

EFFECT OF MODELING INHOMOGENITY OF SOIL STRENGTH AND FAILURE MECHANISM ON THE FAILURE PROBABILITY OF EMBANKMENT

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ABSTRACT

The objective of this paper is to evaluate the influence of modeling the uncertainty of soil strength characteristics and the failure mechanism on the failure probability of the earth structure, using the circle slip method based on the limit equilibrium method and the method to evaluate a critical slip in the multi-layered slope based on the variation principle proposed by the author. In addition, the method was indicated to evaluate the fragility curve simply. The yield seismic coefficient and the critical slip surface are noticed. As a result, it is found that, according to the seismic coefficient that the failure probability becomes almost 100% , the value obtained by the proposal method is about 0.2 and is smaller than that obtained by circle slip method

Keywords: Failure probability of slop, Inhomogeneity of soil strength, Compound log spiral slip surface, Multi-layered ground

INTRODUCTION

In order to evaluate the degree of safety in terms of the limit state of the structure quantitatively, the design principle based on a probabilistic theory has been described in not only the international standard ISO2394 for the basis of the design(e.g. International Standard Organization) but also ISO23946 (e.g. International Standard Organization 2005) in which the seismic action for the geotechnical works is specified. To carry out the design based on the principle mentioned in those codes, it is necessary to evaluate the appropriate index related with the limit state of the structure quantitatively and to establish the response analysis method for obtaining the index quantitatively as well as to quantify the various uncertainty. The researches for the earth structure such as the embankment and the slope is supposed not to be so many, though a lot of researches for the RC pier among the structures(e.g. Nakamura, S. Akiyama, M., Sawada, S., et. al., 2006) have been carried out. It is seemed to be caused by the reason why a basic research according to modeling the slope failure mechanism was not appropriately carried out as well as evaluating the effect of the uncertainty of the mechanism on the failure characteristics because FEM has been expected as the method to evaluate the quantitative amount of the deformation.

For establishing the method to evaluate the fragility curve according to the failure of the earth structure, the effect of the spatial distribution of the strength characteristics and the failure mechanism on the failure probability is described in the report. The embankment among the earth structures is considered as the structure to evaluate the slope failure of the embankment by use of not only a circular slip method based on a limit equilibrium method but also the proposed method by the author (e.g. Nakamura, S., Sawada, S. and Yoshida, Submitted). The characteristics of the method are that the compound log spiral slip surface is used as the shape of critical slip surface by developing the single

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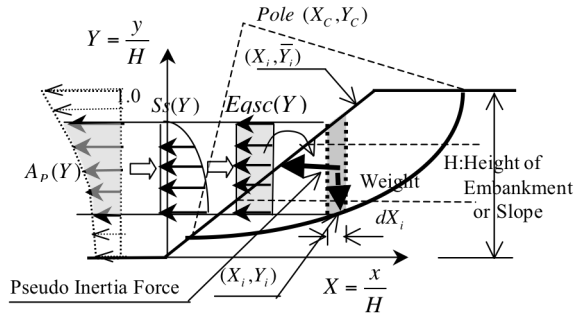


Figure.1 Acting force on the soil column on the slip surface

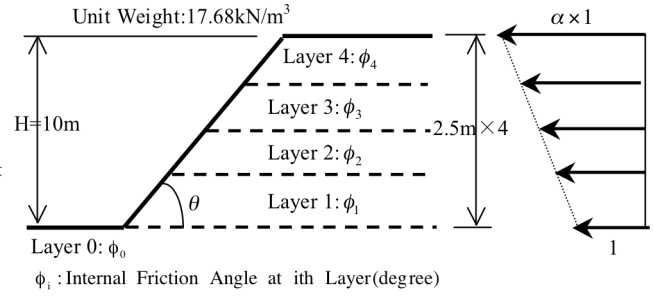


Figure.2 Analytical slope model

log spiral surface based on the variation principle. Furthermore, the critical slip surface is evaluated by considering the spatial distribution of the soil strength and the amplification of the seismic coefficient. And the permanent deformation of the sliding block on the critical slip surface is evaluated based on Newmark method.

