Diagnosis of earth-fills and reliability-based design

Diagnostic de remblais de terre et conception basée sur la fiabilité

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ABSTRACT: This research deals with the maintenance strategy of geotechnical structures such as earth-fill dams and river embankments. To determine the soil parameters, the standard penetration test (SPT) *N*-values are frequently used. Firstly, a statistical model for the *N*-values is determined from sounding test results. In this research, Swedish Weight Sounding (SWS) tests, simpler than SPT, are employed. Secondly, an indicator simulation is conducted to interpolate the spatial distribution of the *N*-values, and the results are utilized to find degraded areas inside the embankments and to maintain the embankments. Based on the statistical model for the *N*-values, the shear strength parameter is derived through the empirical relationships, and then a reliability analysis of the embankments is conducted considering the variability of the internal friction angle. Finally, the effect of improving the embankments is discussed, comparing the calculated risks of the original state with the improved and restored state.

RÉSUMÉ : Cette recherche porte sur la stratégie de maintenance des structures géotechniques comme les barrages en remblais de terre et les digues fluviales. Les valeurs *N* du test de pénétration standard (SPT) sont fréquemment utilisées pour déterminer les paramètres du sol. Premièrement, le modèle statistique de *N* valeurs est déterminé à partir des résultats des essais de sondage. Dans cette recherche, on utilise le sondage par poids suédois (SWS), plus simple que le SPT. Deuxièmement, une simulation indicatrice est effectuée pour interpoler la distribution spatiale de *N* valeurs, et les résultats sont utilisés pour trouver les zones dégradées à l'intérieur des remblais, pour l'entretien des remblais. Basés sur le modèle statistique de *N* valeurs, les paramètres de résistance au cisaillement sont déduits des relations empiriques, ensuite, l'analyse de fiabilité des remblais est effectuée en tenant compte de la variabilité de l'angle de frottement interne. Finalement, l'effet de l'amélioration du remblai est discuté, en comparant l'analyse de risque calculée à partir de l'état initial et de l'état des remblais améliorés et restaurés.

KEYWORDS: earth-fill dam reliability-based design, indicator simulation, statistical model of *N*-value

1 INTRODUCTION

There are many earth-fill dams for farm ponds in Japan. Some of them are getting old and decrepit, and therefore, have weakened. Making a diagnosis of the earth-fills is important for increasing their lifetime, and an investigation of the strength inside the embankments is required for this task. In the present research, firstly, the spatial distribution of the strength parameters of decrepit earth-fills is discussed, and an identification method for the distribution is proposed. Although the strength of earth-fills is generally predicted from the standard penetration test (SPT) *N*-values, Swedish Weight Sounding (SWS) tests are employed in this research as a simpler method of obtaining the spatial distribution of the *N*-values. SWS tests are advantageous in that they make short interval exams possible, because of their simplicity.

To mitigate disasters, improvement works are conducted on the most decrepit earth-fill dams. Since there is a recent demand for low-cost improvements, the development of a design method for optimum improvement works at a low cost is the final objective of this research. A reliability-based design method is introduced here in response to this demand.

Generally, the identification of the spatial correlation of soil parameters is difficult, since the usual sampling intervals are greater than the spatial correlation. Therefore, sounding tests are convenient for determining the correlation lengths. Tang (1979) determined the spatial correlation of a ground by cone penetration tests (CPT). Cafaro and Cherubini (1990) also evaluated the spatial correlation with CPT results. Uzielli, et al. (2005) considered several types of correlation functions for CPT results. Firstly, statistical models for the *N*-values are determined from the SWS test results. Secondly, the relationship between the SPT and the SWS *N*-values is modeled, including the transformation error term. The *N*-value distributions derived from SWS are spatially interpolated with the indicator simulation (Journel and Huijbregts 1978), which is one of the geostatistical methods. The simulated spatial distribution of the *N*-values can be used for the health monitoring of the inside of an embankment. To evaluate the risk to earth-fill dams, due to the earthquakes, the circular slip surface (CSS) method is used as the stability analysis method along with the soil-water coupling finite element method. The finite element method is used to estimate the normal and the shear stress values on the slip surfaces. In this study, the Monte Carlo method (MCM) is combined with the CSS method to obtain the probability of failure. The procedure for the CSS method, combined with the MCM, has also been conducted by Shinoda, *et al.* (2006) and Yoshida, *et al.* (2005).

