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Research Paper

System probabilistic model of rock slope stability considering correlated failure modes

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ABSTRACT

In this paper, a system reliability analysis of rock slope stability with considering all input parameters as stochastic parameter is presented. To perform reliability analysis a cut-set system has been used. For this purpose, Sequential Compounding Method (SCM) as a powerful method for reducing the computational time and accurate evaluation is employed to determine the reliability indices with considering correlations between failure modes which are calculated by defining equivalent linear safety margin for each failure mode. Furthermore, the 3-D system probability of failure surface is presented and the probabilistic model is developed to evaluate the rock slope probability of failure.

1. Introduction

Plane failure is an especial case of the general type of rock failure, in which the rock mass slides on a single surface. Because only one surface is involved; two-dimensional analysis can be carried out using the concepts of a block resting on an inclined plane at limiting equilibrium. Plane failure is especially useful for representing the sensitivity of the stability of rock slope to changes in shear strength, groundwater, and applied forces [1,2].

The characterization of rock masses is subjected to uncertainties due to inadequate information for site characterization and inherent variability of properties within it [3–5]. Probabilistic analyses provide rational means to treat the uncertainties associated with underlying parameters in a systematic manner.

Based on the advantage of probabilistic analysis, considerable research has been carried out in the past few years on rock slope with plane failure [6–9]. Among important contributions the following researches can be mentioned.

Jimenez-Rodriguez et al. [6] a systematic quantitative methodology for the reliability analysis of stability of rock slopes. They presented a disjoint cut-set system formulation with each cut-set corresponding to a different failure mode of the slope. They also discussed methods for the evaluation of the system reliability problem and applied to solve an example problem.

Low [7] illustrated a new spreadsheet-based algorithm for the first-order reliability method (FORM) for a two-dimensional rock slope of Hong Kong.

Duzgun and Bhasin [8] carried out a probabilistic analysis of the Oppstadhornet rock slope with plane failure using first-order reliability method (FORM).

Li et al. [9] aim to propose a systematic quantitative method for system reliability evaluation of rock slope with plane failure involving multiple correlated failure modes. They presented a probabilistic fault tree approach to model system reliability of rock slope and employed n-dimensional equivalent reliability method to perform the system reliability analysis of the slope involving multiple correlated failure modes.

Dershowitz and Einstein [10] presented a complete review of some of the more important stochastic models developed up to that time.

Tamimi et al. [11] investigated the reliability of a rock slope with plane failure through Monte Carlo simulation.

Pathak and Nilsen [12] estimated the value of these variable parameters and study their sensitivity in rock slope stability analyses for Himalayan conditions.

Low [13] analyzed a two-dimensional rock slope in Hong Kong and a three-dimensional hypothetical tetrahedral wedge probabilistically using an intuitive and transparent constrained optimization approach for the first-order reliability method (FORM).

Furthermore, reliability-based design approaches which allow the systematic and quantitative treatment of uncertainty of the

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underlying parameters have become a topic of increasing interest for rock slope engineering.

In the literature, Wang et al. [14] present a Robust Geotechnical Design (RGD) approach. Traditional reliability-based rock slope designs, in which the lowest-cost design is selected from all designs meeting target reliability requirements, are often sensitive to variations in noise factors such as rock shear properties. Consequently, a design that was initially judged acceptable may not satisfy reliability requirements if the variation of rock properties has been greatly underestimated. The RGD approach is presented for purposes of addressing this dilemma, by considering the robustness explicitly in the design process.

Jiang et al. [15] aim to investigate the effect of rock bolt corrosion on time-dependent system reliability of anchored rock slopes. First, a corrosion degradation model for reinforcing steel bars in concrete is selected to model the uniform corrosion of rock bolts. Second, two typical failure modes of rock bolts due to corrosion and the resultant slope failure modes are identified. Subsequently, a Monte Carlo simulation-based reliability approach is proposed to perform system reliability analysis of anchored rock slopes.