DIFFERENCE OF FAILURE CHARACTERISTICS DEPEND ON THE MODELING FAILURE MECHANISM OF EMBANKMENT

The outline of the method to evaluate the compound log spiral slip surface and permanent deformation

The current method proposed by Ling et al. (e.g. H. I. Ling, D. Leshcinsky, 1995) to evaluate the permanent deformation of the slope during earthquake is developed to the method which is possible to consider the amplification of the earthquake ground motion in the slope and the compound log spiral slip surface modeled as the critical slip surface in the multi-layered ground. The proposed method also satisfies with the variation principle as well as the method by Ling et al. In general, the equilibrium equation is derived based on the sum of two kinds of moment in terms of the acted force to the sliding block on the critical slip surface in the slope to be equal to zero. One of the moment is the sliding moment due to the seismic force acting on the block according to the pole of slip surface. The other one is the resistant moment due to the strength acting on the slip surface to the block. Equation (1) represents the equilibrium. Hence, the sliding moment is expressed as the sum of the moment M_{DH} caused by the body weight of sliding block with the moment M_{DH} caused by the action of inertia force. The characteristics of the critical slip surface at each layer in the multilayered ground are able to be derived based on the Baker's solution obtained by the variation principle for a ground with a discontinuity of a soil strength. His solution is that the shape of critical slip surface in each layer is a log spiral and that the pole of the surface in each layer is common. Here, critical slip surface in each layer is expressed as shown in equation (2). In the equation, A_i represents a log spiral constant which is different at each layer and X_c, Y_c represent the location of a common pole of log spiral surface in each layer. The critical slip surface that the critical slip surface specified by the log spiral surface in each layer is named as the compound critical slip surface. β represents the anti-clockwise angle from the vertical direction to the direction between the pole and the point (X,Y) on the slip surface.

$$M = M_R - M_D = M_R - (M_{DV} + M_{DH}) = 0 \quad (1)$$

$$\left. \begin{aligned} X_j &= X_c + A_j \exp(-\beta \varphi_{m,j}) \sin \beta \\ Y_j &= Y_c + A_j \exp(-\beta \varphi_{m,j}) \cos \beta \end{aligned} \right\} \quad (2)$$

Next, the resistance moment is expressed by using the normalized strength constant of the cohesion $N_m(Y_i)$ at the depth of Y_i as shown in expression (3). Here, X_i, Y_i represent the normalized coordinates x, y of the slip surface with the height H of the slope. Moreover, \bar{Y}_i and Y'_i represents the normalized coordinates y of the slope surface and the inclination of the slip surface at the horizontal coordinate X_i . The moment M_{DH} is obtained in consideration of the amplification of the earthquake ground motion as shown in the following procedure. First of all, the response shear stress on the slip surface at an arbitrary depth generated by the amplification of the earthquake ground motion in the

Table 1 Comparison of yield seismic coefficients and residual settlement at the top of slope obtained by each method

	No Reduction		Reduction 1		Reduction 2		Reduction 3	
	Yield seismic Coefficient	Permanent Displacement /H	Yield seismic Coefficient	Permanent Displacement /H	Yield seismic Coefficient	Permanent Displacement /H	Yield seismic Coefficient	Permanent Displacement /H
Proposed method	0.2736	0.6815	0.2157	0.8022	0.2422	0.7859	0.2638	0.7088
			(0.79)	(1.18)	(0.89)	(1.15)	(0.96)	(1.04)
Circular slip method	0.2921	0.3240	0.2373	0.5263	0.2614	0.5054	0.2826	0.4041
			(0.81)	(1.62)	(0.89)	(1.55)	(0.97)	(1.25)

Note) The values in parentheses represents the ratio to the value in No Reduction.

embankment is obtained under the assumption that the distribution of the horizontal acceleration with a depth at a time is the same along the horizontal direction. Then acceleration distribution in the soil column on a small width of the slip surface is expressed as the distribution $A_p(Y_i)$ from either the slope surface or the top of the embankment to the slip surface as shown in Figure1. The response shear stress $\tau(Y_i)$ is obtained by the integration from the acceleration at the top \bar{Y}_i of the embankment to that at the slip surface as shown in equation (4) based on the assumption that the soil column is a horizontally layered. Next, the response shear force $T_s(Y_i)$ is calculated by multiplying the shear stress $\tau(Y_i)$ with the small width dx . By assuming the soil column to be rigid body, an equivalent seismic coefficient which acts on the soil column is calculated by the equation (5). $\bar{\rho}$ and $h(X_i)$ represent the average mass density and the height of the earth column. The sliding moment M_{DH} is obtained as shown in equation (6) by using inertia force calculated by acting the equivalent seismic coefficient on the soil column. Finally, the critical slip surface and the yield seismic coefficient are obtained as well as the current method based on the equilibrium equation of the obtained moments.

