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# 점추정법을 이용한 평면파괴의 파괴확률 산정

박혁진[1)]

# Evaluation of Failure Probability for Planar Failure Using Point Estimate Method

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**Abstract.** In recent years, the probabilistic analysis has been used in rock slope engineering. This is because uncertainty is pervasive in rock slope engineering and most geometric and geotechnical parameters of discontinuity and rock masses are involved with uncertainty. Whilst the traditional deterministic analysis method fails to properly deal with uncertainty, the probabilistic analysis has advantages quantifying the uncertainty in parameters. As a probabilistic analysis method, the Monte Carlo simulation has been used commonly. However, the Monte Carlo simulation requires many repeated calculations and therefore, needs much effort and time to calculate the probability of failure. In contrast, the point estimate method involves a simple calculation with moments for random variables. In this study the probability of failure in rock slope is evaluated by the point estimate method and the results are compared to the probability of failure obtained by Monte Carlo simulation method.

**KeyWords:** Monte Carlo Simulation, Point Estimate Method, Probability of Failure, Uncertainty

**초 록**. 최근 들어 확률론적 해석 방법이 암반사면공학에서 많이 사용되고 있으며 이는 불연속면과 암반의 지질학적 및 지반공학적 특성에 불확실성이 포함되며 이러한 불확실성에 의해 해석결과에 영향을 미치고 있기 때문이다. 암반사면의 안정성 해석에서 주로 사용되고 있는 전통적인 결정론적인 해석에서는 이러한 불확실성을 해석에 고려하기 어려운 반면 확률론적 해석에서는 불확실성을 수량화하여 해석에 고려할 수 있다는 장점을 가지고 있다. 이러한 확률론적 해석방법으로는 몬테카를로 방법이 주로 사용되고 있으나 방법은 파괴확률을 획득하기 위하여 많은 반복된 계산이 요구되며 따라서 많은 시간과 노력이 필요하다는 단점을 가지고 이다. 반면 본 연구에서 제안된 점추정법은 확률변수의 통계적 파라미터, 즉, 평균과 표준편차만을 이용하여 단순한 계산을 통해 파괴확률을 구할 수 있는 장점을 가지고 있다. 따라서 본 연구에서는 점추정법을 이용하여 평면파괴의 파괴확률을 산정하였으며 이를 몬테카를로 방법과 비교해 보았다.

**핵심어**: 몬테카를로 방법, 점추정법, 파괴확률, 불확실성

## 1. Introduction

Uncertainties in geologic conditions and geotechnical parameters are inevitable in rock engineering. In rock slope engineering, which is an aspect of rock engineering studies, uncertainty is involved in most geometric and strength parameters of discontinuity in rock masses. Therefore, uncertainty may be in the form of a large scatter in the attitude and the geometry of discontinuity or laboratory test results performed to characterize discontinuity strength parameters and properties. Consequently, in order to deal properly with uncertainty, those parameters should be considered and treated as random variables.

A conventional deterministic analysis is carried out on the basis of the factor of safety concept and it requires a fixed representative value for each input parameter without regard for the degree of uncertainty involved in parameters. Therefore, the deterministic analysis often fails to represent uncertainty and variability, which are common in rock engineering. In contrast, the probabilistic analysis has an advantage to overcome the

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shortcomings of the deterministic analysis since the probabilistic analysis is able to deal with random variables quantitatively. Therefore, the probabilistic approach has been applied to treat uncertainty in discontinuity properties, and the probability of failure has been evaluated as the probabilistic analysis results. The Monte Carlo simulation method has been commonly used as a probabilistic analysis method. The simulation involves repeated simulation process, using in each simulation a particular set of values of the random variables generated in accordance with the corresponding probability distributions. However, the Monte Carlo simulation is required a great number of repeated calculations and therefore, the method needs much effort and time to calculate the probability of failure. Therefore, the other alternative approaches such as first order second moment method and point estimate method have been proposed to evaluate the probability of failure with a simple calculation. In this study, the point estimate method as alternative method to the Monte Carlo simulation is introduced and used to overcome the limitations of the deterministic analysis method and Monte Carlo simulation, and evaluate the probability of failure.