Xu et al. [16] present a feasible approach to addressing the problem of reliability-based design (RBD) approach, which allows for consideration of the uncertainty of input parameters. The design of a rock slope system may be either cost-inefficient (overdesign) or unsafe (under-design). The uncertainty about the variation of input parameters is a critical issue in a RBD. The feasible approach is presented to addressing this problem using robust design concept.

The goal of this paper is developing a system probabilistic model to evaluate the rock slope probability of failure as function of safety factor and its correlation of variation. The model involves multiple correlated failure modes with considering all input parameters as stochastic parameter. In this way, the stability of the rock slope is modeled as a system that is included a correlated series assembly of correlated parallel sub-systems. For this purpose, using SCM as a powerful method for reducing the computational cost and accurate evaluation with considering correlations between different failure modes is valuable. The truncated normal distribution is used to describe the location of the tension crack, cohesion and friction angle along the failure surface, reinforcing force, slope face angle, dip of the slope failure plane, height of the slope, and unit weight of the rock in slope. Also a truncated exponential distribution is used to describe the percentage of the tension crack filled with water.

2. Plane failure mechanism

Plane failure is composed of two blocks resting on an inclined plane, which are separated by a vertical tension crack (Fig. 1). The positions of the tension crack and the water level in it are random. In addition to account for the effect of rock reinforcement, a passive force with uncertain magnitude is applied at the toe of the slope. For occurring a typical plane failure in a rock slope, the following geometrical conditions must be satisfied [1]:

- A continuous plane on which sliding occurs must strike parallel or nearly parallel (within approximately ±20°) to the slope face.
- The dip of the failure plane must be less than the dip of the slope face.
- The dip of the failure plane must be greater than the angle of friction of this plane.
- Surfaces of separation that provide negligible resistance to sliding must be present in the rock mass to define the lateral boundaries of the failing block.

For calculating the factor of safety of the rock slope with plane failure by limit equilibrium method, all forces acting on the slope into components parallel and normal to the sliding plane is resolved. The factor of safety of the sliding block is the ratio of the resisting forces to the driving forces. The resisting forces are included the total normal forces, the tangent of the friction angle and the cohesive force and the driving forces are included the shear forces acting down the plane. The reliability analysis of rock slope with plane failure performs by establishing a clear distinction between success and failure events. Based on the stability model of the Hoek and Bray [1,6] with proper modifications to consider the interaction between two blocks, it is assumed that the slope is safe when the factor of safety of block A (FS_A) is greater than one (Fig. 1).

Two different cases may be distinguished in the analysis, depending on the interaction between blocks A and B, as follows [6]:

Case 1: Block B is stable by itself; i.e., there is no interaction between blocks.
Case 2: Block B is unstable; i.e., block B will tend to slide, which will impose an interaction force (I_F) on block A. Each case discuss separately in next subsections.

2.1. Case 1: No interaction between two blocks

In this case, the factor of safety against sliding for block A can be calculated by Eq. (1):

$$FS_A = \frac{c_A A_A + (T\cos\theta + W_A\cos\psi_P - U_A - V\sin\psi_P)\tan\phi_A}{W_A\sin\psi_P + V\cos\psi_P - T\sin\theta} \tag{1}$$

where

c_A = The cohesion along the failure surface for block A
ϕ_A = The friction angle along the failure surface for block A
W_A = The weight of block A
θ = The inclination of the reinforcing force (the angle between the normal direction of the failure surface and the reinforcing force)
T = The reinforcing force
ψ_P = The dip of the slope failure plane
A_A = The area of contact with the failure surface:

$$A_A = (H - z)\csc\psi_P \tag{2}$$

U_A = The uplift force due to water pressure on failure surface for block A:

$$U_A = \frac{1}{2}\gamma_w z_w (H - z)\csc\psi_P \tag{3}$$

V = The horizontal force due to water in crack:

$$V = \frac{1}{2}\gamma_w z_w^2 \tag{4}$$

where

H = The height of the slope
z = The distance between the slope top and the bottom of the vertical tension crack
γ_w = The unit weight of water
z_w = The water depth in tension crack

$$z_w = \xi_{z_w} h \tag{5}$$

where

ξ_{z_w} = The proportion of water depth in tension crack with respect to depth of tension crack
h = The depth of tension crack.