and, $k_{ss} = \frac{\alpha k_{s1}\varepsilon_y + \alpha k_{s2}(\varepsilon' - \varepsilon_y)}{\varepsilon'}$

b) If the point has not failed in earlier iteration,

I) for, ε', less than yield strain, ε_y,

$$\{\Delta\sigma\}_e = (1-\alpha)[D]\{\Delta\varepsilon\}_e + (\alpha - \alpha')[D]\{\varepsilon\}_e$$

and, for interface element,

$$\{\Delta\sigma\}_e = (1-\alpha)[D_m][D]\{\Delta\varepsilon\}_e + (\alpha - \alpha')[D_m][D]\{\varepsilon\}_e \qquad \text{(A-22)}$$

II) for ε' greater than yield strain, ε_y,

$$\{\Delta\sigma\}_e = \frac{E_1 - \frac{\Delta\bar{\sigma}}{\Delta\varepsilon'}}{E_1}[D]\{\Delta\varepsilon\}_e + (\alpha - \alpha')\frac{E_s}{E_1}[D]\{\varepsilon\}_e \qquad \text{(A-23)}$$

where, $\Delta\bar{\sigma} = \alpha E_1(\varepsilon_y + \Delta\varepsilon' - \varepsilon) + \alpha E_2(\varepsilon' - \varepsilon_y)$ (A-24)

and, $E_s = \frac{E_1\varepsilon_y + E_2(\varepsilon' - \varepsilon_y)}{\varepsilon'}$

for interface element,

$$\{\Delta\sigma\}_e = \frac{k_{s1} - \frac{\Delta\bar{\tau}}{\Delta\varepsilon'}}{k_{s1}}[D_m][D]\{\Delta\varepsilon\}_e + (\alpha - \alpha')\frac{k_{ss}}{k_{s1}}[D_m][D]\{\varepsilon\}_e \qquad \text{(A-25)}$$

where, $\Delta\bar{\tau} = \alpha k_{s1}(\varepsilon_y + \Delta\varepsilon' - \varepsilon) + \alpha k_{s2}(\varepsilon' - \varepsilon_y)$ (A-26)

and, $k_{ss} = \frac{\alpha k_{s1}\varepsilon_y + \alpha k_{s2}(\varepsilon' - \varepsilon_y)}{\varepsilon'}$

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USING GEOTECHNICAL DATABASE FOR MODELING SPATIAL VARIABILITY OF SOIL PROPERTIES

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ABSTRACT

This paper presents a probabilistic model to determine bore-hole spacing and spatial variability of soil properties during site investigation. Using this model, it is possible to evaluate the bore-hole spacing and important soil properties for the estimation error used in reliability-design. However, this model requires correlation distance and variance of soil properties as important data input. The geotechnical data-base system for Saga plain, Japan is used to establish the relationship between these statistical variables and soil characteristics, such as, undrained shear strength, layer thickness, etc. The exploration spacing for different estimation errors is suggested for site investigation.

INTRODUCTION

Site exploration gives important information about the ground profile and important soil properties. The accuracy of such information, however, depends upon the number of sample, the quality of test data and the location of sample. If the information from such exploration is limited and there is a need to estimate the ground information or the soil properties at unsampled location, one may ask how reliable is the estimate to meet the safety requirement in the design. Of course, carrying out additional exploration or increasing the number of samples can reduce uncertainty due to spatial variability of soil properties. However, sometimes it will result in what is called "wasteful redundancy" in the information collected. So, it is important to choose an optimum exploration spacing that gives the best estimate of the ground profile and the soil properties considering overall aspects of safety and economy.

