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IDENTIFICATION PROCEDURE OF SHALLOW WEAK LAYER IN WEATHERED SLOPE

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It is very important to investigate the strength of surface layers in order to mitigate the risk of shallow slope failures or debris flows. A synthesized approach to the geophysical survey method and sounding tests is developed in the present study. The surface wave method (SWM) is selected as the geophysical survey method, while dynamic cone penetration (DCP) is selected as the sounding test method. From SWM and DCP, the shear velocity, V_s, and the DCP blow count, N_d, respectively, as well as two kinds of results, need to be transformed to the standard penetration test blow count, N_{SPT}, in order to synthesize the two methods. The indicator simulation (IS) method, which is a kind of geostatistical method, is employed to simulate the random field of N values by synthesizing two types of results. The proposed procedure is applied to evaluate the strength of the weak surface layer of a cut slope composed of weathered granite. The distribution of the weak layer could be evaluated by the spatial distribution of the probability of N <2.

Keywords: slope stability, dynamic cone penetration, surface wave method, transformation error.

1 Introduction

Slope failures due to heavy rain are frequent events that occur every year. In particular, debris flows cause severe damage. Although countermeasures are required to mitigate disasters, the areas of high risk are very large and sufficient countermeasures are impossible. It is important to identify the dangerous locations of the slopes at times of heavy rain and to evaluate the risks in order to prioritize the locations for the countermeasures. In the present research, a geophysical survey and the sounding techniques are applied for this task, and the distribution of strength in the surface layer of a slope is visualized. High-density sampling is required to identify the spatial distribution of strength, and sounding technics are convenient. Generally, the strength parameters are assumed based on standard penetration tests (SPTs) with the use of empirical relationships. In this research, dynamic cone penetration (DCP) tests (JGS, 2015), which are simpler than SPTs and applicable to slope areas and narrow spaces, are employed.

As the geophysical method, the surface wave method (SWM) (Hayashi, 2004) is used in this research. From the SWM and DCPs, the shear velocity, V_s, and the DCP blow count, N_d, respectively, as well as two kinds of results, need to be transformed to the standard penetration test blow count, N_{SPT}, in order to be synthesized. The indicator simulation (IS) method (Deutsch and Journel, 1992), a kind of geostatistical method, is employed to simulate the random field of

N values. Finally, the proposed procedure is applied to an actual cut slope area composed of weathered granite soil, and its applicability for practical use is verified.

2 Statistical model of *N* value

2.1 *Modeling method*

A representative variable for the soil properties, s, is defined by Equation (1) as a function of location $\mathbf{X}=(x, y, z)$. Variable s is assumed to express the sum of mean value m and random variable U, which is a normal random variable in this study.

$$s(\mathbf{X}) = m(\mathbf{X}) + U(\mathbf{X}) \tag{1}$$

The random variable function, $s(\mathbf{X})$, is discretized spatially into random vector $\mathbf{s}^t=(s_1,s_2,...,s_M)$, in which s_k is a point estimation value at location $\mathbf{X}=(x_k, y_k, z_k)$. The soil parameters, which are obtained from the tests, are defined here as $\mathbf{S}^t=(S_1,S_2,..., S_M)$. The symbol M signifies the number of test points. Vector $\mathbf{S}$ is considered to be the realization of random vector $\mathbf{s}^t=(s_1,s_2,...,s_M)$. If variables s_1, s_2,...,s_M constitute the M - variate normal distribution, the probability density function of s can then be given by the following equation:

$$f_S(\mathbf{s}) = (2\pi)^{-\frac{M}{2}} |\mathbf{C}|^{-\frac{1}{2}} \exp\left\{-\frac{1}{2}(\mathbf{s}-\mathbf{m})^t \mathbf{C}^{-1}(\mathbf{s}-\mathbf{m})\right\} \tag{2}$$

in which $\mathbf{m}^t=(m_1,m_2,...,m_M)$ is the mean vector of random function $\mathbf{s}^t=(s_1,s_2,...,s_M)$; it is assumed to be the following regression function. In this research, a 2-D statistical model is considered, namely, horizontal coordinate x, and vertical coordinate z. The element of the mean vector is described as

