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Rock slopes stability reliability assessment based on geometrical properties

A.Johari¹, A.HooshmandNejad², M.Ezzi²

¹- Assistant Professor, Department of Civil and Environmental Engineering, Shiraz University of Technology, Shiraz, Iran
²- Ms Candidate of Geotechnical Engineering, Department of Civil and Environmental Engineering, Shiraz University of Technology, Shiraz, Iran

johari@sutech.ac.ir
A.Hooshmand@sutech.ac.ir
M.Ezzi@sutech.ac.ir

Abstract

Probabilistic analysis of rock slope stability has been used as an effective tool to evaluate uncertainty so prevalent in variables and has received considerable attention in the literature. Generally, uncertainties in the geometrical properties and rock parameters are two main observations in reliability assessment. In this research the geometrical properties are selected as stochastic variables for rock slope stability with plane sliding. The Monte Carlo simulation is employed in probabilistic analysis and reliability assessment. The selected stochastic parameters are angle of failure surface, height of the overall slope and angle of slope face, which are modeled using a truncated normal probability distribution function. The results show the safety factor has a distribution near normal. Sensitivity analysis and parametric study illustrate the angle of failure surface is the most effective parameter in rock slope stability with plane sliding.

Keywords: Reliability, Monte Carlo, Rock slope stability

1. INTRODUCTION

Stability of a slope is a random process that is dependent on the distributions of the controlling parameters which have probabilistic nature rather than being deterministic. Probabilistic evaluation of slope failures is increasingly seen as the most suitable framework for accounting for uncertainties in design. Generally, two main observations can be made concerning the existing body of work on this subject. The first common approach accounts for the uncertainty in the geometrical properties of the fracture network in the slope, and the second one considers uncertainties in the slope performance.

Many probabilistic techniques have been devised for analysis of stability of rock slopes with uncertain input parameters. These methods can be grouped into five categories: approximate methods, response surface method, stochastic finite element method, analytical methods, and Monte Carlo simulation. Approximate methods are modified versions of three methods namely, Point Estimate Method (PEM) [1,2], First Order Second Moment reliability method (FOSM) [3] and First Order Reliability Method (FORM) [4]. All these approaches require knowledge of the mean and variance of all input variables as well as the performance
function that defines safety factor (e.g. Eq. (1)). A number of attempts have been made to apply the Point Estimate Method [5–7]; FOSM [8], and FORM [9,10] in analysis of stability of slopes. The Response Surface Method (RSM) replaces the numerical model with an approximated model, which can be used to estimate the system response and analyze uncertainty propagation [11]. A number of recent attempts have been made to apply the response surface method to slope stability analysis [e.g., [12]].

Stochastic finite element method requires significant modification of existing deterministic numerical codes, and becomes impossible for most engineers with no access to the source code of proprietary commercial software [13]. Some research on the application of this method in slope stability analysis has been documented in the literature [14,15].

In analytical methods, the probability density functions of input variables are expressed mathematically. They are then integrated analytically into the adopted rock slope stability analysis model to derive a mathematical expression of the density function of the factor of safety. The Jointly Distributed Random Variables (JDRVs) method lies in this category [16–18]. A recent research has been made to apply analytical method to slope stability analysis by JDRV method [19,20].

Monte Carlo simulation uses randomly generated points to cover the range of the values that enter into a calculation [21]. As many as 100,000–1,000,000 generation points may be required to adequately represent a probabilistic solution. The computation of probabilities by Monte Carlo simulation is a procedure commonly adopted to solve problems that are not readily solved by analytical methods. Many attempts have been made to analyze the stability of slopes using Monte Carlo simulation [22–27].

In addition, uncertainty in the geometrical characterization of fractures within the rock mass has lead to the development of stochastic fracture network models which are widely discussed and well documented in the literature [28-32].

In this research uncertainty in geometrical properties of slope is considered to analysing the rock slope stability and evaluate safety factor of plane failure.

2. ROCK SLOPE WITH PLANE FAILURE

In the present study, planar sliding rock slope is considered. Figure 1. shows this type of sliding and its parameters. For this type of sliding failure the equation for determination of safety factor can be expressed as:

$$Fs = \frac{cA + (W \cos \psi_p - \alpha \sin \psi_p - U - F_w \sin \psi_p \tan \varphi)}{W (\sin \psi_p + \alpha \cos \psi_p) + F_w \cos \psi_p}$$  \hspace{1cm} (1)

Where:

$$Z = H \left(1 - \sqrt{\cot \psi_f \tan \psi_p} \right)$$  \hspace{1cm} (2)

$$W = \frac{\gamma_r H^2}{2} \left[1 - \left(\frac{Z}{H}\right)^2 \cot \psi_p - \cot \psi_f \right]$$  \hspace{1cm} (3)

$$U = \frac{\gamma_w Z_w A}{2}$$  \hspace{1cm} (4)

$$A = \frac{H - Z}{\sin \psi_p}$$  \hspace{1cm} (5)

$$F_w = \frac{\gamma_w Z_w^2}{2}$$  \hspace{1cm} (6)
Figure. 1. Geometrical definition of the rockstability with plane sliding.