$$M_R = \sum_{i=1}^n N_m(Y_i) [(Y_i - Y_c) - (X_i - X_c)Y'] dX_i \quad (3)$$

$$\begin{aligned} \tau(Y_i) &= \int_{Y_i}^{\bar{Y}_i} \bar{\rho} \cdot A_p(Y_i) dY = \int_{Y_i}^{\bar{Y}_i} \bar{\rho} \cdot C_{SD} \cdot C_F(Y_i) dY \\ &= \bar{\rho} \cdot C_{SD} \int_{Y_i}^{\bar{Y}_i} C_F(Y_i) dY \end{aligned} \quad (4)$$

$$Eqsc(Y_i) = \frac{T_s(Y_i)}{\bar{\rho} \cdot h(X_i) dX_i \cdot g} \quad (5)$$

$$M_{DH} = \sum_{i=1}^n Eqsc(Y_i) (\bar{Y}_i - Y_i) \frac{(\bar{Y}_i + Y_i)}{2} dX_i \quad (6)$$

Comparison with the circular slip method

In order to evaluate the effect of the difference of the shape according to the critical slip surface on the slope failure mechanism, the characteristics of failure such as critical slip surface and yield seismic coefficient calculated by the proposed method is compared with those by a current circular slip method. The analytical slope model with the height 10m and the inclination angle 45 degrees is shown in Figure 2. As for the other soil constants, it was assumed that the unit weight is the value shown in Figure 2 and that the cohesion is 17.68kPa. Furthermore, the internal friction angle is considered as the parameter to evaluate the effect of the spatial inhomogeneity of the soil strength on the shape of the critical slip surface and the yield seismic coefficient. The fundamental value of the internal friction angle assumed to be 30 degrees. The material model is named as No Reduction. As the other material models, three cases are considered by changing the internal friction angle in two layers among four layers in the slope to be 25 degrees. The model for the reduced internal friction angle in the first and second layer above the base layer, the model for that in the second and third layer above the base layer and the model for that in the third and fourth layer above the base layer are named as Reduction 1, Reduction 2 and Reduction 3 respectively. The function which specifies the

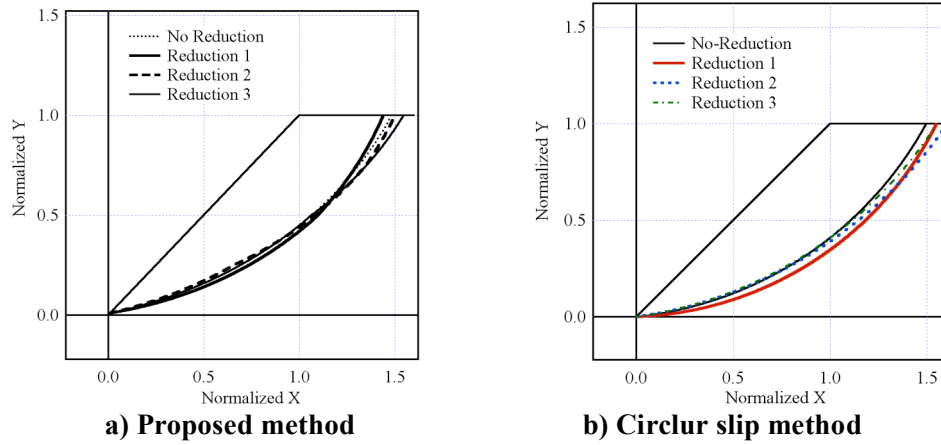


Figure.3 Comparison of critical slip surface obtained by proposed method with that obtained by circular slip method