## 2. Probabilistic Analysis Methods

### 2.1 Monte Carlo simulation and its limitation

The Monte Carlo simulation technique is the numerical simulation method that solves mathematical problems through random sampling and repeated calculation. The simulation is frequently applied to evaluate the probability of failure for a mechanical system, in particular, when the direct integration is not practical or when the equation to integrate is difficult to obtain. In the Monte Carlo simulation procedure, values of each component are randomly generated from its respective probability density functions and then these values are used to evaluate the factor of safety. By repeating the process, a series of factors of safety corresponding to a different set of values of the random variables is obtained. This method is called as the most complete method for probabilistic analysis since all the random variables are represented by their probability density function and the probability of failure as the result of reliability analysis is represented by the probability density function (Mostyn and Li, 1993).

The Monte Carlo simulation is the most widely used among the probabilistic analysis methods because the deterministic model for rock slope failure is not easy to solve using analytical means.

However, this process is required much effort and time to generate a sufficient number of different factor of safety. Especially, a large number of repeated calculations are required in case that the probability of failure is small. Another disadvantage is that the simulation should be supplied by the complete information for probability distributions and the statistical moments (mean and standard deviation). Consequently, if the complete information is not provided, the information should be assumed and the possibility that the output may be distorted is great. In addition, it should be pointed out that the task of determining the probability distribution function is difficult for rock joint strength parameters comparing with for engineering materials such as concrete and steel.

As an alternative method to the Monte Carlo simulation, the point estimate method has been proposed and this method is adopted in this study. The point estimate method is the approximate procedure that can be accommodated by relatively simple algebraic calculation. This method requires only statistical moments and simple calculation.

### 2.2 Point estimate method

This method was proposed by Rosenblueth (1975) and presented by Harr (1981) for the solution of geotechnical problems. The method allows one to use several correlated random variables given by their two or three statistical moments (mean, standard deviation, skewness) to obtain results expressed in terms of the first statistical moments of the examined parameter. Whilst the Monte Carlo method is required the complete probability distributions of the random variables and the considerable computing time, the point estimate method is required only statistical moments of random variables and a simple calculation with moments of random variable. The moments of factor of safety are determined for all possible combinations of point estimate of each random variable. Consequently, the probability of failure is estimated from the moments of factor of safety. The method is initially limited to a three correlated variable analysis and extended to any number of correlated or independent random variables. For instance, to obtain the mean of the factor of safety function for the independent random variables, FS is determined for all possible combinations of one low and one high value (point estimate) of each random variable and the results are weighted by the product of their associated probability concentrations $p_{i+}$ or $p_{i-}$, and then summed. The entire procedure can be summarized by the following equations:

Given information concerning the first three moments of a random variable, x and the function $FS = FS(x)$, the $x_-$, $x_+$, $p_-$, and $p_+$ are obtained by

$$p_+ = \frac{1}{2}\left[1 \pm \sqrt{1 - \frac{1}{1+[\beta(1)/2]^2}}\right] \quad (1)$$

$$p_- = 1 - p_+ \quad (2)$$

$$x_+ = E[x] + \sigma(x)\sqrt{\frac{p_-}{p_+}} \quad (3)$$

$$x_- = E[x] - \sigma(x)\sqrt{\frac{p_+}{p_-}} \quad (4)$$

Then

$$E[FS] = p_- FS(x_-) + p_+ FS(x_+) \quad (5)$$

$$E[FS^2] = p_- FS^2(x_-) + p_+ FS^2(x_+) \quad (6)$$

$$\sigma_{FS} = \sqrt{E[FS^2] - (E[FS])^2} \quad (7)$$

where $\beta(1)$ is coefficient of skewness.