$$m_k = a_0 + a_1 x_k + a_2 z_k + a_3 x_k^2 + a_4 z_k^2 + a_5 x_k z_k \tag{3}$$

in which (x_k, z_k) means the coordinate corresponding to the position of parameter s_k, while a_0, a_1, a_2, a_3, a_4, and a_5 are the regression coefficients. The y-direction is modelled as a linear function, since the information for the transverse direction of the embankment axis is insufficient.
$\mathbf{C}$ is the $M\times M$ covariance matrix, which is selected from the following four types in this study:

$$\begin{aligned}
&\mathbf{C} = \left[C_{ij}\right] = \\
&\sigma^2 \exp\left(-\left|x_i - x_j\right|/l_x - \left|z_i - z_j\right|/l_z\right) \quad \text{(a)} \\
&\sigma^2 \exp\left\{-\left(x_i - x_j\right)^2/l_x^2 - \left(z_i - z_j\right)^2/l_z^2\right\} \quad \text{(b)} \\
&\sigma^2 \exp\left\{-\sqrt{\left(x_i - x_j\right)^2/l_x^2 + \left(z_i - z_j\right)^2/l_z^2}\right\} \quad \text{(c)} \\
&N_e \sigma^2 \exp\left(-\left|x_i - x_j\right|/l_x - \left|z_i - z_j\right|/l_z\right) \quad \text{(d)} \\
&i, j = 1,2,\cdots,M
\end{aligned}
\qquad
\begin{cases} N_e = 1 & (i=j) \\ N_e \le 1 & (i \ne j) \end{cases} \tag{4}$$

in which the symbol $[C_{ij}]$ signifies an i-j component of the covariance matrix, σ is the standard deviation, and l_x, and l_z are the correlation lengths for the x and z directions, respectively. Parameter N_e is related to the nugget effect. Akaike's Information Criterion, AIC (Akaike, 1974), is defined by Equation (11) considering the logarithmic likelihood.

$$\mathrm{AIC} = -2\times\max\left\{\ln f_S(\mathbf{S})\right\} + 2L = M\ln 2\pi + \min\left\{\ln|\mathbf{C}| + (\mathbf{S}-\mathbf{m})^t\,\mathbf{C}^{-1}(\mathbf{S}-\mathbf{m})\right\} + 2L \quad (5)$$

in which L is the number of unknown parameters included in Equation (2). By minimizing AIC (MAIC), the regression coefficients of the mean function, the number of regression coefficients, the standard deviation, σ, a type of covariance function, the nugget effect parameter, and the correlation lengths are determined. In other words, the determined parameters and the selected covariance function correspond to the minimum AIC.

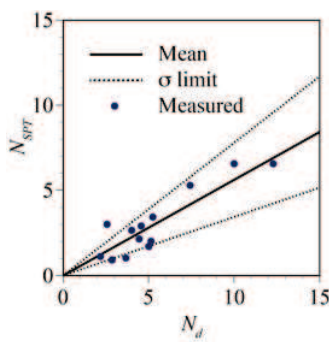


Figure. 1 Relationship between SPT N values and DCP blow counts.

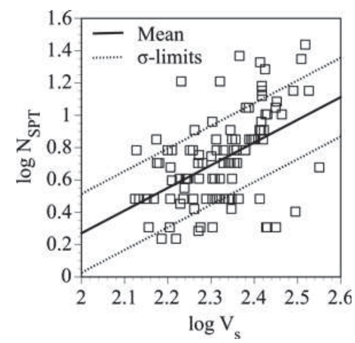


Figure 2. Relationship between STP N value and velocity of shear wave.

2.2 *Relationships of SPT with DCP and SWM*

Figure 1 shows the relationship between the results of SPT and DCP for a river dike. Equation (6) presents the regression line between DCP blow counts, N_d and the SPT N value.

$$N_{SPT} = 0.562N_d \quad (6) \qquad N_{SPT} = 0.562N_d\left(1+0.388\varepsilon_1\right) \quad (7)$$

The coefficient for the variation in the regression line is determined as 0.388. The determined σ-limits are also shown in Figure 1 by the broken lines. Considering the variability of the relationship, the SPT N value is derived by Equation (7).
in which ε_1 is the $N(0,1)$ type of reduced normal variable.

