Slope Stability

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The issue of slope stability is one of the most important and yet most difficult geotechnical problems. Assessing slope stability is particularly difficult because of the many uncertainties involved in the process. To take these uncertainties into account, probabilistic methods are used, and the reliability approach is adopted. There are many methods for reliability assessment of earth slope stability. However, there is no system that would organize all of these methods in an unambiguous way. In fact, these methods can be classified in different ways: by assignment to a deterministic classification of methods, by description of uncertainties of soil parameters, by level of reliability according to the theory of reliability, etc. The huge number of articles summarizing the research in this field, but in various “disordered” directions, certainly do not facilitate the understanding or ultimately the practical application of the reliability approach by the engineer. We propose a universal classification system of reliability methods for evaluating the stability of earth slopes. This proposal is preceded by a brief literature review of both historical background and contemporary study on reliability analysis of earth slope stability.

Keywords: earth slope reliability ; classification system ; literature review

1. Introduction

The assessment of slope stability in terms of reliability analysis is still an active research topic being investigated by many scientific centres around the world. In only the last dozen years or so, in the leading geological and geotechnical journals as well as proceedings summarising international conferences, several thousand publications have appeared on this subject. Research is being conducted in different directions covering a wide spectrum of problems related to the deterministic and probabilistic methods used, comparative analyses, modelling of uncertain soil parameters (random variable, random field), influence of randomness of various factors affecting slope stability, types of problem, acting loading, calculation procedures with the possibility of simplifying these calculations, etc. In the present form, such a huge number of articles, of which only some contribute to the development of the discipline, is a disorderly “multidirectional” collection. It seems obvious that it should be systematised, because even for most researchers specialising in this subject, the quantity of disordered information can lead to confusion and possibly even incorrect conclusions. Of course, such a collection still would not give the engineer a universal tool for work. On the contrary, it would consistently discourage them from reliably analysing slope stability. In fact, the unwillingness of engineers to apply reliability to slope analysis and other geotechnical problems results from the lack of basic knowledge of statistics and probability theory or from common misconceptions with respect to the requirements regarding probabilistic methods, especially from the insufficiency of convincing literature illustrating the implementation and benefits of such analyses. To facilitate putting the reliability approach to slope stability into practice, the applied methodologies and procedures should be simple, well-known to engineers and able to solve real slope problems. In order to achieve this, it is first necessary to set in order and systematise the extensive literature on the subject, comprehend its particular aspects and then classify it. Also, some concepts and terms, not only those appearing in recent literature, should be clarified. Thus, a brief overview of earth slope stability reliability approaches starting from the historical background and moving to contemporary research is presented in this paper. In the latter, apart from the methods of analysis, particular attention is paid to the issues developed in the last dozen or so years such as system reliability and description of random soil properties, especially spatial variability. Some comments on applications of reliability approaches to slope stability analysis are discussed as well. The state of research in the subject presented in an orderly manner, as well as the explanation of a number of terms and concepts occurring here, will bring the engineer closer to understanding this difficult issue and will contribute to the wider application of the reliability approach in geotechnical practice.

This paper proposes a classification system of reliability methods for earth slope stability assessment that integrates deterministic slope stability methods, modelling of uncertain soil parameters and reliability level (commonly used in the structural safety analysis). Also, in the case of the most sophisticated approaches, further divisions related to improvement of computation efficiency are suggested.

2. Methods for Evaluating the Stability of Earth Slopes

In general, there are two types of analyses for evaluating the stability of slopes against failure: deterministic and probabilistic (reliability). In the first case, three basic approaches have been developed: the limit equilibrium method (LEM), the displacement-based finite element method (FEM) used by the strength reduction method (SRM) (also called shear strength reduction (SSR)) and limit analysis (LA) by lower and upper bound solutions theorems. The limit equilibrium method utilises an assumed slip surface and determines its static equilibrium, usually by discretising the assumed failing soil mass into slices. The forces are then summed for each slice, creating a statically determinate problem following some assumptions. By introducing the factor of safety for the entire sliding mass, global equilibrium is maintained for a system on the verge of failure. The LEM is the oldest technique for evaluating slope stability and the most commonly used in practice. However, it is restricted by its arbitrary choice of failure mechanism and by interslice forces. Several variants of this method have been proposed [1][2][3][4][5][6]. In the FEM by SRM used in evaluating slope stability, soil strength parameters continuously decrease until the first indications of failure appear. The safety factor is defined as the ratio of the real shear strength of the soil to the reduced shear strength. This method seems to be superior to the LEM because there is no need for the primary guess at determining the critical failure surface. In addition, this method does not require any assumptions about interslice forces. FEM analysis is a more rigorous and universal technique, but often less attractive due to its dependence on mesh density and the available computational capacity. The primary advantage of this method is that the critical slip surface is found automatically from the shear strain, which increases as the shear strength decreases. Unfortunately, other ‘‘slip’’ surfaces (i.e., local minima) are omitted. However, because of the high speed of modern computer systems, analysis by FEM is used today more often than before. The finite element method by strength reduction method was first proposed and applied to slope stability by Zienkiewicz et al. [7] and then used to assess slope stability in, among others, [8][9][10]. Limit analysis models soil as a material that is perfectly plastic and obeys an associated flow rule. This method employs a dichotomy of theorems to provide a solution: either upper bound or lower bound plasticity. The upper bound theorem of limit analysis is predominantly used in solving slope stability problems. Unfortunately, the application of LA is still limited, since most of the research findings are chart-based and prepared for particular cases, and there is no stability chart available to cover a wide range of different slope material properties, geometries, etc. The concept of limit analysis was proposed by Drucker and Prager [11] and was utilised in slope stability in [12][13][14] and others. A review of the three basic deterministic approaches of slope stability, including their shortcomings and possible errors, is discussed in [15].