If $\beta(1) = 0$, that is, the probability density function is symmetrical, above equations reduce to

$$p_+ = p_- = \frac{1}{2} \quad (8)$$

$$x_+ = E[x] + \sigma[x] \quad (9)$$

$$x_- = E[x] - \sigma[x] \quad (10)$$

For correlated random variables, additional adjustment must be made to the probability concentrations. Where symmetrically distributed variables are assumed, the point estimates are taken at one standard deviation above and below the expected value, respectively.

For two random variables, four points $p_{++}$, $p_{+-}$, $p_{-+}$, $p_{--}$ are considered and functional relationship is $FS = FS(x_1, x_2)$.

$$p_{++} = p_{--} = \frac{1+\rho}{4} \quad (11)$$

$$p_{+-} = p_{-+} = \frac{1-\rho}{4} \quad (12)$$

$$FS_{\pm\pm} = FS(FS[x_1] \pm \sigma[x_1], FS[x_2] \pm \sigma[x_2]) \quad (13)$$

$$E[FS] = p_{++}FS_{++} + p_{+-}FS_{+-} + p_{-+}FS_{-+} + p_{--}FS_{--} \quad (14)$$

$$E[FS^2] = p_{++}FS^2_{++} + p_{+-}FS^2_{+-} + p_{-+}FS^2_{-+} + p_{--}FS^2_{--} \quad (15)$$

where $\rho$ is the coefficient of correlation.

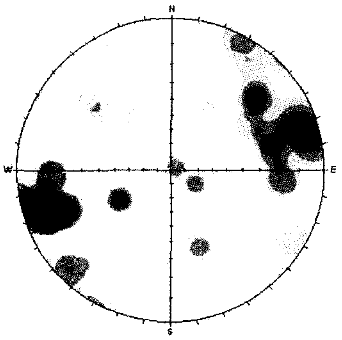
## 3. Study Area

The study area is located along the Han River and in the construction site which the improvement of railway (Joong-ang line) between Dukso and Yangsoo in Namyangjoo, Kyonggi-do, is planned. The bedrock of this area is composed of banded gneiss and felsic gneiss of Archaeozoic to Proterozoic Era, and the felsic gneiss intrudes banded gneiss. In this area, Kyonggang fault whose orientation is from NS to N30E and small faults whose orientations are similar to Kyonggang fault are observed. In addition, foliation whose attitude is 267/47 is commonly observed in banded gneiss which covers mostly in study area.

The orientation of planned cut slope is 245° and the slope angle is planned as 65°. The expected height of the slope is approximately 35 m. Using scanline method and borehole image processing system, approximately 300 discontinuity orientation data were obtained and 15 cores for direct shear test are obtained from field.

## 4. Analysis of Random Properties for Discontinuity

In order to carry out the probabilistic analysis, the random properties of discontinuity should be obtained. This analysis is accompanied by statistical technique called statistical inference. The statistical inference is the technique that random properties of population are inferred from the sample obtained by field survey or laboratory tests. This is very important procedure in probabilistic analysis since as Kulatilake et al. (1985)



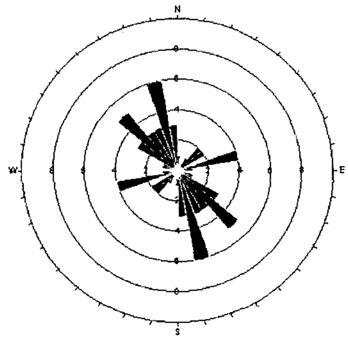




**Figure 1.** Stereographic plot and rose diagram for discontinuity orientations.

pointed out, the different probabilistic properties for random variables cause the different analysis results.

Another thing which should be noted is that the selection of random variables can be quite different from one researcher to another. Some have adopted only the geometric parameters of discontinuity and groundwater conditions as random variables, whereas others also involve strength parameters as random variable. In this study, the orientation and shear strength parameters of discontinuity are chosen as random variable. This is because those two parameters are important parameters in kinematic and kinetic instability analysis of rock slope stability analysis, respectively.