The surface waves are closely correlated to the shear waves V_S, which in turn have a strong correlation to the elastic modulus and the N values. The relationship between log N_{SPT} and log V_S is shown with σ limits in Figure 2. The regression equation is described by

$$\log N_{SPT} = 1.403\log V_S - 2.537 \quad (8) \qquad N_{SPT} = V_S^{1.403}\times 10^{(\sigma_2\varepsilon_2 - 2.537)} \quad (9)$$

Adding the error term, the SPT N values are defined by Equation (9).
where σ_2 is the standard deviation depicted in Figure 2 and ε_2 is the $N(0,1)$ type of reduced normal variable. The value of σ_2 is 0.244 in Figure 2.

3 Indicator simulation method

In this research, the accurate spatial distribution of the STP N value is estimated based on two kinds of data. One is the sounding test and the other is the surface wave method, a type of elastic wave survey method. These two sets of results are conveniently synthesized with the indicator simulation method, a geostatistical method, which can simultaneously treat hard data (primary data) and soft data (secondary data). Herein, the DCP results are the hard data, while the surface wave results are the soft data.

An indicator value, i, for a parameter, R is expressed by

$$i(\mathbf{u};r_k)=\begin{cases}1, & (R(\mathbf{u})\le r_k)\\ 0, & (R(\mathbf{u})>r_k)\end{cases}\qquad k=1,\ldots,K \tag{10}$$

in which vector $\mathbf{u}=(x,z)$ means the positions where the data were measured and parameter R is given as a function of $\mathbf{u}$. The values of r_k (k=1, 2, ..., K) are K-specific values of R and the threshold value for binary parameter i. The posterior probability distribution function of variable R, $F(\mathbf{u},r_k|(n+n'))$, updated by the soft data, is defined in the following:

$$F\left(\mathbf{u};r_k\middle|(n+n')\right)=\mathrm{Prob}\left\{R(\mathbf{u})\le r_k\middle|(n+n')\right\}=\lambda_0F(r_k)+\sum_{\alpha=1}^{n}\lambda_\alpha(\mathbf{u};r_k)i(\mathbf{u}_\alpha;r_k)+\sum_{\alpha'=1}^{n'}\nu_{\alpha'}(\mathbf{u};r_k)w(\mathbf{u}_{\alpha'};r_k)$$

$$\lambda_0=1-\sum_{\alpha=1}^{n}\lambda_\alpha(\mathbf{u};r_k)-\sum_{\alpha'=1}^{n'}\nu_{\alpha'}(\mathbf{u};r_k) \tag{11}$$

where $F(r_k)$ is the prior distribution function derived from the DCP data, and $i(\mathbf{u}_\alpha,r_k)$ means the binary value of the hard data at point $\mathbf{u}_\alpha$. For threshold value r_k, $w(\mathbf{u}_\alpha,r_k)$ is the probability distribution of the soft data, and n and n' are the numbers of hard and soft data, respectively. Parameters λ and ν are the weighting parameters corresponding to arbitrary point $\mathbf{u}_m$ for the interpolation; they are determined by solving Equation (12).

$$\begin{aligned}&\sum_{\beta=1}^{n}\lambda_\beta(\mathbf{u}_m)C_{\beta\alpha}+\sum_{\beta'=1}^{n'}\nu_{\beta'}(\mathbf{u}_m)C_{\beta'\alpha}=C_{m\alpha},\quad \alpha=1,....,n\\ &\sum_{\beta=1}^{n}\lambda_\beta(\mathbf{u}_m)C_{\beta\alpha'}+\sum_{\beta'=1}^{n'}\nu_{\beta'}(\mathbf{u}_m)C_{\beta'\alpha'}=C_{m\alpha'},\quad \alpha'=1,....,n'\end{aligned} \tag{12}$$

in which $C_{\beta\alpha}$, $C_{\beta'\alpha'}$, $C_{m\alpha}$, and $C_{m\alpha'}$ are the covariance matrices between two points, namely, ($\mathbf{u}_\beta$, $\mathbf{u}_\alpha$), ($\mathbf{u}_{\beta'}$, $\mathbf{u}_{\alpha'}$), ($\mathbf{u}_m$, $\mathbf{u}_\alpha$), and ($\mathbf{u}_m$, $\mathbf{u}_{\alpha'}$), respectively. The soft data, w, are derived from the following process based on the indicator kriging (Deutsch and Journel, 1992). Through the equation, α and β stand for the hard data points, while α' and β' stand for the soft data points.