In general, the probabilistic methods used in geotechnical engineering can be divided into two groups, depending on the description of the uncertainties of the soil parameters: the single random variable (SRV) approach and the random field (RF) approach. The former method is commonly used in practice due to its concise concepts and simplicity in analysis. The latter reliably analyses the spatial variability of the soil properties. Regarding slope stability, these methods make use both of the LEM and FEM and rarely LA. Interest in the analysis of slope stability using the reliability approach began over 50 years ago. The number of papers on this subject has increased considerably since 1975, when a second ICASP International Congress was held in Aachen. After that, the correction factor methods, the first-order second-moment (FOSM), second-order second-moment (SOSM) and Monte Carlo (MC) methods, dominated. However, the majority of probabilistic or reliability methods made use of traditional slope stability analysis techniques, i.e., LEM [16][17][18][19][20][21][22][23][24][25]. In the case of a highly nonlinear function of factor of safety, computations of the derivatives are impossible or inconvenient, thus rendering FOSM results inaccurate. In addition, different results can be obtained depending on how the limit state function is formulated. To avoid the main drawback of the FOSM and SOSM methods (in which the results unduly depend on the mean value), as observed in [26][27], the first-order reliability method (FORM) has begun to be widely used [28][29][30][31]. It is well known that FORM works only for slopes with a small probability of failure or a high reliability index. Otherwise, this method underestimates the probability of failure of slopes. A summary of research on probabilistic analysis of slope stability was given in the monograph [32]. A review of the literature on this topic can also be found in [24] or [33]. A significant change in approach to probabilistic slope analysis occurred with the use of the finite element method (FEM) for geotechnical problems. Different probabilistic methods related to FEM have been proposed, such as the perturbation method, the Neumann expansion method, the partial differential method, the spectral stochastic finite element method (SSFEM), etc. Along with the development of computers and software, the MC simulation became dominant because of its relative ease of application. This method is a conceptually simple tool for reliability analysis of slope stability regardless of the form of the performance function or the number of scenario failure events. It employs statistical averaging over random samples generated from the probability density function of the parameters to evaluate the probability of failure. It is the easiest to apply; however, its simulations are usually time consuming and computation demanding. The MC method is also robust to various deterministic analysis methods for slope stability analysis, such as LEM or FEM/FDM.

3. Classification System

In a structural safety analysis, there are different levels of reliability, depending on the importance of the structure, grouped under four basic levels:

- level 1—partial factor approach — employs only one “characteristic” value of each uncertainty parameter;
- level 2—estimates two values of each uncertainty parameter, usually the mean value, standard deviation, and the correlation between these parameters;
- level 3—best estimate of the probability of failure—knowledge of the join distribution of all uncertain parameters is required;
- level 4—reliability methods appropriate for structures of major economic importance, taking into account the structures’ economic value, including the consequences of their failure.

The level 2 reliability methods are included in limit state design codes. Methods of level 2 include a range of approximate or iterative procedures such as the perturbation method, FOSM, SOSM, FORM, SORM, PEM, etc. Methods of level 3, in the strict sense, require determining the mathematically exact probability of structural failure as a result of integrating the joint probability density function of random variables. In the case of slope stability, they can only be used for simplified, idealised cases. However, in a broader sense, level 3 methods require estimates of all probabilistic measures. The Monte Carlo simulation method has become the dominant procedure here as a result of the rapid development of computer techniques that have taken place in recent years. In order to improve the efficiency of this method while maintaining the accuracy of calculations, various reduction techniques have been developed (e.g., stratified sampling, Latin Hypercube simulation, importance sampling and Russian roulette and splitting). The response surface method and the methods of artificial neural networks have also grown in popularity in the analysis of the reliability of slopes. Both methods allow all probabilistic measures to be estimated and can also be qualified to the level 3 reliability method.

