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A new approach for persistence in probabilistic rock slope stability analysis

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ABSTRACT: Discontinuity persistence is defined as the fraction of area (or length) that is actually discontinuous, with reference to a discontinuity plane which is through the rock mass containing a combination of discontinuities and intact rock regions. Although persistence is one of the most significant discontinuity parameters in slope stability analysis, it is impossible in practice to measure the discontinuity area accurately in a field investigation. Therefore, several researches have carried out on the basis of different approaches such as numerical analysis and fracture mechanics. In this study, the persistence is considered as a random variable since the persistence is difficult to obtain in the field and subsequently involves uncertainty. In addition, while most previous stability analyses have assumed that discontinuity on the failure plane is fully persistent, the probability that the joint length is long enough to produce a rock block failure (or that the joint length is equal to or greater than maximum sliding dimension) is evaluated in this study. That is, the probability of failure obtained from the previous approach is a conditional probability on the premise that the discontinuity on the failure plane is fully persistent. This approach simply uses joint length data rather than the persistence value in the procedure of obtaining the probability of fully persistent joint. Later the probability that fully persistent joint exists is multiplied by the probability of slope failure which itself is based on the assumption that joints are fully persistent. Consequently, in order to overcome the limitation of a conservative analysis, assuming 100% joint persistence, the proposed approach suggested new persistence concept based on the discontinuity length information. In this study, the proposed concept applies to the practical example.

Key words: persistence, probability of failure, probability analysis, discontinuity

1. INTRODUCTION

The joint persistence is defined as the ratio of total length of joints to the length of the failure plane if it is assumed that the failure takes along a straight line segment (Jennings, 1970). The persistence has been recognized as one of the important parameters which affect the shear strength of discontinuity, and many researches, therefore, have suggested many different approaches to properly deal with the persistence. Jennings (1970) defined the persistence in terms of the total joint length on the plane and intact rock (rock bridge) length intersecting the plane. After that, Einstein et al. (1983) have defined the persistence as the fraction of area, which is usually discontinuous, with respect to the total area of the failure plane. However, the persistence is difficult to obtain from field since the mapping of each joint persistence is impossible in practical base. Therefore, most rock slope stability analyses assume that the 100% persistent joint exists on failure surface. In addition, since the statistical technique for obtaining and describing the joint geometries is utilized, the most geometric characteristics, such as orientation, length, space as well as persistence should be considered as random variable. However, most previous approaches were considered the persistence as fixed value. In this study, a new procedure to evaluate discontinuity persistence is proposed. In this approach, the persistence is taken into account random variable. In addition, the random property of discontinuity length is used instead of persistence itself which is difficult to obtain on practical basis.

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2. TRADITIONAL DEFINITION OF JOINT PERSISTENCE

Persistence is one of the most significant joint parameters affecting rock mass strength, but it is difficult to quantify. Therefore, many researchers have tried to define the persistence quantitatively in many different ways. ISRM (1978) defined the joint persistence as the areal extent or size of a discontinuity along a plane. With reference to a joint plane (a plane through the rock mass containing a combination of discontinuities and intact rock regions), joint persistence is defined as the fraction of area that is actually discontinuous (Einstein et al., 1983). Therefore, the persistence value (K) can be expressed in the limit form (Fig. 1):

$$K = \lim_{A_D \to \infty} \frac{\sum_i a_{Di}}{A_D} \tag{1}$$

in which D is a region of the plane with area A_D and a_{Di} is the area of the ith joint in D. However, it is impossible in practice to measure the discontinuity area accurately in a field survey. This is because rock exposures are small and only two-dimensional. Consequently, Einstein et al. (1983) suggested that persistence can only be roughly quantified by observing the discontinuity trace length on a rock exposure surface and joint persistence can be expressed as a limit length ratio along a given line on a joint plane in terms of trace length:

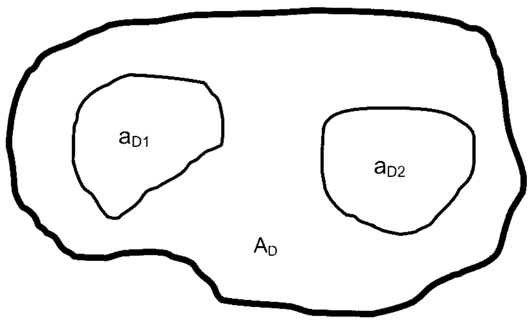

Fig. 1. Discontinuity persistence given in joint area terms.