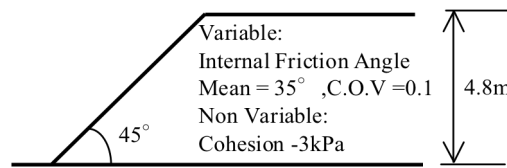


Figure.4 Analytical Model

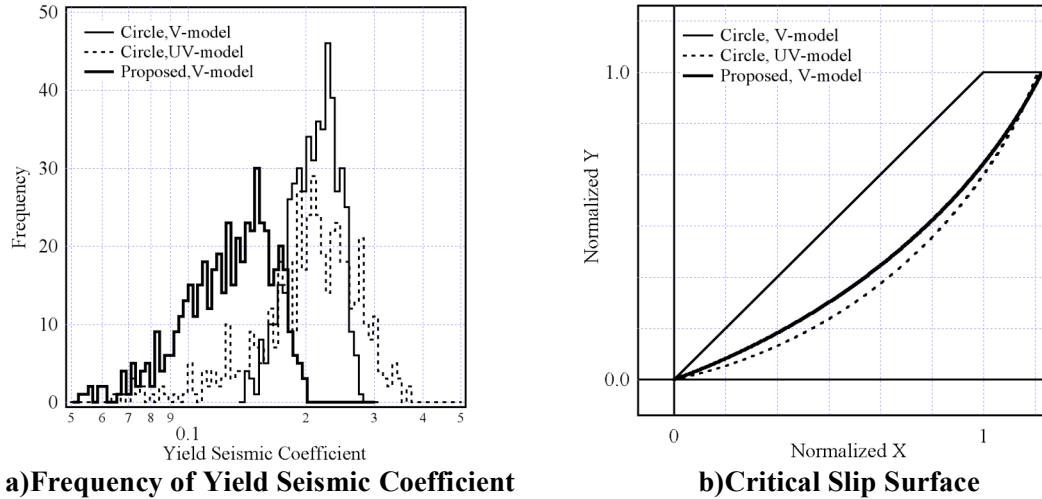
amplification of earthquake ground motion was assumed to be the simple linear amplified function. The magnification value at the top of embankment to the bottom is assumed to be 1.5. Furthermore, the input wave to calculate a permanent deformation was given at the bottom as the sinusoidal time history. The amplitude of the wave and the frequency was assumed to be 1.0 and 1.0 Hz respectively.

Table.1 shows the comparison of the yield seismic coefficient and the permanent deformation normalized by the slope height H obtained by the proposed method with those obtained by the circular slip method. The comparison of the critical slip surfaces for each material model obtained by both the method is shown in Figure3. The values in parentheses under the yield seismic coefficient and the permanent displacement in the table show the ratio of those values in case of each Reduction to the values in case of No Reduction. It is found that the spatial distribution of the soil strength influences the critical slip surface and the yield seismic coefficient remarkably though the reduction of the internal friction angle is small with only five degrees. In addition, the position of the critical slip surface obtained by the circular slip method using a single arc as the shape of the slip surface is deeper than the position of that obtained by the proposed method. The tendency is seemed to be remarkable in case of Reduction1. It is found that permanent displacement obtained by the proposed method is larger than that obtained by the circular slip method because the yield seismic coefficient obtained by the proposed method is smaller than that obtained by the circular slip method.

THE DIFFERENCE OF SLOPE FAILURE CHARACTERISTICS DEPEND ON MODELING SPATIAL INHOMOGENEOUS DISTRIBUTION OF SOIL STRENGTH

In order to evaluate the failure probability of slope, it is necessary to consider the uncertainty for modeling the material property adequately. Modeling inhomogeneous spatial distribution of soil strength is noticed as the characteristics of material property. The effect of the modeling on the failure mechanism is evaluated. The analytical slope model has the simple shape with the height 4.8m and the inclination angle with 45 degrees as shown in Figure 4. Sandy soil is taken as the material of soil.

The internal friction angle is used as the parameter for considering the spatial variation of soil strength. As for the other constant of the soil material, an cohesion and a unit weight were assumed as the deterministic values to be 3.0kPa and 17.68 kN/m² respectively. As the statistical characteristics of



a)Frequency of Yield Seismic Coefficient
b)Critical Slip Surface
Fig.5 Comparison of Frequency of yield seismic coefficients and critical slip surfaces obtained by each method

the inhomogeneous spatial distribution of the internal friction angle, the mean value and coefficient of variation (C.O.V.) were considered to be 35 degrees and 0.1 respectively. Moreover, the spatial distribution $F(y_i)$ is taken into account of the function with respect to the depth and is expressed as the sum of a mean value f_m which represents the average trend with the changeable component $f(y_i)$ as shown in equation (7). Model proposed by Yamazaki (e.g. Yamazaki, F. Shinozuka, S., 1988) is used to represent the changeable component because the spatial distribution can be easily calculated by using the Fourier transform. Here, the correlation length in a vertical direction is set to be 1.0m. The value and the coefficient of variation were set based on the current research (e.g. Nakamura, S., Sawada, S. and Matsumoto, T., submitted).