### 4.1 Discontinuity Orientation

Discontinuity orientation plays important role in rock slope stability analysis, especially for kinematic stability analysis. In fact, the discontinuity orientation data obtained from the field are widely scattered and therefore, involve uncertainty and variability. However, the traditional deterministic analysis uses a fixed single value, that is, mean orientation, from the widely scattered orientation and consequently, the uncertainty and variability in the discontinuity orientation data are not taken into account.

Figure 1 is the stereograph plot and rose diagram for discontinuity orientations measured from field. Based on the field measurement, the orientations are clustered using the algorithm suggested by Mahtab and Yegulalp (1984). In addition, in this study, the Fisher distribution is chosen in order to model the orientation data distribution since Fisher distribution provides a valuable model for discontinuity orientation data in view of its simplicity and flexibility (Priest, 1993). This distribution is assumed that a population of orientation values is distributed about some true value (Fisher, 1953). This assumption is directly equivalent to the idea of discontinuity normals being distributed about true value within a set. However, Fisher distribution is a symmetric distribution and therefore, provides only approximation for asymmetric data. Einstein and Baecher (1983) and Muralha and Trunk (1993) describe alternative models such as Bingham and bivariate normal, that can provide better fit for asymmetric orientation data. However, such models are more complex in their parameter estimation and in the formulation of probabilistic results. Table 1 shows the results of clustering process. Four different discontinuity sets were identified, and their mean orientations and Fisher constants were listed. Fisher constant is a measure of the degree of clustering within the population.

**Table 1.** Results of clustering on discontinuity orientation data.

| Joint set | Mean dip dir/ dip | Fisher const. |
|---|---|---|
| J1 | 078/80 | 53 |
| J2 | 270/28 | 280 |
| J3 | 255/64 | 58 |
| J4 | 115/18 | 23 |

### 4.2 Shear Strength Parameter of Discontinuity

Shear strength of the potential failure surface is also one of the most important factors affecting rock slope stability. Determination of the appropriate shear strength value is a critical part of a slope stability analysis because small changes in the parameter cause significant

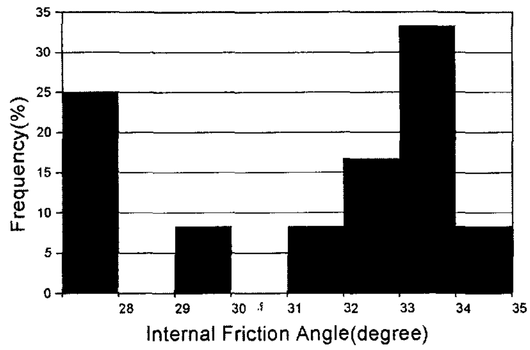



**Figure 2.** Distribution of internal friction angle.

changes in slope stability. Therefore, sufficient amount of data which can represent the field condition should be provided. However, due to the limitation of the number of tests and the difficulty of sampling, the number of the shear strength data is usually not enough. This causes uncertainty involving in shear strength data and consequently, the shear strength parameter is considered as random variable. Total 15 core samples for direct shear test were obtained in field and tested in lab. The friction angle ranges from 27.0° to 32.2° and its mean value and standard deviation are 32.2° and 3.0, respectively. From the direct shear test results, approximately 0.07 MPa of cohesion is obtained as mean value. However, as noted by Hoek (1997), cohesion is a mathematical quantity related to surface roughness in rock mechanics. Therefore, in this study, the cohesion is considered as zero and the friction angle is only considered as discontinuity strength parameters. Figure 2 shows the distribution of friction angle for discontinuity, and this distribution does not show any typical distribution that can be used in probabilistic analysis. Therefore, the probability density function is inferred from the author's previous studies (Park and West, 2001) and consequently, the normal distribution is considered as the representative density function for the friction angle.