$$K = \lim_{Ls \to \infty} \frac{\sum_i l_{Si}}{L_S} \tag{2}$$

where L_s is the length of the straight-line segment S, and l_{si} is the length of the ith joint segment in S. Jennings (1970) proposed that joint persistence could be expressed using a trace length term on the rock exposure surface as

$$K = \frac{\sum JL}{\sum JL + \sum RBR} \tag{3}$$

where $\sum JL$ represents the total length of the joint segments and $\sum RBR$ is the total length of segments crossing rock bridges (Fig. 2).

Singh and Sun (1989) and Scavia (1990) applied fracture mechanics concept to evaluate the stability of rock which does not have 100% persistence failure plane. Kemeny (2003) proposed a fracture mechanics model in slope stability, which is considered the time dependent degradation of rock bridge cohesion. The fracture mechanics considers rock slope failure as a result of joint initiation and propagation. Therefore, the joint tip stress intensity factor is governing parameter with respect to the rock slope stability and the factor of safety is defined in terms of stress intensity factor. Consequently, this approach has the limitation that the factor of safety defined as the stress intensity factor indicates crack stability, but not the overall stability of the slope.

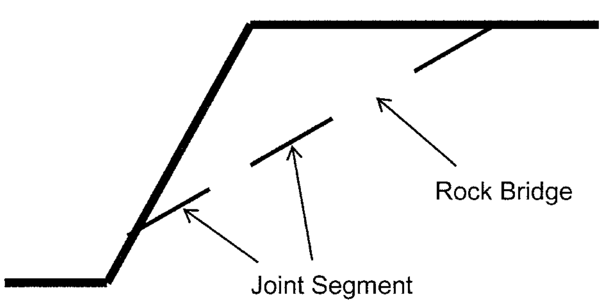

Fig. 2. Discontinuity persistence given in joint length term (After Jennings, 1970).

3. IMPORTANCE OF DISCONTINUITY PERSISTENCE

The reason that discontinuity persistence is important in slope stability analysis is because of its major effect on rock mass strength. The shear strength available for a rock bridge is one to two orders of magnitude greater than the shear strength available on the discontinuity. As Einstein et al. (1983) and West (1996) suggested, joint persistence can be used to estimate the strength of a rock mass against sliding along a given plane. If the plane of sliding has area A and a 100% persistent joint is assumed, the shearing resistance (R) can be expressed as:

$$R = (\sigma \tan\phi_j + c_j)A \tag{4}$$

where ϕ_j and c_j are the friction angle and cohesion of the joint, respectively. However, if the joint is not persistent, failure occurs through the rock bridge and only parallel to the discontinuity. In this case, the shear resistance to sliding is evaluated as:

$$R = A_r(\sigma \tan\phi_r + c_r) + A_j(\sigma \tan\phi_j + c_j) \tag{5}$$

where the intact rock portion and a jointed portion have area A_r and A_j, respectively and ϕ_r and c_r are the friction angle and cohesion of intact rock, respectively.

However, the more serious problem concerning persistence is that its extent is difficult to measure because direct mapping of discontinuities within a rock mass is not possible. In practice, 100% persistence on the shear planes is assumed. However, the possibility of a 100% persistent discontinuity on the shear planes is quite low under field conditions. In addition, as Einstein et al. (1983) suggested, persistence should be considered as a random variable because every joint in a set does not have the same value and these values are uncertain. Therefore, a new approach is requisite for the probabilistic analysis which is able to properly deal with persistence as random variable, and statistical parameters and a probability density distribution should be evaluated to characterize joint persistence as a random variable.

4. A NEW CONCEPT OF PERSISTENCE PROPOSED IN THIS STUDY

Hudson and Priest (1983) recognized that two kinds of persistence could be identified: intermittent joints as in Figure 3(a) and impersistent discontinuities as in Figure 3(b). Intermittent joints in Figure 3(a) require that the planes contain a patchwork of discontinuities and intact rock regions through the rock mass. As discussed previously, the previous concept of persistence implies that two or more joints occur on the same plane, so the previous persistence concept is based on the concept of intermittent joints.