$$F(y_i) = f_m + f(y_i) \quad (7)$$

Next, as for the spatial inhomogeneity of the internal friction angle, the model whose variable is specified a single value in the embankment (the model is named UV-model) and the model whose variable is considered as the different values in all layers of the embankment (the model is named V-model) are used. The 500 cases for UV-model were generated using the normal random number under the assumption that a statistical characteristic according to the variation of the internal friction angle was specified as the normal distribution. As for the analytical model, the embankment was divided into eight layers. The depth of each layer is 0.6 m. The strength in each layer was specified at the center position. The 500 cases for V model were generated as well as UV-model by considering the variation of the strength with the depth shown in equation (7).

The frequency distribution of yield seismic coefficient obtained for V models by the proposed method is shown in Figure 5a). Furthermore, That obtained for both models by use of the circular slip method is also shown in Figure 5a) for the comparison with the results obtained by the proposed method. And the average critical slip surface obtained by the proposed method is shown in Figure 5b) as well as that obtained for two models by the circular slip method. The average critical slip surface was evaluated as the mean value of the all depths at the same horizontal position for the calculated 500 critical slip surfaces. The shape of the average critical slip surface shown in Figure 5b) is almost similar with that obtain for the strength model with mean internal friction angle. And the distribution of the yield seismic coefficient by the proposal method is located in a smaller seismic coefficient in comparison of that obtained by the circular slip method as well as the previous chapter. Furthermore, based on the comparison of the frequency distribution of the yield seismic coefficient obtained for the two models by the circular slip method, the variation of the yield seismic coefficient by V-model is found that the range between the larger bound of yield seismic coefficient and the smaller bound of that is smaller than the range for UV-model.

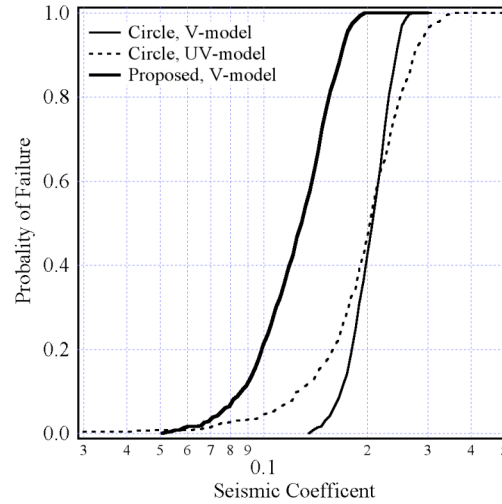


Figure.6 Fragility curve of slop with respect to slop failur occurrence

EVALUATION OF FRAGILITY CURVE OF SLOPE FAILURE

The relation between the probability generating a slope failure and the seismic coefficient acting to the slope is named as a fragility curve according to the slope failure. In general, the slope failure is defined as the state that the safety factor specified by the ratio between the sliding moment M_D and the resistant moment M_R becomes less than 1.0. The probability is possible to be obtained by the Monte Carlo method etc. However, a huge calculation is needed to evaluate the probability by use of the Monte Carlo method because the slip safety factors for the all ground models considering the variation of the material property shown in the previous chapter have to be calculated. Ohtori et al. [e.g. Ohtori, Y., 2003] have proposed the method to evaluate a fragility curve of the earth structure based on the intensity of earthquake ground motion when the safety factor becomes 1.0. Here, the intensity of earthquake ground motion when the safety factor becomes 1.0 is just the same with yield seismic coefficient for generating slope failure of the embankment. Slope failure probability $F(C_s)$ against the acted seismic coefficient C_s is possible to obtain from equation (8) according to the probability density function of the yield seismic coefficient shown in Figure.5 a). U represents the step function here.

