15 was created, with the 15 columns involve the following slope parameters: height, inclination, water table elevation, length of infiltration at slope top, ground density, porosity and permeability, percent of infiltration with respect to precipitation, protection coefficient provided by existing walls at slope bottom, effective cohesion and friction angle. The last two are random variables, which were represented by their minimum, medium and maximum values, as a consequence of triangular distribution of values.

Table 1 contains those numerical values adopted in the analysis for the three main types of geological formations occurring in the region.

Table 1. Shear strength properties of formations in study area

FORMATIONS	Cohesion c' (kPa)			Friction angle f' (º)		
	Min	Mean	Max	Min	Mean	Max
Sandstones	1	14	18	20	32	34.5
Silty Clays	18.5	33	45	14.5	22	24
Complex	11.5	23.5	29	18	27	29.5

These two random variables allow the application of the Monte Carlo method for probabilistic analysis of slope stability.

4. MATHEMATICAL ALGORITHM

In order to obtain ingredients for the risk mapping purpose, a mathematical algorithm was programmed as the flow-chart of Fig. 4 summarizes.

The input data is divided in two parts: a fixed one with slope properties and geometry, and a time-dependent one which is continuously receiving information on the rain fall in the region, together with and updating of water table elevation in each one of the 11 sectors.

Rain data transmission is achieved by means of a SMS (Short Message Service) communication technique, every time one more millimeter (liter per square meter) falls in the rain gauge. At the remote server there is a computer assisted by a GSM modem, where the SVS.EXE program is processed.

An image of the rain gauge and its communication device is presented in Fig. 5.

This program is able to calculate water table variations along time, depending on the amounts of infiltrated rain water (according to the Enoki et al. model) [5] and the percolation volumes at slope toes.

Three types of slope failure mechanisms were included in the software, according to available historic descriptions:

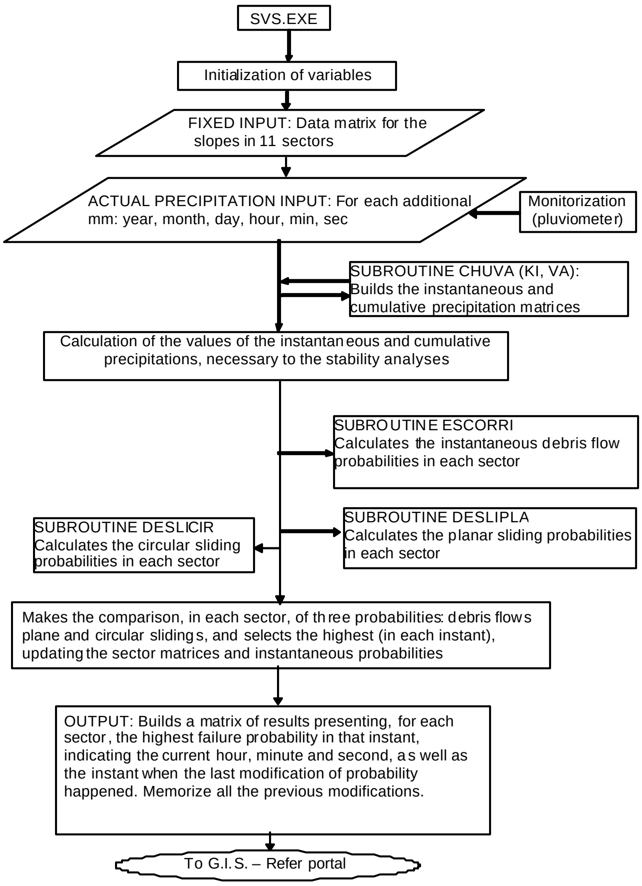

Fig. 4. Program flow-chart for computing slide probability under continuously monitored rain conditions

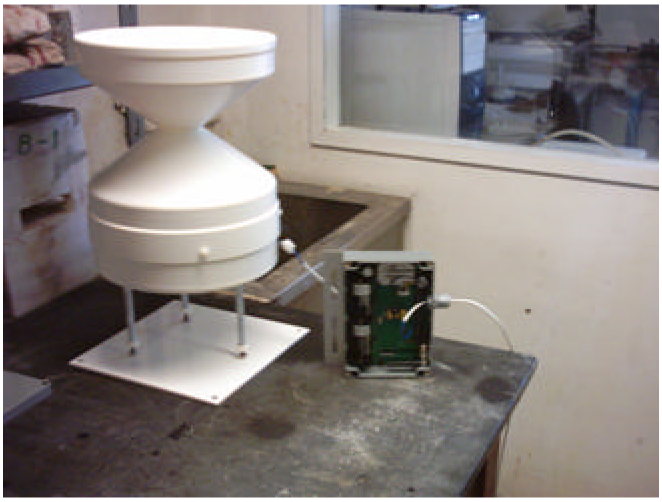

Fig. 5. Rain field data acquisition system

a) Debris flows, due to superficial erosion caused by heavy rains precipitated during short periods of time;

b) Deep-seated slides, either along planar or circular surfaces of movement, as a consequence of slope collapses related with mounting ground water pressures.