However, from a practical point of view, it appears that

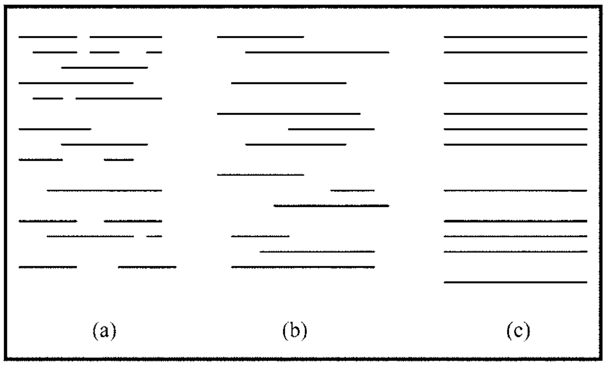

Fig. 3. Traces of: (a) intermittent; (b) impersistene; and persistent joint (After Hudson and Priest, 1983).

intermittent joints are geologically unlikely (Mauldon, 1994). Mauldon (1994) concluded that intermittent joints would seem to imply the existence of weakness planes through the rock mss, but locally separated to form visible joints. Consequently, the intermittent discontinuity should be treated as persistent, i.e. continuous across the region of interest, at least for the purpose of mechanical analysis.

To this end, a new approach which accounts for persistence is proposed on the basis of the impersistent joint concept in Figure 3(b) in spite of the limitations of measurement. Joint persistence, in this study, is described as a function of the length of individual joints and the maximum sliding dimension, determined by slope geometry, joint orientation and joint dimension (Fig. 4). The length of individual joints is obtained by random sampling from the probability density function of joint length, which is determined by statistical analysis using field data.

Based on the proposed joint persistence concept, the probability that the joint length is long enough to form a block capable of sliding is evaluated. That is, using information on statistical parameters and the probability distribution of discontinuity length, which is assumed as an exponential distribution in many researches, a large number of individual joint length values are generated using Monte Carlo simulation. Then each value of the generated joint length is compared to the sliding dimension and the probability that the joint length is equal to or greater than the maximum sliding length is calculated. For this, the height of slope is divided into 10 intervals. Then the probability of fully persistent joint (the probability that the joint length is equal to or greater than the maximum sliding length) is evaluated by grouping daylighting points according to elevation interval (Fig. 5). That is, the probability of fully persistent joint for the ith elevation interval (P_{pi}) is calculated as:

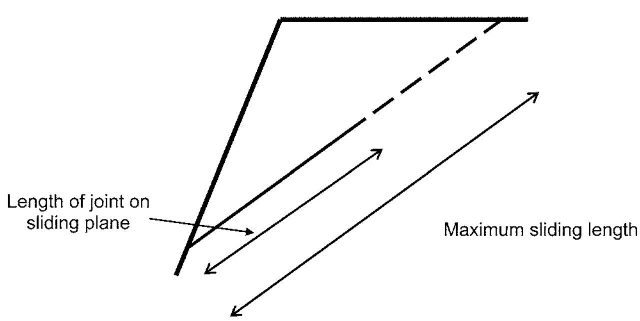

Fig. 4. Geometrical feature of sliding dimension and joint on sliding plane.

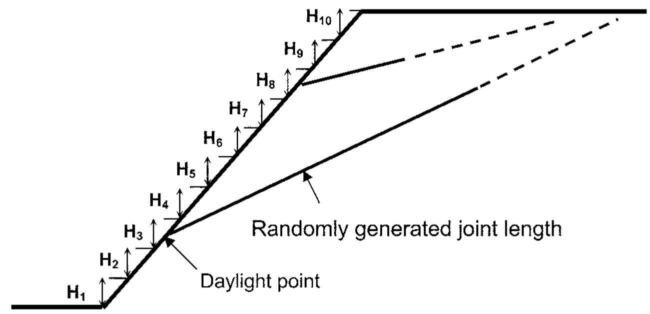

Fig. 5. Elevation intervals.

$$P_{Pi} = \frac{N_{pi}}{N_i} \tag{6}$$

in which N_i is the total number of iteration in the ith elevation interval and N_{pi} is the number of iteration that the length of a randomly selected joint is equal to or greater than maximum sliding length in the ith elevation interval.