$$F(C_s) = \frac{1}{n} \sum_{j=1}^n U[C_s - f(C_{ys,j})] \quad (8)$$

The Fragility curve calculated by using equation (8) based on Figure.5 a) is shown in Figure.6. The acted seismic coefficient that the slope failure probability obtained by the proposed method becomes about 100% is about 0.2 that is smaller than the value obtained by the circular slip method. In addition, as for the fragility curve obtained by the circular slip method, the acted seismic coefficient that the failure probability for the case of UV-model becomes about 100% is larger than the value obtained for the case of V-model. Furthermore, the seismic coefficient caused the slope failure in the case of UV-model is smaller than that in the case of V-model. As for the failure risk of the embankment and the slope, it is supposed that the risk for UV-model which has the wide range between the seismic coefficient with 100% of the slope failure probability and the seismic coefficient caused the slope failure in comparison of the range for V model is evaluated to be lager than that for V-model because the seismic coefficients that the slope failure probability becomes 0.5 are the same with the values for the both model.

CONCLUDING REMARKS

The objective of this report is to make a clear the both the effects of the uncertainty of soil strength and the modeling slope failure on the slope failure probability. Two methods are used to evaluate the

failure characteristics of slope. One is the proposed method to evaluate the critical slip surface in the multi-layered ground by use of the compound log spiral based on the variation principle. The other one is the circular slip method among the current slope stability analysis methods. In addition, the simple method to evaluate Fragility curve according to slope failure of the earth structure was shown. The yield seismic coefficient and a critical slip surface that was specified for the safety factor to be 1.0 are noticed as the failure mechanism of the earth structure in this report. The following results are obtained.

(1) The acted seismic coefficient that the slope failure probability obtained by the proposed method becomes about 100% is about 0.2 that is smaller than the value obtained by the circular slip method.

(2) It is supposed that a risk of slope failure slope for the model considering the spatial distribution of the soil strength with depth in the embankment is larger than that for the model considering the variation of the soil strength which is assumed to be a single value in the embankment.

Here, the failure of earth structure is specified as the state that the seismic coefficient acts on the sliding block more than the yield seismic coefficient without considering the deformation of sliding block caused by the slip as the limit state. However, it is seem to have to evaluate the risk considering the failure specified by the degree of the deformation of the slope proposed by Yoshida et al. (e.g. Yoshida, I., 2005). This is seemed to be a future issue.

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REFERENCES

- International Organization for Standardization. ISO 2394: General Principle on Reliability for Structure, <http://www.iso.org/>
- International Organization for Standardization, ISO 23469:2005 Bases for design of structures – Seismic action for designing geotechnical works, <http://www.iso.org/>
- Hoe I. Ling and Dov Leshchinsky, Seismic performance of simple slope, Soils and Foundations, Vol.35, No.2, pp.85-94, 1995
- Nakamura, S., Akiyama, M., Sawada, S., Annaka T. and Nishioka T., Study on the Evaluation of Fragility Characteristics associated with Damage Degree of RC Bridge System and Its Application, Journal of Japan Association of Earthquake Engineering, Vol.6, No.2, p.p.17-34, 2006 (in Japanese)
- Nakamura, S., Sawada, S. and Yoshida, N., Proposal of the Method to Evaluate Permanent deformation for the multi-layered slope and its Application Journal of Geotechnical Engineering , Japan Society of Civil Engineer, (Submitted in Japanese)
- Nakamura, S., Sawada, S. and Matsumoto, T., Comparison of Non-linear Seismic Response for One and Two Dimensional Considering the Spatial Distribution due to Inhomogeneity of soil Properties, Journal of Geotechnical Engineering , Japan Society of Civil Engineer, (Submitted in Japanese)
- Ohtori, Y., Yoshida, I, Ishikawa, H. and Takeda T., Estimation of Annual Failure Probability of Soil Structure by Limit Seismic Intensity Parameter, JCOSSAR, pp.695-700, 2003(in Japanese)
- Yamazaki, F. Shinozuka, S. , Digital Generation of Non-Gaussian Stochastic Field, ASCE, Engineering Mechanics, Vol.114, pp.1183-1197, 1988
- Yoshida, I., Arakawa, T., Kitazume, T. and Ohotsu, H., Study on seismic probabilistic stability analysis of slope, Journal of Geotechnical Engineering , Japan Society of Civil Engineer, No.785/III-70, pp.27-37, 2005(in Japanese)