The probability of debris flows is found by means of joining backanalysis of slope failures in the region with the general triggering curve for those events in various continents, as proposed by Kanji [6] (see Fig. 6).

For case b), safety factors are repeatedly computed for each sector, every time a new millimeter of rain is recorded, and subsequent probabilities of slope collapse are calculated. The greatest value among the three failure probabilities is then found and it is considered the risk margin for the instabilization of each sector at that instant.

Subsequently, the data base records all values and transmit them to the processing system of the railway company, thus providing a permanent display of geotechnical risk intervals for every sector of the line under monitoring. These data are available for the purpose of anticipating decisions on present safety conditions regarding train circulation in the region, therefore contributing for the implementation of a traffic tele-management system.

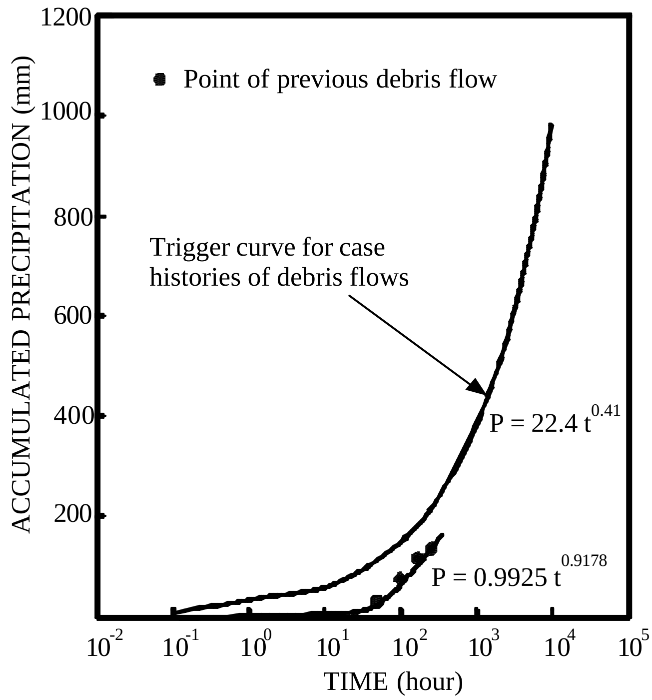

Fig. 6 Debris flows triggering curves, for many international events and for the Santarem region

5. GEOTECHNICAL RISK MATRIX AND TELE-MANAGEMENT

To provide an interaction between the probabilities of instabilization of the slopes in the 11 sectors and is useful application, a matrix of risk levels was proposed, as table 2 shows.

Table 2. Proposed intervals of geotechnical risk levels and their effects on the safety of train circulation

RISK LEVELS / PARAMETERS	1	2	3	4
	SECTORS WITH LOW RISK OF COLLAPSE	SECTORS WITH FAIR RISK OF COLLAPSE	SECTORS WITH HIGH RISK OF COLLAPSE	SECTORS WITH VERY HIGH RISK OF COLLAPSE
PROBABILITY OF INSTABILIZATION	0 – 50 %	51 – 80 %	81 – 95 %	96 – 100 %
IMPLICATIONS FOR RAILWAY TRAFFIC	NONE	ATTENTION	PRECAUTION	DANGER

The matrix is composed by four levels of risk, according to the increasing probabilities of each slope collapse, and their values are correlated with expected consequences for the conditions of railway traffic, namely safety, attention, precaution and danger.

Due to its recent implementation, there are no hints on needed changes in the methodology, although future modifications, particularly on the range of probability values associated with risk levels, are expected.

6. CONCLUSIONS

A methodology is proposed for providing continuous evaluations of the geotechnical instability risk in the slopes adjacent to a 10 km pilot section of a railway which suffered many slide events in the past. Under the existing field conditions, application of a remote and continuous rain monitoring system was selected as the option to provide information on the evolution of slope safety conditions, thus evaluating geotechnical risk as a function of time and space.

Application of this continuous flow data to improve safe train circulation during rainy periods is thus available and it opens the possibility to develop a close tele-management of train circulation, as well as providing important data to plan adequately the maintenance workings that are required at a railway sector before catastrophic events take place.

ACKNOWLEGEMENTS

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