The strength parameter, namely, internal friction angle ϕ, derived from SWS tests, is considered to be the probabilistic variable in this research. Additionally, two transformation error terms, namely, the error terms from the SWS N-value to the SPT *N*-value, and from the *N*-value to the internal friction angle, are introduced to the MCM. Finally, the risk to an earth-fill dam is calculated from the costs that would be incurred due to embankment failure and probability failure. In this study, the effect of improving an embankment is evaluated as a reduction in risk between the original and the improved states.

2 INSITU TEST RESULTS

Although high-density sampling is required in order to evaluate the spatial distribution of soil parameters, the amount of data is not sufficient in the general sampling plans. In such cases, sounding is a convenient way to identify the spatial distribution structure of soil parameters. In this research, an embankment at Site H is analyzed, for which SWS tests were conducted at 9 points, at 5-m intervals, along the embankment axis, as shown in Figure 1. The soil profile of the embankment is categorized as intermediate soil.

Generally, the strength parameters are assumed based on standard penetration tests (SPT) with the use of empirical relationships. In this research, Swedish weight sounding tests, which are simpler than SPT, are employed instead of SPT. Inada (1960) derived the relationship between the results of SPT and SWS. Equation (1) shows the relationship for sandy grounds, and the relationship is shown in Figure 2.

$$N_{SWS} = 0.67 N_{SW} + 0.002 W_{SW} \tag{1}$$

in which NSWS is the N-value derived from SWS, NSW is the number of half rations and WSW is the total weight of the loads. Based on this data, the variability of the relationship is evaluated in this study, and the coefficient of variation is determined as 0.354. The determined σ-limits are also shown in Figure 2 with broken lines. Considering the variability of the relationship, the SPT N-values are derived by

$$N_{SPT} = (1 + 0.354\varepsilon_r) N_{SWS} \tag{2}$$

in which ε_r is an $N(0,1)$ random variable.

3 STATISTICAL MODEL OF *N*-VALUES

3.1 *Determination method*

A representative variable for the soil properties, s is defined by Equation (3) equation as a function of the location $\mathbf{X}=(x, y, z)$. Variable s is assumed to be expressed as the sum of the mean value m and the random variable U, which is a $N(0,1)$ type normal random variable in this study.

$$s(\mathbf{X}) = m(\mathbf{X}) + U(\mathbf{X}) \tag{3}$$

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

$$f_S(\mathbf{s}) = (2\pi)^{-M/2} |\mathbf{C}|^{-1/2} \exp\left\{-\frac{1}{2}(\mathbf{s}-\mathbf{m})^t \mathbf{C}^{-1}(\mathbf{s}-\mathbf{m})\right\} \tag{4}$$

in which $\mathbf{m}=(m_1,m_2,...,m_M)$ is the mean vector of random function $\mathbf{s}=(s_1,s_2,...,s_M)$ and is assumed to be the following regression function. In this research, a 2-D statistical model is considered, namely, the horizontal coordinate x, which is parallel to the embankment axis, and the vertical coordinate z are introduced here, while the other horizontal coordinate y, which is perpendicular to the embankment axis, is disregarded.

$$\mu_k = a_0 + a_1 x_k + a_2 z_k + a_3 x_k^2 + a_4 z_k^2 + a_5 x_k z_k \tag{5}$$

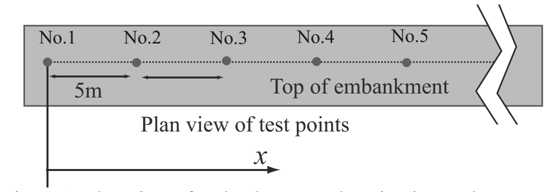


Figure 1. Plan view of embankment and testing interval.

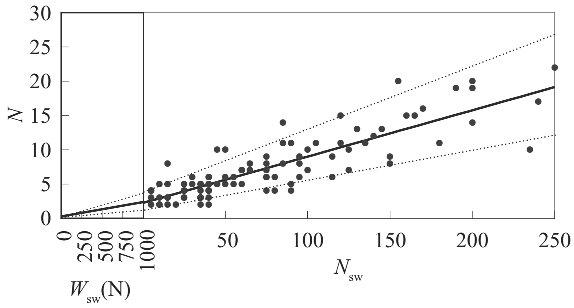


Figure 2. Relationship between SWS results and SPT N-values.

in which (x_k, z_k) means the coordinate corresponding to the position of the parameter s_k, and a_0, a_1, a_2, a_3, a_4, and a_5 are the regression coefficients.