## 5. Probabilistic Analysis for Planar Failure in Rock Masses

### 5.1 Results of deterministic analysis

For the purpose of comparison between the deterministic analysis and the probabilistic analysis method, the deterministic analysis is carried out using the same data used in the probabilistic analysis. This analysis uses the same deterministic models and the same formula as used in the probabilistic method. In addition, the mean values of each discontinuity parameter are selected as the representative value and used in the deterministic analysis as is commonly done by most engineers for deterministic analysis.

**Table 2.** Evaluation of factor of safety on various water tables.

| Height of water table | Factor of safety |
|---|---|
| 0% | 0.36 |
| 10% | 0.35 |
| 20% | 0.31 |
| 30% | 0.23 |
| 40% | 0.13 |
| 50% | 0 |

The analysis is divided into two parts, kinematic analysis and kinetic analysis. The kinematic analysis is to examine the possibility that the rock body defined by discontinuities can move or not is checked based on the discontinuity orientation. Subsequently, in the kinetic analysis, the kinetic feasibility is checked using the limit equilibrium concept. As the first step of the deterministic analysis, the representative orientation data for each set are selected. Then the selected data are used in the stereographic analysis as an expedient of kinematic analysis. In the deterministic analysis result, only Set 3 shows the possibility of planar failure in the kinematic analysis. That is, Set 3 only satisfies the conditions for kinematic instability, which are i) the dip direction of the discontinuity must be within 20 degrees of the dip direction of the slope face, ii) the dip of the discontinuity must be less than the dip of slope face and thereby must daylight in the slope face. Therefore, the factor of safety for Set 3 is calculated for the various water tables (Table 2). As can be seen in Table 2, the factor of safety is reducing as the water table is increasing. The FS ranges from 0.364 when the slope is completely dry to 0 when the water table is located at the half of the slope height. This result indicates that the slope is unstable even in the dry condition.

### 5.2 Point estimate methods

Based on the random properties of discontinuity parameters, the probabilistic analysis is carried out using point estimate method. In this analysis, the probabilistic analysis procedure is divided into two parts, kinematic analysis and kinetic analysis as does in the deterministic analysis.

For the point estimate method, the kinematic instability cannot be analyzed unlike the Monte Carlo method because the deterministic model for kinematic analysis does not exist. Therefore, in this study, the probability of kinematic instability is evaluated by the Monte Carlo simulation and used. In the kinematic analysis, Set 2 and Set 3 show the kinematic instability but Set 1 and Set 4 are stable for kinematically. Set 2 and Set 3 show 12% and 68.4%, respectively as the probabilities of kinematic instability and they are analyzed as kinematically unstable. This result disagrees with the result of the deterministic analysis result since only Set 3 is analyzed as kinematically unstable in the deterministic analysis. This is because the deterministic analysis does not consider the scattering in discontinuity orientation data.

Consequently, the representative orientation data for Set 2 does not satisfy the unstable condition. However, the probabilistic analysis shows that the part (12%) of the discontinuity orientation data satisfies the unstable condition. Since the kinematic analysis shows the possibility that Set 2 and Set 3 are kinematically unstable, the kinetic analysis is subsequently carried out for Set 2 and Set 3. For Set 2, the mean FS evaluated by point estimate method ranged from 1.19 to 0.79 (Table 3). According to the analysis results on the basis of the mean value of safety factor, the slope is stable when the slope is dry, but becomes unstable after the water table reaches the 70% height of the slope since the factor of safety is dropped under 1.0. However, the probability of kinetic instability is evaluated 8.5% in the dry condition by point estimate method considering mean and standard deviation of FS, which means that the uncertainty in FS calculation is considered. According to Priest and Brown (1982), the acceptable failure probability for permanent slope is 1% and 10% for temporary slope. Based on their criteria, the slope is not adequate for permanent slope since the probability of failure is 8.5% for completely dry slope. When the water table is located at 20% of slope height, the slope is even not proper for temporary slope because the probability of kinetic instability is 10.2%. In addition, when the water table is increased to full height of slope, the probability of kinetic instability reaches 98.8%. Consequently, the slope is risky even in the dry condition. This discrepancy between the deterministic analysis and point estimate analysis is caused by the uncertainty in the discontinuity parameters. That is, because the uncertainty in parameters does not take into account, the deterministic analysis does not indicate the possibility of slope instability.