The procedure for the actual simulation is summarized as follows:

1) In Equation (9), random numbers are assigned to variable ε_2 for the N_{SPT} at points $\mathbf{u}_{\alpha'}$ (α'=1,2, ..., n'). The probability distribution of w is determined by the iteration of the Monte Carlo method at each point as the soft data herein. The number of iterations is 1,000 in this study.

2) The prior distribution, $F(r_k)$, from Equation (7), is determined with a fixed value for ε_1.

3) Parameters $\lambda_\beta(\mathbf{u})$, ($\beta$= 1, 2,..., n) and $\nu_{\beta'}(\mathbf{u})$, (β'= 1, 2,..., n') for the position $\mathbf{u}=\mathbf{u}_m$, (m: the arbitrary point number) are determined by solving Equation (12).

4) Based on the posterior distribution, $F(\mathbf{u},r_k|(n+n'))$, the random numbers are created from Equation (13).

$$r^{(l)}(\mathbf{u})=F^{-1}\left(\mathbf{u};p^{(l)}\middle|(n+n')\right) \tag{13}$$

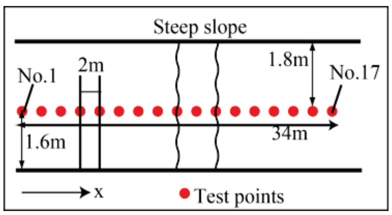
where p is the uniform random number from 0 to 1.0, and l is the iteration number for the Monte Carlo method. Finally, a random number, $r^{(l)}$, is assigned to the N_{SPT}

5) Steps 2), 3), and 4) are repeated with random number, ε_1 as the Monte Carlo method.

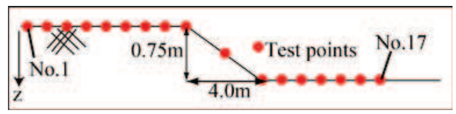
4 Case study

4.1 *Description of sample site*

The investigation was conducted in a cut slope whose material is decomposed granite. The plane view and the cross section are presented in Figures 3(a) and (b), respectively. There is a steep slope in the center part of the site. As seen in the figures, the locations of the test points for SWM are indicated and the DCP tests were conducted at points x = 2, 7, 12, 17, 22, 27, and 32 m. The testing interval was 2 m.



(a) Plane view.



(b) Cross section.

Figure 3. Profile of investigation site and test points of SWM.

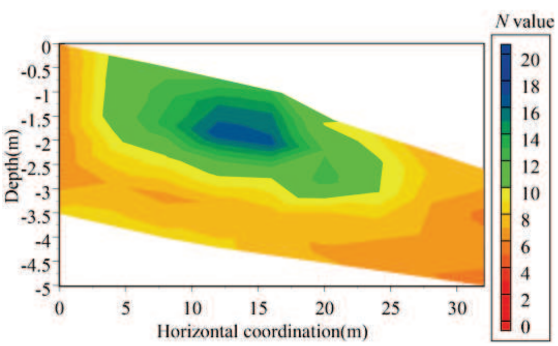


Figure 4. Distribution of N from SWM.

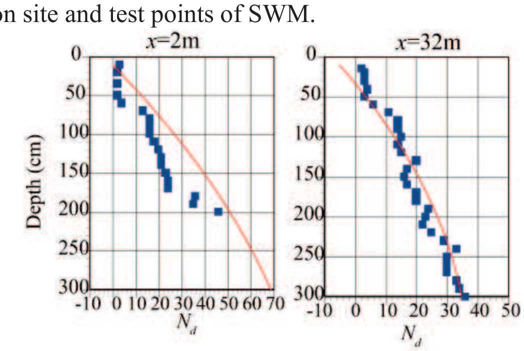


Figure 5. Distributions of DCP blow counts. (Marks: measured values. Solid lines: mean)

4.2 *Results of site investigation*

Figure 4 depicts the N value distribution transformed from shear wave velocity V_s, through Equation (8), as a result of the SWM results. There is a hard area at the steep center part. Figure 5 presents the N_d values of DCP at x =2 and 32 m as the representative cases.
From the N_d distribution, the mean and covariance functions are identified as follows:

$$m_{N_d,k} = -15.768 + 2.848x_k + 35.744z_k - 0.818x_k^2 - 0.161z_k^2 - 0.574x_k z_k \quad (14)$$

$$C = [C_{ij}] = 10.09^2 \exp(-|x_i - x_j|/3.66 - |z_i - z_j|/0.71) \quad (15)$$

The mean function (Equation (14)) is depicted in Figure 5 as solid lines. In the covariance function (Equation (15)), the correlation lengths are given as l_x=3.66 m and l_z=0.71 m, which are considered to be reasonable values compared to those in the previous work (Phoon and Kulhawy, 1999), since the horizontal correlation length is roughly five times longer than the vertical one.