$\mathbf{C}$ is the $M\times M$ covariance matrix, which is selected from the following four types in this study.

$$\begin{aligned}
\boldsymbol{C} &= [C_{ij}] = \\
&\sigma^2 \exp\left(-|x_i - x_j|/l_x - |z_i - z_j|/l_z\right) && \text{(a)} \\
&\sigma^2 \exp\left\{-(x_i - x_j)^2/l_x^2 - (z_i - z_j)^2/l_z^2\right\} && \text{(b)} \\
&\sigma^2 \exp\left\{-\sqrt{(x_i - x_j)^2/l_x^2 + (z_i - z_j)^2/l_z^2}\right\} && \text{(c)} \\
&N_e \sigma^2 \exp\left(-|x_i - x_j|/l_x - |z_i - z_j|/l_z\right) && \text{(d)} \\
&\begin{cases} N_e = 1 & (i = j) \\ N_e \le 1 & (i \ne j) \end{cases} && i, j = 1, 2, \cdots, M
\end{aligned} \tag{6}$$

in which the symbol $[C_{ij}]$ signifies a i-j component of the covariance matrix, σ is the standard deviation, and l_x and l_z are the correlation lengths for x and z directions, respectively. Parameter N_e is the nugget effect. The Akaike's Information Criterion, AIC (Akaike 1974) is defined by Equation (7), considering the logarithmic likelihood.

$$\begin{aligned}
\text{AIC} &= -2 \cdot \max\{\ln f_S(\mathbf{S})\} + 2L \\
&= M \ln 2\pi + \min\left\{\ln|\mathbf{C}| + (\mathbf{S}-\mathbf{m})^t \mathbf{C}^{-1}(\mathbf{S}-\mathbf{m})\right\} + 2L
\end{aligned} \tag{7}$$

in which L is the number of unknown parameters included in Equation (4). By minimizing AIC (MAIC), the regression coefficients of the mean function, the number of regression coefficients, the standard deviation, σ, a type of the covariance function, the nugget effect parameter, and the correlation lengths are determined.

3.2 *Determination of statistical model of SWS N-values*

The mean function and the covariance function of the SWS *N*-values, N_{SWS}, are determined with MAIC, and the mean and the σ-limits are exhibited in Figure 3. Although the covariance functions given by Equation (6) were examined, the available correlation lengths were not identified. Therefore, additional mean functions are examined. Since the periodic tendency, whose period is about 10 m along the horizontal axis, is found, the term sin{(x/5-1/2)π} was added to Equation (5). The determined mean function is

$$m = 1.98 + 0.816\sin\left[\left(\frac{x}{5} - \frac{1}{2}\right)\pi\right] + 0.157z \quad (8)$$

The covariance function is determined by

$$C_{ij} = (0.75)^2 \exp\left(-|x_i - x_j|/6.14 - |z_i - z_j|/0.63\right) \quad (i \neq j) \quad (9)$$
$$C_{ij} = (1.24)^2 \quad (i = j)$$

The horizontal correlation length is identified to be approximately ten times of the vertical one. Since this rate is similar to the values published previously (e.g. Soulie et. al. 1990), the correlation lengths identified here are judged to be appropriate. The boundary between the base ground and the embankment is determined based on the SWS results.

The *N*-distribution predicted based on the determined statistical models with aid of the indicator simulation method (Deutsch and Journel 1990), which is one of the geo-statistical methods, and interpolates the point-estimated *N*-values, is exhibited in Figure 4. The horizontal periodicity of the *N*-values is presented according to the figure.

4 RELIAIBILITY-BASED DESIGN OF A FILL-EMBANKMENT

4.1 *Statistical model of an embankment*

A stability analysis is conducted and the risk is evaluated for an earth-fill dam at Site H to analyze the transversal section, the mean of the equation. As a mean function, Equation (12) is proposed by averaging Equation (8) along the *x* –axis, while the covariance function is defined as Equation (13), in which coordinate *x* is replaced by *y* of Equation (9), and depth *z* is replaced by elevation *h*. This assumption is based on the reason why the embankments are compacted horizontally in the construction, and the correlation structure at the same elevation is homogeneous.

$$m = 1.89 + 0.157z \quad (12)$$
$$C_{ij} = (0.75)^2 \exp\left(-|y_i - y_j|/6.14 - |h_i - h_j|/0.63\right) \quad (i \neq j)$$
$$C_{ij} = (1.24)^2 \quad (i = j) \quad (13)$$