In case of Set 3, the mean factor of safety is 0.365 in completely dry slope. That is, the slope is unstable even in the completely dry condition when the mean factor of safety is considered. The mean factor of safety is reducing as the water table in slope is increasing. The analysis results of point estimate method show the same results. That is, the probability of kinetic instability is 100% even when the water table in slope is 0.

## 6. Comparison Between The Analysis Results

As mentioned previously, the deterministic analysis fails to indicate the kinematic possibility of planar failure in Set 2. This is because the representative orientation of Set 2 does not satisfy the unstable condition. However, the probabilistic analysis indicates that 12% of the scattered orientation data for Set 2 satisfy the unstable condition. Therefore, the kinetic analysis is not calculated in the deterministic analysis. However, the probabilities of kinetic instability which are evaluated on the basis of random properties of parameters range from 8.5% to 98.8% and this indicates that the slope is unstable.

On the other hand, the result of the deterministic analysis for Set 3 is coincident with the result of the probabilistic analysis. This discontinuity set is kinematically unstable both in the deterministic and the probabilistic approach. In the kinetic analysis, the FS is ranged from 0.36 to 0 and this result indicates that the slope is unstable in the deterministic analysis. This result is coincident with the results of the point estimate analysis. The probability of kinetic instability is 100% and this means that the slope is very dangerous and has a high possibility that the planar failure will occur.

In order to compare the point estimate analysis results with the results of Monte Carlo method, the probabilistic analysis using Monte Carlo simulation is carried out

**Table 3**. Results of point estimate analysis.

| Height of water table | Set 2 | | | Set 3 | | |
|---|---|---|---|---|---|---|
| | Mean FS | STD FS | Probability of kinetic instability | Mean FS | STD FS | Probability of kinetic instability |
| 0% | 1.19 | 0.138 | 0.085 | 0.365 | 0.042 | 1.0 |
| 10% | 1.18 | 0.137 | 0.088 | 0.351 | 0.041 | 1.0 |
| 20% | 1.17 | 0.136 | 0.102 | 0.306 | 0.036 | 1.0 |
| 30% | 1.15 | 0.134 | 0.125 | 0.232 | 0.027 | 1.0 |
| 40% | 1.13 | 0.131 | 0.168 | 0.128 | 0.015 | 1.0 |
| 50% | 1.09 | 0.126 | 0.237 | 0 | 0 | 1.0 |
| 60% | 1.05 | 0.122 | 0.351 | | | |
| 70% | 0.99 | 0.115 | 0.517 | | | |
| 80% | 0.94 | 0.109 | 0.724 | | | |
| 90% | 0.87 | 0.100 | 0.905 | | | |
| 100% | 0.79 | 0.092 | 0.988 | | | |

(Table 4). The Monte Carlo analysis results show that the slope is unstable for Set 2 and Set 3. The probabilities of kinetic instability for Set 2 are 16.5% and 85.6% respectively when the slope is completely dry and 100% saturated. For Set 3, the probabilities of kinetic instability are ranged from 87.5% in the dry condition to 100% when the water table is located at 50% of the slope height. However, the values of kinetic instability probabilities evaluated from the Monte Carlo simulation are different from the values of the probabilities evaluated from the point estimate (Table 5). This is because the point estimate method is the approximation method. That is, whilst the Monte Carlo simulation carried out the analysis using the complete information for random variable such as moments and probability density function, the point estimate method uses only the statistical moments for random variables as input parameters.