4.3 *Simulation results*

Figure 6 presents the IS results from 300 iterations. Figure 6(a) gives the mean of the N value and shows that the thickness of the weak layer is larger on the left and right sides. Figure 6(b) gives the standard deviation and shows that the variability of the N value is small at the surface layer. Figure 6(c) presents the probability that $N < 2$, namely, the possibility of a very weak area. Although the value of N=2 is not an absolute threshold, the value can be a sign of the existence of a very soft layer. According to the figure, the possibility is very high on the left and right sides of the slope. Figure 7 depicts the prior distribution, the probability distribution of soft data, and the posterior distribution of N_{SPT} at x = 4.0 m and z=1.5m. The variability of posterior is greatly reduced, since the two kinds of information are synthesized.

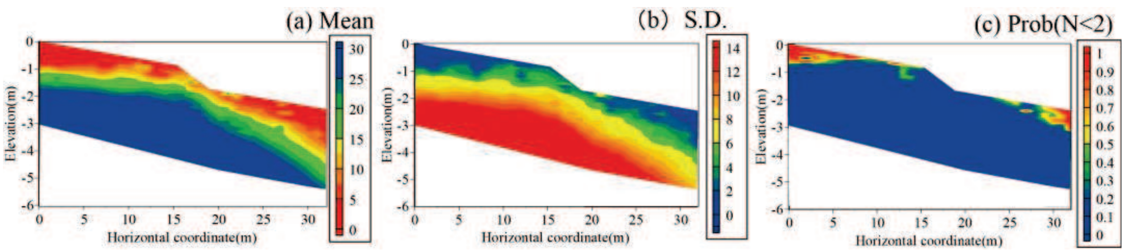


Figure 6. Simulated N_{SPT} values by IS.

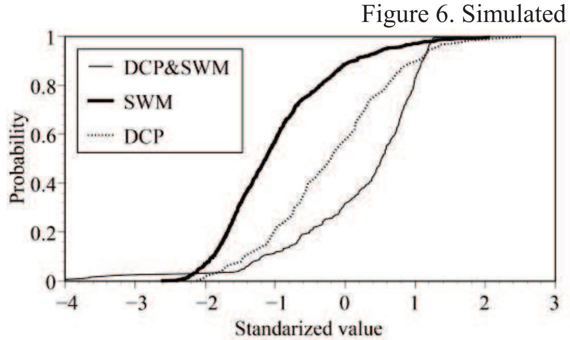


Figure 7. Probability distributions. (x =4.0m , z=1.5m)

DCP: prior distribution of N_{SPT} from N_d.
SWM: distribution of soft data for N_{SPT} based on V_s.
DCP&SWM: posterior distribution of N_{SPT}.
All parameters are standardized as:

$$s_k = \frac{N_{SPT,k} - 0.562 m_{N_d,k}}{0.562 \sigma_{N_d}}$$

$$\sigma_{N_d} = 10.09$$

5 Conclusions

(1) The transformation equations and the error terms from N_d and V_s to N_{STP} have been derived.
(2) A spatial distribution model for the DCP results, N_d, has been successfully identified at an actual slope site.
(3) The synthesized approach for the surface wave method (SWM) and dynamic cone penetration tests (DCP) has been conducted with an indicator simulation, and the weak surface area of the investigated cut slope has been identified.

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References

Akaike, H., A new look at the statistical model identification, *IEEE Trans. on Automatic Control*, AC-19(6), 716-723,1974.
Deutsch, C. V. and Journel, A. G., *Geostatistical Software Library and User's Guide*, Oxford University Press,1992.

Hayashi, K., "Estimation of near-surface shear wave velocity model using surface -waves", *Journal of JSNDI*, 53(5), 254-259, 2004 (in Japanese).

Japanese Geotechnical Society, Japanese Geotechnical Society Standards for geotechnical and geoenvironmental investigation methods –, Maruzen, 2015.

Phoon, K-K. and Kulhawy F.H.. Evaluation of geotechnical property variability, *Can. Geotech. J.*, 36, 625-639. 1999.