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Research Paper

System reliability analysis of soil slopes with general slip surfaces using multivariate adaptive regression splines

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ABSTRACT

A data driven multivariate adaptive regression splines (MARS) based algorithm for system reliability analysis of earth slopes having random soil properties under the framework of limit equilibrium method of slices is considered. The theoretical formulation is developed based on Spencer method (valid for general slip surfaces) satisfying all conditions of static equilibrium coupled with a nonlinear programming technique of optimization. Simulated noise is used to take account of inevitable modeling inaccuracies and epistemic uncertainties. The proposed MARS based algorithm is capable of achieving high level of computational efficiency in the system reliability analysis without significantly compromising the accuracy of results.

1. Introduction

It is now widely recognized that the soil parameters are uncertain, and thereby the conventional factor of safety based deterministic slope stability analyses are increasingly being replaced by slope reliability analyses under a probabilistic framework. In recent years, numerous slope reliability studies have been reported in the literature [1,2,3,4,6,5] assuming the single mode of failure, i.e., failure by sliding along a potential slip surface. There is also a growing appreciation that a slope can have many potential slip surfaces constituting a series system; and the probability of failure of the slope is greater than that associated with any one of these slip surfaces [7,8,9,10,11,12,13,14,15,16,17]. It has been commonly opined that the total or overall probability of failure of a slope (under the framework of system reliability) is the ultimate goal to achieve.

In the early studies [8,9,18], system failure probability of a slope is reported in terms of two bounds [19] which are sometimes widely separated. Most of the other studies fall under the two categories of methods suggested by Zhang et al. [13], namely, Method 1 and Method 2. In Method 1, the system failure probability is evaluated directly by generating a large number of potential slip surfaces and performing Monte Carlo simulation (MCS) based on calculating the minimum factor of safety among them for each set of sampled values of soil properties (realisation) [12,20]. In Method 2, on the other hand, a few representative slip surfaces are first identified from amongst the large number of potential slip surfaces, and the system failure probability is then evaluated by performing Monte Carlo simulation based on calculating the minimum factor of safety among these representative slip surfaces for each realisation [21,16,22]. The results obtained from these two methods are found to be practically the same. Further, because the Monte-Carlo simulation requires high computational effort and time, several response surface methods (RSMs) have also been used for system reliability evaluations, e.g., polynomial-based RSM [23], Kriging methodology [24,25], the artificial neural network (ANN) [26], the support vector machine (SVM) [27], the high dimensional model representation (HDMR) [28], and others. An excellent review on the application of various RSMs for slope reliability analysis is available in the literature [29].

Alternatively, in order to evaluate the system reliability of a soil slope, for each set of sampled values of soil properties in a Monte Carlo analysis, one could find the critical slip surface and its corresponding minimum factor of safety [30,31] instead of finding the minimum factor of safety among a fixed set of slip surfaces generated before the simulation starts (as in Method 1 and Method 2). The overall probability of failure (or system failure probability),

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$p_{F,\ s}$, will then be the ratio of the number of times the minimum factor of safety is less than 1.0 to the total number of simulation runs. While the former approach is more logical of the two approaches, the latter approach (as in Method 1 and Method 2) is computationally simpler and thus more commonly used in the literature. It is therefore necessary to investigate to what extent the results obtained based on the two approaches differ, as well as which approach leads to a more conservative estimate of the safety of a slope as a system. Further, whichever approach is used, it requires considerable computational effort and time. To enhance the computational efficiency, the relationship between the minimum factor of safety and the uncertain parameters is approximated by the multivariate adaptive regression splines (MARS) based surrogate model in this study. Although the application of MARS to geotechnical engineering field is not very common, only found recently in slope stability analysis by Liu and Cheng [32], its application in other fields of engineering is very much appreciated recently [33,34,35,36,37]. Moreover, previous studies have focused mainly on the application of various RSMs for approximating the relationship between the factor of safety and uncertain parameters. In this study, however, the MARS has been made use of not only to approximate the relationship between the minimum factor of safety and uncertain parameters, the location of the critical slip surfaces are also predicted by MARS. Thus the objective of the present study is also to explore the potential of MARS as an efficient mapping route in slope reliability analysis.