The analytical sections of the original embankment, and the improved and restored embankment are exhibited in Figure 5. The embankment is improved by constructing an inclined core, and by covering the original embankment with the additional soil for reinforcement. The material properties are given in Table 1. The soil parameters are determined from the SPT *N*-values and the laboratory soil tests. The Bs means the embankment material; it is determined from the *N*-values based on the SWS results to consider the spatial distribution. The effective internal friction angle $\phi = \phi_d$, is obtained from the conversion, namely, Equation (14) (Hatanaka and Uchida 1996). In the equation, $5.3\varepsilon_f$ is the conversion error, in which ε_f is an *N*(0,1) type normal random variable, and the ratio of 5.3 is the standard deviation.

$$\phi' = (20N_1)^{0.5} + 20 + 5.3\varepsilon_f \quad (14)$$
$$N_1 = N_{SPT} / (\sigma_v'/98)^{0.5} \quad (15)$$

in which σ_v' is the effective vertical stress.

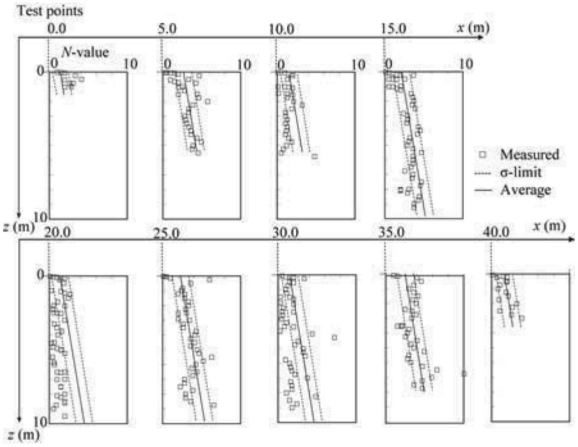


Figure 3. Spatial distribution of NSWS and statistical model.

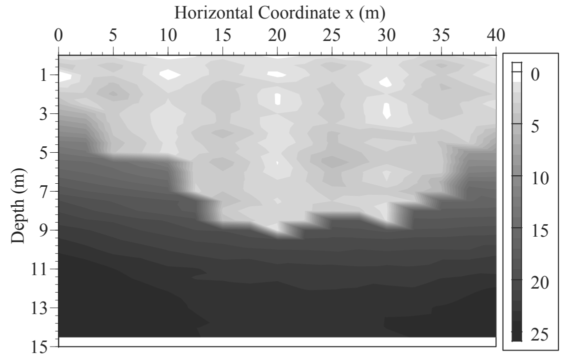
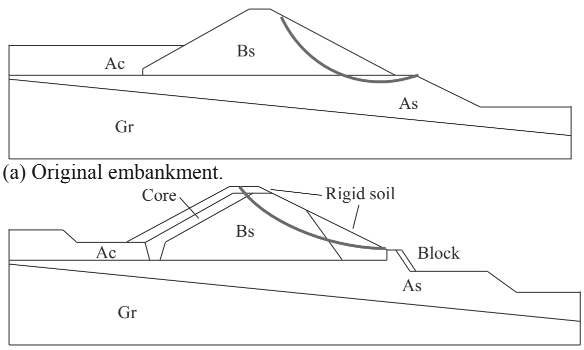


Figure 4. Predicted spatial distribution of N-value.



(b) Restored embankment.
Figure 5. Cross sections and critical slip surfaces of embankments.

4.2 *Reliability analysis*

In the stability analysis, the pore water pressure is required; it is calculated with a saturated-unsaturated seepage finite element analysis (e.g., Nishigaki 2000). In the restored embankment, the water table level is dramatically reduced by the existence of the impermeable zone. Consequently, this reduction can make the embankment stable.

The circular slip surface method is employed as the stability analysis in this study. For uncertain factors, the random numbers are assigned, and the stability of the embankments is evaluated as the probability of failure with the use of the Monte Carlo method. For the reliability analysis, Equation (16) is defined as a performance function, in which the internal friction angle is a probabilistic parameter. As the load of the earthquake, the design earthquake intensity of 0.15 is considered.

$$g = \sum_{i=1}^{n} (\tau_{fi} - \tau_{si}) l_i \quad (16)$$

Table 1. Parameters of embankment materials.