Then the probability of fully persistent joint (P_p) is calculated as:

$$P_p = \sum_{i=1}^{10} P_{pi} \tag{7}$$

Later this value is multiplied by the probability of slope failure which itself is based on the assumption that joints are fully persistent. Then the probability of rock slope failure is expressed as;

P[rock slope failure]=P[rock slope failure|fully persistent joint]×P[fully persistent joint exists] (8)

The assumption of the fully persistent joint in rock slope stability analysis is quite common in deterministic analysis as well as probabilistic analysis since the persistence is difficult to obtain from field and not easy to include in slope stability analysis. Therefore, the probability of slope failure which is based on the assumption of fully persistent joint is a conditional probability which has a premise that the joint is fully persistent. Consequently, on the basis of probability theory, the probability of slope failure is the result of the multiplication of the conditional probability of slope failure which is assumed fully persistent joint and the probability that the fully persistent joint exists.

Therefore, in the initial step of the approach, probability of rock slope failure, same as in most previous probability analyses, is evaluated assuming fully persistent discontinuities. Finally the probability that the joint length is long enough to produce a rock block failure is evaluated and multiplied by the conditional probability of failure. Consequently the probability of failure, which takes into account non-persistent discontinuity, is obtained.

In addition to overcoming the limitation of a conservative analysis, assuming 100% joint persistence, the proposed approach in this study differs from previous persistence concepts. Previous work focused on the effect of persistence on shear strength. Therefore, consideration of partial persistence caused an increase in shear strength on the joint surface and a consequent increase in the reliability or safety of the rock slope. By contrast, the proposed approach simply uses joint length data rather than the persistence value. This is significant because field determination of persistence is not possible on a practical basis and the existence of two or more persistent joints on the same plane is geologically unlikely as concluded by Mauldon (1994). Therefore, the new approach expresses the probability that the joint length is equal to or greater than the maximum sliding length, which is multiplied by the probability of failure of the rock slope, the latter being evaluated assuming a fully persistent joint. This approach yields a result similar to the previous procedure, that is, the reliability of the rock slope is increased. In addition, an advantage of this approach is the inclusion of joint length information. The joint length is one of the most important factors that characterize joint properties, but is not accounted for in the traditional factor of safety calculation for rock stability. Besides, the persistence is considered as a random variable as Einstein et al. (1983) proposed since the persistence is difficult to obtain in the field and involves uncertainty.

5. CASE STUDY

The proposed approach for discontinuity persistence has been applied to practical examples (Fig. 6). A rock slope in North Carolina, USA has been selected to apply the approach. The site consists of an extensive rock cut along Interstate highway 40 in western North Carolina, USA. This area along Interstate 40 shows excellent exposures of a series of meta-sedimentary rocks of late Precambrian age. Major rock types in this area are a gray, thin bedded to laminated feldspathic meta-sandstone and a green slate with thin interbeds of fine meta-sandstone (Wiener and Merschat, 1975). Bedding is distinct and the rock is highly jointed. The study site has experienced several large landslides during and after construction. On July 1, 1997, a large rockslide occurred in the area after heavy rainfall and more than 100,000 cubic meters of rock were removed during mitigation of this rock slide. After the rock slide, the mitigation work has been carried out to stabilize the rock slope. In this study, the probabilistic analysis has been applied in order to analyze the stability of the slope.

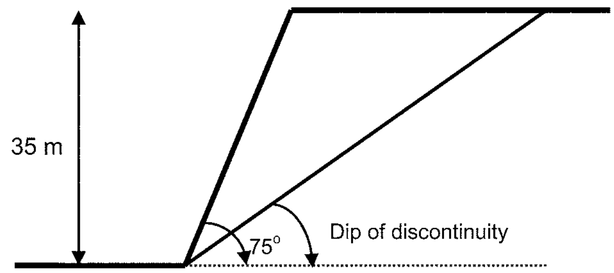

Fig. 6. Slope dimensions used in the case study.