In the deterministic approach to slope stability, three basic approaches—the limit equilibrium method (LEM), the displacement-based finite/different element method (FEM/DEM), and limit analysis (LA)—have been developed. Probabilistic methods used in geotechnical engineering are commonly divided into two groups, depending on the description of the uncertainties of the soil parameters: the single random variable (SRV) approach and the random field (RF) approach.

The proposal of a classification of reliability methods of slope stability is presented the **Table 1**. It combines deterministic methods of slope stability with random modelling of the soil medium and includes levels of reliability.

Table 1. Classification of reliability methods of earth slope stability.

The abbreviations in Table 1 refer to the random soil model, deterministic slope stability method and reliability level. For example: SRVLEM1—soil modelled as a single random variable (SRV), limit equilibrium method (LEM) and Level 1 reliability method; RFFEM3—soil modelled as a random field, finite/different element method and Level 3 reliability method; etc.

Currently, the FEM/DEM is the predominant deterministic method of stability assessment, soil is usually modelled as a random field and level 3 reliability methods are usually applied. Most of the research focus here is on computation efficiency. Thus, the RFFEM3 methods can be divided into two groups depending on how the performance function of slope stability is simplified and on the reduction techniques (**Figure 1**).

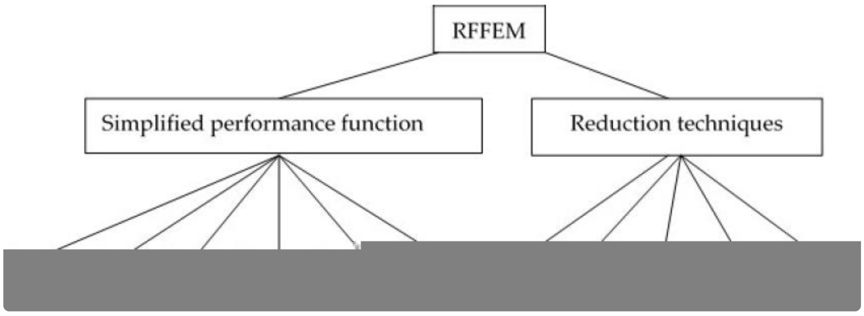

Figure 1. Division of RFFEM3 methods. RSM—response surface method. Improved RSM methods: KM—Kriging methodology, SM—surrogate models, ANN—artificial neural network, SVM—support vector machine, GA—genetic algorithms, SS—subset simulation, IS—importance sampling, LHS—Latin Hypercube sampling, AS—adaptive sampling, DS—directional simulation.

Slopes can be subjected both to static (gravity) and dynamic (earthquake, waves) loads as well as environmental loads (rainfall, temperature changes). Also, slope failure modelling can be carried out in a two-dimensional or three-dimensional analysis. However, these factors should not affect the proposed classification system of reliability methods. Instead, new subdivisions could be introduced on their basis.

4. Conclusions

In reviewing the reliability methods for evaluating earth slope stability, several important conclusions emerged. First of all, this issue has probably been the most published (as a geotechnical problem in terms of reliability) both because of its importance and level of difficulty. Many methods of probabilistic analysis have been developed, and thanks to the rapid progress of computer techniques, there has also been rapid development and acceleration of reliability analysis methods. It was also important to improve the method of ground investigation and to introduce the spatial variation of soil parameters into the calculation model. Unfortunately, the papers on reliability analysis of slopes actually cover basically all possible aspects, while the journals or proceedings in which they are published are not thematically assigned. Thus an attempt was made to organise the huge number of publications by assigning them to several research directions. In this paper, a review of the literature on reliability assessment of earth slope stability is presented in a fairly concise manner.

Generally, the engineer is quite conservative when it comes to applying new methods, especially when they are not simple—and such are probabilistic methods and reliability analysis. The terms and concepts explained as well as the general characteristics of the methods used should help the engineer to understand the benefits of the reliability approach to geotechnical problems and contribute to its application in practice.

Many probabilistic methods of slope stability assessment are known, and they can be divided according to different criteria. However, the classification of these methods for earth slopes has not yet been developed. The disorder that occurs as a result may make it difficult or discouraging for an engineer to read publications. The classification system proposed in this article organises these methods and will contribute to a better perception of this difficult issue.

This literature review shows that although reliability methods are extremely advanced and the computational possibilities almost unlimited, in practice, the simplest methods are usually used. This is mainly due to the fact that engineers are not familiar with probabilistic concepts; thus, it is difficult to incorporate them into practice.

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