Furthermore, in almost all the previous studies on system reliability analysis of earth slopes, the shape of the slip surface is assumed as circular and the Bishop's simplified method (BSM) is used as a slope stability model. As the BSM does not satisfy horizontal force equilibrium, it is commonly regarded as an approximate method. The shape of actual slip surface is also, in general, not circular except in a homogeneous slope without discontinuities of any kind [38]. Keeping the above in view, in this study, while no assumptions have been made regarding the shape of the slip surface, the slope stability evaluation is based on the Spencer method valid for general slip surfaces [39] satisfying all conditions of statical equilibrium, which is definitely more rigorous than the Bishop's simplified method, especially for non-homogeneous slopes.

2. Adopted methodologies

2.1. Slope stability analysis – deterministic and probabilistic

A typical slope, found in various civil engineering projects including dams, embankments and open cut for highways, is as shown in Fig. 1. The stability of these slopes along potential failure surfaces is of major interest. Slope stability analyses based on the limit equilibrium approach have conventionally been performed in a deterministic manner and the entire process consists of two parts, namely, computation of factor of safety of a given or trial slip surface, and then search for the critical slip surface having the minimum factor of safety FS_{min} (known as the deterministic critical slip surface) using an optimization technique. The Spencer method of slices valid for general slip surfaces [39] is regarded as one of the rigorous methods as it does not make any a priori assumption regarding the shape of the slip surface and satisfies all conditions of equilibrium [40]. The computation of factor of safety (FS) in Spencer method involves solution of a pair of nonlinear stability equations. An efficient method of solution first formulates the problem as an optimization problem and then solves it using a powerful optimization technique [41]. Therefore, the deterministic slope stability analysis in this study leads to a 2-tier analysis and the optimization problem in each tier of analysis has been solved using the sequential quadratic programming (SQP) [42] technique which has been rated as a powerful optimization technique [31] and can be easily implemented in the MATLAB platform with its optimization toolbox.

Under the framework of single mode of failure, similar to the deterministic analysis, the probabilistic slope stability analysis can be viewed as the problem of locating the slip surface corresponding to the lowest value of reliability index β_{min} (or the highest value of the probability of failure), called the probabilistic critical slip surface of the slope. The first order reliability method, (FORM) which is widely accepted as the most versatile among the approximate methods of reliability analysis [43], has been adopted in this study. The computational procedure for the determination of the probabilistic critical slip surface based on FORM involves a 3-tier optimization: (i) evaluation of performance function requiring the evaluation of Spencer's factor of safety involves the first tier of optimization; (ii) evaluation of the reliability index, β based on FORM involves the second tier of optimization, and (iii) the search for the surface of minimum reliability index (β_{min}) involves the third tier of optimization. The SQP technique has been employed in the MATLAB platform to solve the optimization problem involved in each tier of analysis. More detailed description of the computational procedure for the determination of the probabilistic critical slip surface based on FORM can be found elsewhere [4,44,45]. The computer program developed and used in the referred studies was validated with reference to two benchmark slope problems. The availability of such a computer program has been made use of in the present study for the purpose of determination of the probabilistic critical slip surface.

2.2. MARS-based MCS for system reliability analysis of slopes

2.2.1. Formulation of Multivariate Adaptive Regression Splines (MARS)

An efficient mathematical relationship between input parameters and output feature of interest for a system under investigation based on few algorithmically chosen samples can be established with the help of MARS [33]. It is a nonparametric regression proce-

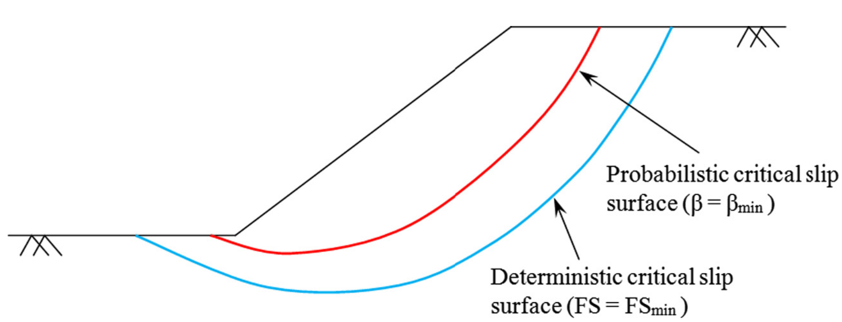

Fig. 1. A typical slope with potential slip surfaces.