Field investigation was carried out to collect the discontinuity geometric data such as orientation, length and spacing. In addition, the direct shear test was also carried out and the shear strength parameters for discontinuity are obtained. The obtained discontinuity orientation data were corrected for sampling bias and clustered by the algorithm proposed by Mahtab and Yegulalp (1982). Six major discontinuity sets were delineated in this area and their representative orientations were 217/77 (dip direction and dip) for J1, 183/05 for J2, 163/63 for J3, 196/56 for J4, 227/37 for J5 and 061/66 for J6. After performing the clustering procedure, the appropriate probability density function was determined for a discontinuity orientation distribution. Due to its simplicity and flexibility, Fisher distribution was selected. This distribution is based on the assumption that a population of orientation values is distributed about a "true" value (Fisher, 1953). This assumption is similar to the concept of discontinuity normals being distributed about some true value within a set.

For discontinuity length, discontinuity trace length data were obtained by the author from a field survey on road cuts along Interstate Highway 40. Approximately 300 data points were sampled with the author collecting the semi-trace length of discontinuities using the detailed scanline method. After obtaining this discontinuity length data, lengths were reclassified on the basis of discontinuity sets and the mean length for each set was evaluated. In addition, the negative exponential distribution was utilized to represent random property of discontinuity trace length. This is because many researches (Wallis and King, 1980; Priest and Hudson, 1981; Baecher, 1983; Kulatilake et al., 1993; Kulatilake et al., 2003) and the author in the previous research (Park and West, 2001) concluded that the exponential distribution is suitable to represent the discontinuity trace length distribution.

For discontinuity spacing, the lognormal probability density function was used as the distribution model to represent the random property of discontinuity spacing. Literatures proposed the use of a lognormal probability distribution for discontinuity spacing. Rouleau and Gale (1985), Sen and Kazi (1984), Park and West (2001) and Kulatilake et al. (2003) suggested that the lognormal probability density distribution was appropriate, based on their goodness of fit tests.

The probability density function of the shear strength

Table 1. Input for discontinuity properties.

Set I.D.	J1	J2	J3	J4	J5	J6	Probability density function
Mean Orientation (dip direction /dip)	217/77	183/5	163/63	196/56	227/37	061/66	Fisher
Fisher Constant	42	53	29	119	36	106	
Mean Friction Angle (degree)	30	30	30	30	30	30	Normal
STD DEV of Friction Angle	3	3	3	3	3	3	
Mean Length (m)	1	1	1	0.5	60	1	Exponential
Spacing (m)	1.6	3.5	0.43	4.5	1.0	2.7	Lognormal

parameters, especially friction angle, can be inferred from previous research, and from an analysis performed by the author in nearby study area in North Carolina (Park, 1999; Park and West, 2001). Several researchers have suggested a normal distribution or truncated normal distribution as the probabilistic density function for the internal friction angle (Mostyn and Li, 1993; Hoek, 1998; Nilsen, 2000; Pathak and Nilsen, 2004). Based on experience by the author, this can be confirmed using a Chi-square goodness-of-fit test on direct shear strength testing data. Therefore, a truncated normal distribution is considered for the density distribution of the internal friction angle for the study area.

The random or probabilistic properties of discontinuity parameters used in this study are listed in Table 1. In addition, mean and standard deviation values for each parameter are listed. On the other hand, the slope geometries such as orientation and height of slope are considered as the deterministic parameters (Table 2). Using the discontinuity and slope parameters, the possibility of planar failure is analyzed. The Hoek and Bray's simple equation (1981) has been utilized for the analysis of planar failure;

$$FS = \frac{cA + W\cos\alpha\tan\phi}{W\sin\alpha} \tag{9}$$

Where FS is the factor of safety, α is the dip angle of discontinuity, A is the area of failure plane, c is the cohesion for discontinuity and ϕ is the friction angle for discontinuity. In addition, W is the weight of the sliding block.

For the probabilistic analysis, the Monte Carlo simulation technique is utilized. The Monte Carlo technique is a numerical simulation method that solves mathematical problems through random sampling and repeated calculation. In this study the simulation procedure developed by Park and West (2001) has been used.

The results of probabilistic analysis are listed in Table 3. "P_f @ 100% persistence" means that the probability that the FS is less than 1 using equation (9) through repeated calculation when the discontinuity plane is assumed to be 100%

Table 2. Input for slope geometry.