Another possibility is that the probabilities of kinetic instability in the point estimate method are assumed normally distributed. That is, in Monte Carlo simulation,

**Table 4.** Results of Monte Carlo simulation analysis.

| Height of water table | Set 2 | Set 3 |
|---|---|---|
| | Probability of kinetic instability | Probability of kinetic instability |
| 0 | 0.165 | 0.875 |
| 10% | 0.170 | 0.907 |
| 20% | 0.175 | 0.946 |
| 30% | 0.217 | 0.974 |
| 40% | 0.265 | 0.991 |
| 50% | 0.324 | 0.998 |
| 60% | 0.398 | 1.0 |
| 70% | 0.495 | 1.0 |
| 80% | 0.639 | 1.0 |
| 90% | 0.730 | 1.0 |
| 100% | 0.856 | 1.0 |

**Table 5.** Comparison between results of Monte Carlo simulation and Point estimate method.

| Height of water table | Set 2 | | Set 3 | |
|---|---|---|---|---|
| | Probability of kinetic instability | | Probability of kinetic instability | |
| | M.C. | PEM | M.C. | PEM |
| 0 | 0.165 | 0.085 | 0.875 | 1.0 |
| 10% | 0.170 | 0.088 | 0.907 | 1.0 |
| 20% | 0.175 | 0.102 | 0.946 | 1.0 |
| 30% | 0.217 | 0.125 | 0.974 | 1.0 |
| 40% | 0.265 | 0.168 | 0.991 | 1.0 |
| 50% | 0.324 | 0.237 | 0.998 | 1.0 |
| 60% | 0.398 | 0.351 | 1.0 | 1.0 |
| 70% | 0.495 | 0.517 | 1.0 | 1.0 |
| 80% | 0.639 | 0.724 | 1.0 | 1.0 |
| 90% | 0.730 | 0.905 | 1.0 | 1.0 |
| 100% | 0.856 | 0.988 | 1.0 | 1.0 |

the probability of kinetic instability is obtained from the probability density function of factors of safety which are evaluated after many repeated calculations. However, in the point estimate method, the moments of FS distribution are obtained and the probability density function for FS should be assumed. Therefore, if the probability distribution evaluated by Monte Carlo simulation is normally distributed, the analysis results of the Monte Carlo and point estimate will be shown the similar results.

However, although there are some discrepancies between Monte Carlo simulation and the point estimate method, the point estimate method is very useful. The analysis results show that similar analysis results are obtained from the Monte Carlo simulation and point estimate analysis. That is, except for the cases which the heights of water table are 0 to 10% for Set 2 in point estimates method, all analysis results indicate that the slope is not adequate for permanent slope and dangerous. In addition, if the probability density functions for input parameters cannot be inferred from the collected data, the point estimate analysis is the best way to evaluate the probability of kinetic instability.

Moreover, the point estimate method reduces the computing time. In order to obtain the previous results in Monte Carlo method, approximately 10,000 cycles of repeated calculations was performed. However, the point estimate method required a single simple calculation.

## 7. Conclusion

Most rock engineering problems involve uncertainty and variability, which are inevitably difficult to establish and predict. Uncertainty and variability are caused by insufficient information of site conditions and incomplete understandings of a failure mechanism. Therefore, the probabilistic approach has been proposed to consider and quantify the uncertainty and variability. The Monte Carlo simulation has been commonly used in the probabilistic analysis. However, the Monte Carlo method requires the complete information about the probability density function and statistical moments, which are not acquired readily in practice. In addition, the Monte Carlo simulation requires a great amount of computing time. In order to overcome the shortcomings, the point estimate method is used in this study. Comparing the point estimate analysis with the Monte Carlo simulation, the analysis results have been compared. Both analysis methods indicate that Set 2 and Set 3 have high possibility for planar failure. However, the deterministic analysis fails to show the failure possibility in Set 2.

Even though the values of the probabilities evaluated from the Monte Carlo method are different from those evaluated from point estimate method, the point estimate method has advantages to reduce computing time and to carry out the analysis using only statistical moment information.

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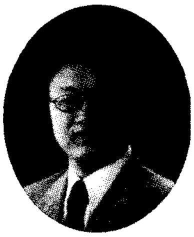
**박 혁 진**



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