Materials	Young's modulas (kN/m^2)	Cohesion (kN/m^2)	Internal friction angle (°)	Unit weight (kN/m^3)	Permeability (cm/s)	Poisson's ratio
Bs	11200	20	*	20.3	4.0×10^{-5}	0.3
As	16800	20	37.4	20.3	2.9×10^{-4}	0.3
Ac	1000	10	37.4	15.0	5.6×10^{-8}	0.2
Gr	25000000	100	50.0	23.0	1.0×10^{-9}	0.3
Block	25000000	100	50.0	23.0	1.0×10^{-9}	0.2
Core	16800	20	37.4	20.3	4.0×10^{-7}	0.2
Rigid soil	16800	20	37.4	20.3	4.0×10^{-5}	0.3

* The internal friction angles of the embankment are derived from the N-values.

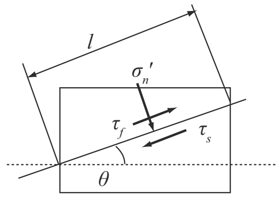


Figure 6. Slip surface across an element

where τ_f and τ_s are the shear strength and the shear force on the slip surface exhibited in Figure 6, which shows a slip surface across a finite element. In the figure, l_i is the length of the slip surface of element i, and n is the number of elements, which a slip circle crosses. The strength, τ_f is defined by the Mohr-Coulomb law of Equation (17). Normal stress σ_n and shear force τ_s are defined in Figure 6, and calculated with the soil and water coupling finite element method in this study. In the finite element analysis, the pore pressure is estimated in the saturated zone identified with the saturated - unsaturated seepage analysis, and the negative pore water pressure in the unsaturated zone is disregarded. This assumption can simplify the analysis and make an evaluation for the stability that is on the safe side.

$$\tau_f = c' + \sigma_n' \tan\phi' \tag{17}$$

$$\sigma_n' = \frac{(\sigma_z' + \sigma_y')}{2} + \frac{(\sigma_z' - \sigma_y')}{2}\cos 2\theta - \tau_{yz}\sin 2\theta \tag{18}$$

$$\tau_s = \frac{(\sigma_z' - \sigma_y')}{2}\sin 2\theta + \tau_{yz}\cos 2\theta \tag{19}$$

in which c' is the effective cohesion, ϕ' is the effective internal friction angle, σ_z' and σ_y' are the vertical and the horizontal stresses, τ_{yz} is the shear stress, and θ is the angle between a horizontal plane and a slip surface. The probability failure is evaluated with Equation (20) through the use of the Monte Carlo method.

$$P_f = \text{Probability}(g < 0) \tag{20}$$

For the internal friction angle ϕ' of the embankment material Bs, is dealt with as a random variable. Firstly, the random numbers considering the spatial distribution derived from Equations (12) and (13) are assigned to the N_{SWS}. Secondly, the random variable N_{SPT} is evaluated by Equation (2) by considering the conversion error ε_r, and then the ϕ' is obtained with Equation (14), including the conversion error term $5.3\varepsilon_f$. The Monte Carlo method is iterated 1000 times.

4.3 *Risk evaluation*

Two cases of the original embankment and the restored one are compared, whose cross sections are shown in Figures 5(a) and (b). In the figures, the representative slip surfaces, which give the minimum safety factors, are exhibited. In Table 2, the results of the reliability analysis are shown, in which F_s is the average factor of safety, P_f is the probability of failure, C_f is the failure cost, including the damage to houses, agricultural facilities, and farm lands, and C_F is the value of the expected failure cost. The average factor of safety is almost 1.0 for the

Table 2. Result of reliability analysis.

	Fs	P_f	C_f	C_F
Original	1.04	0.197	2,000	3,940
Restored	1.62	0	2,000	0

$C_F = C_f \times P_f$ Unit (10000 JPY)

original embankment, and the probability of failure is nearly 20%, which seems very high. For the restored embankment, on the other hand, the probability of failure is nearly zero and the evaluated reduction in risk is drastic, at a value of 39,400,000 JPY. The reduction value means the effect of the improvement work for the embankment.

5 CONCLUSIONS

(1) A method to determine the statistical models of the soil strength was presented. The indicator simulation, which is one of the geostatistical methods, was employed. With the proposed procedure, a detailed spatial distribution of the *N*-values was exhibited.

(2) Based on the determined statistical model of the internal friction angle, including the spatial distribution of the *N*-values, the two conversion errors, from the SWS *N*-value to the SPT *N*-value, and the SPT *N*-value to the internal friction angle, the reliability analysis was conducted for an earth-fill embankment, and the probability of failure was evaluated for the original state of the embankment and the restored state of the embankment. By comparing the risks between the original state and the restored one, the effect of the improvement work of the embankment was evaluated

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