Orientation of slope (dip direction/dip)	Height of slope (m)	Unit weight of rocks (t/m^3)
210/75	34	2.56

Table 3. Results of probabilistic analysis.

Set	P_f @ 100 % persistence	Probability of totally persistent joint	Probability of failure
J1	0.018	0.001	0.00002
J2	0	0.001	0
J3	0	0.13	0
J4	0.014	0	0
J5	0.67	0.62	0.42
J6	0	0.001	0

persistent. "Probability of fully persistent joint" implies a probability that the fully persistent joint exists. Therefore, the probability of failure in Table 3 is the multiplication of P_f @ 100% persistence and P (fully persistent joint).

The probabilities of fully persistent joint for J1, J2, J3, J5, and J6 are 0.1%, 0.1%, 13%, 62%, and 0.1%, respectively. In case of J4, the probability that fully persistent joint exists is 0 because the length of the discontinuity is too small compared to maximum sliding dimension. However, the probabilities of fully persistent joint for J1, J2, and J6 (which show 0.1%) and the probability of fully persistent joint for J3, 13%, are different even though the mean lengths of the discontinuity sets for J1, J2, J3, and J6 have same value as 1m in Table 3. This is because the mean orientations for each set are quite different. In case of J1, the mean dip angle of discontinuity is greater than dip angle of slope, so there is little chance of existence for fully persistent joint since most randomly generated joints for J1 cannot daylight. For J2, the dip angle of discontinuity is too small, so the maximum sliding dimension would be much longer than the randomly generated joint lengths and the probability of fully persistent joint is very low. For J6, the dip direction of discontinuity is very different from the dip direction of slope. Therefore, there is quite little chance of formation for fully persistent joint geometrically. In contrast, for J3, the orientation of discontinuity is similar to the orientation of slope, so the probability of fully persistent joint increases to 13%. In case of J5, which is a bedding plane, the mean length is obtained as 60 m and the orientation of the discontinuity is similar to the orientation of slope. Therefore, the probability of fully persistent joint is evaluated to 62%.

For P_f @ 100% persistence for J1, J4, and J5 are 1.8%, 1.4% and 67%, respectively. The P_f @ 100% persistence for J2, J3, and J6 show 0 and those indicate that those discontinuities are safe in planar failure. The probabilities of failure, which are evaluated by multiplication of the previous two probabilities, are 0.002% for J1 and 42% for J5. In case of J5, the kinetic analysis based on the equation (9) indicates the J5 has high possibility of failure and moreover J5 has long enough to produce 100% persistent failure plane.

6. CONCLUSIONS

Discontinuity persistence is defined as the fraction of area (or length) that is actually discontinuous, with reference to a discontinuity plane which is through the rock mass containing a combination of discontinuities and intact rock regions. Since the shear strength available for a rock bridge is one or two orders of magnitude greater than the shear strength available on the discontinuity, the discontinuity persistence is important in slope stability analysis. However, it is impossible in practice to measure the discontinuity area accurately in a field investigation. Therefore, in the previous probabilistic analysis, the probability of failure is evaluated on the assumption that the discontinuity on the failure surface is 100% persistent. This assumption is common in the deterministic analysis as well as the probabilistic analysis.

The new approach for discontinuity persistence has been proposed in this study. Discontinuity persistence is described in this study as function of the length of individual joints and the maximum sliding dimension, determined by slope and joint geometry. Then the probability of fully persistent joint (that is, the length of joint is equal to or greater than the maximum sliding dimension) is evaluated. That is, the probability that the joint length is long enough to form a block capable of sliding is evaluated and multiplied by the probability of slope failure. The new approach has the following advantages. This approach provides more realistic analysis results since the length of discontinuity affects the probability of failure. As mentioned previously, the previous studies supposed 100% persistent joint and it is not appropriate because the mean length of each discontinuity set is quite differ from one to another and this different discontinuity length will affect the reliability of rock slope in practice. In addition, the approach overcomes the limitation of conservative analysis which assumed 100% persistent joint.

While this study has proposed new approach for discontinuity persistence, this approach is applicable for only one joint forming failure plane and in case that the joint is not offset from the sliding surface. Therefore, further researches are required to apply to other cases such as stepped failure in rock masses.

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