FS is the factor of safety against sliding, Z is depth of tension crack, Zw is depth of water in tension crack, A is area of wedge,W is Weight of rock wedge resting on failure surface, H is Height of the overall slope, U is uplift force due to water pressure on failure surface, F_w is the horizontal force due to water in crack, α is horizontal earthquake acceleration, c is cohesive strength along sliding surface, φ is friction angle of sliding surface,Ψ_p is angle of failure surface, measured from horizontal, Ψ_f is angle of slope face, measured from horizontal,γ_r is unit weight of rock, γ_w is unit weight of water.

3. STOCHASTIC PARAMETERS
In this research, two sets of parameters are considered in Eq.(1), fixed parameters Zw, c, φ, α, γ_r, γ_w and stochastic parameters Angle of slope face (Ψ_f), Angle of failure surface(Ψ_p), height of the slope(H) which were assumed to be uncorrelated. Slope height, angle of slope face and angle of fracture are all modeled using a truncated normal probability distribution function (pdf) which are illustrated in figures 2-4.

4. EXAMPLE
To demonstrate the efficiency and accuracy of the proposed method in determining the probability density distribution curve of the safety factor in rock slopes with plane sliding, an illustrative example is presented.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ψ_f (degree)</td>
<td>50</td>
<td>2</td>
<td>60.00</td>
<td>40.55</td>
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<tr>
<td>Ψ_p (degree)</td>
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<td>2</td>
<td>39.53</td>
<td>19.45</td>
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</table>

<table>
<thead>
<tr>
<th>Table 2- Deterministic parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ_r (kN/m³)</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>22</td>
</tr>
</tbody>
</table>
Figure 2. Probability distribution function of angle of face surface

Figure 3. Probability distribution function of angle of slope face

Figure 5. shows the probability distribution functions of the factor of safety determined by Monte Carlo simulation. The probability of safety factor is defined by area beneath the (pdf) plot with FS≤1 in Figure 5. Figure 6. shows the cumulative distribution curve of safety factor. It can be seen that the probability of failure (FS≤1) for this slope is about 70%, indicating that the slope will most likely be unstable. With these stochastic parameters, the maximum probability value of FS is about 1.2. In deterministic calculation designers attain a specific value for safety factor which demonstrates that in this situation the slope would fail, but the probability of failure is not specified. Therefore, the designer cannot have an engineering judgment. In fact, reliability assessment and engineering judgment are employed together to develop risk and decision analyses.
5. SENSITIVITY ANALYSIS

To appraise the response of plane sliding in rock slope (equation 1) with respect to changes in stochastic parameters, a sensitivity analysis was carried out using the Monte Carlo simulation. For this purpose the three stochastic input parameters were increased based on their standard deviation (new mean = old mean + 3.0×std). The results are shown in Figure 7. Additionally the cumulative distribution cures are plotted in Figure 8. To evaluate the influence of changes in each parameter, the parameter was increased while the ranges of the other stochastic input parameters were kept constant. It can be seen that the angle of failure surface is the most effective parameter in safety factor of rock slopes.
6. PARAMETRIC ANALYSIS

For further verification of the proposed model, a parametric analysis was performed. The main goal was to determine how each parameter affects the stability of rock slopes. Figure 9 presents the predicted values of the probability of failure (instability) as a function of each parameter where others were constant. For this purpose, in six steps, the probability density function of each stochastic input parameter was increased based on their standard deviation (new pdf = old pdf + 1/3 x std). The results of the parametric analysis indicate that, as expected, the probability of failure (instability) increases due to increasing height of slope (H), angle of failure surface (Ψp) and angle of slope face (Ψf).

7. CONCLUSION

Analysis of stability of rock slopes is a probabilistic problem due to the uncertainty in the geometrical properties of the joint/fracture network in the slope. In this paper, the application of the Monte Carlo simulation in assessing the reliability of analysis of rock slope stability with plane sliding was investigated. A sensitivity analysis was carried out to assess the influence of various stochastic parameters using the Monte Carlo method. In addition, for further verification of the proposed model, a parametric analysis was performed. The results showed the near
normal (pdf) for FS which specified probability of failure for different value of FS. Furthermore it was revealed that the angle of failure surface is the most effective parameter in safety factor of rock slopes.

8. REFERENCES


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