Although the ground thickness or engineering soil properties at an unsampled location on the ground can be directly estimated from neighboring bore-holes either by interpolation or geotechnical judgement, one cannot determine however the estimation errors in such determinative procedures. The predictive geostatistical procedures, such as ordinary and universal kriging based on the theory of regionalized variables (Matheron, 1971) are best suited for this purpose; not only that they give better interpolation than determinative methods but also evaluate estimation errors for such interpolations. Kriging is a collection of generalized liner regression techniques for minimizing an estimation error obtained from a priori model for a covariance (Journel and Huijbregts, 1978; and Deutsch and Journel, 1998). Although kriging was initially introduced to provide estimates for unsampled values (Krige, 1951; and Matheron, 1971), it is being used increasingly to build probabilistic models of uncertainty about these unknown values (Journel, 1989).

Based on the kriging principle mentioned above, this paper presents a simple probabilistic model to evaluate unknown value and estimation error of soil properties at unsampled location in the ground. This model can also be used to evaluate the borehole spacing. The statistical parameters, namely, a correlation distance and variance for this model are established using a geotechnical datebase system for Saga plain, Japan. Finally, the exploration spacing for different values of estimation error is suggested for the site investigation.

PROBABILISTIC ESTIMATION MODEL

Predictive geostatistics characterize any unsampled value of soil property w as a random variable W. The random variable W, and more specifically its probability distribution (mean and standard deviation), is usually location-dependent (Webster and Burgess, 1980); hence this variable is denoted as $W(u)$ where u is a location coordinates vector.

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Figure 1 shows the ground space Ω where the soil data $w(u_1)$ and $w(u_2)$ for two bore holes 1 and 2, are known, and the interpolated data $w(u_0)$ and its estimation error is required at the bore hole at location 0.

Let $\hat{w}(u_0)$ to be an estimate of $w(u_0)$, which can be modeled as a linear combination of $w(u_1)$ and $w(u_2)$ as follows (Krige, 1951; and Matheron, 1971):

$$\hat{w}(u_0) = \lambda_1 w(u_1) + \lambda_2 w(u_2) \tag{1}$$

where λ_1 and λ_2 are the weights to be determined.

From Eq. (1), the expectation $E(\hat{w}(u_0))$ of $\hat{w}(u_0)$, can be derived as follows:

$$E(\hat{w}(u_0)) = \lambda_1 m_1 + \lambda_2 m_2 = m_0 \tag{2}$$

where, m_0, m_1 and m_2 are the means of $w(u_0)$, $w(u_1)$ and $w(u_2)$, respectively.

Let us separate the random variable $w(u_i)$ $(i = 0, 1, 2)$ into a random part $R(u_i)$ of zero mean and a trend part $m(u_i)$, and by the virtue of Eq. (2), the square error $(\sigma_E)^2$ of the estimator $\hat{w}(u_0)$ can be obtained as follows:

$$\sigma_E^2 = E\{[w(u_0) - \hat{w}(u_0)]^2\} \tag{3}$$

$$= E\{[R(u_0) - \hat{R}(u_0)]^2\} \tag{4}$$

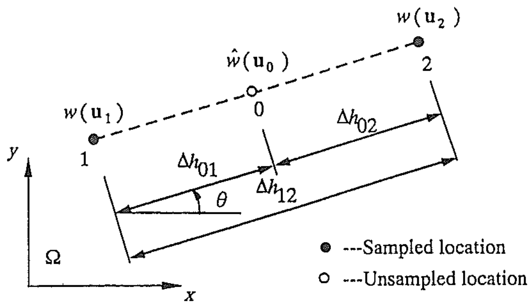
$$= E[R^2(u_0)] - 2E[R(u_0)\hat{R}(u_0)] + E[\hat{R}^2(u_0)] \tag{5}$$

$$= Var_0 - 2\lambda_1 C_{01} - 2\lambda_2 C_{02} + \lambda_1^2 Var_1 + 2\lambda_1\lambda_2 C_{12} + \lambda_2^2 Var_2 \tag{6}$$

where C_{ij} is covariance of $R(u_i)$ and $R(u_j)$ $(i \neq j, i = 0, 1, 2; j = 0, 1, 2)$. Var_i is variance of $R(u_i)$ $(i = 0, 1, 2)$.

From Eq. (2) and Eqs. (3-6), a new function F is obtained using Lagrange parameter μ, as follows:

$$F = \sigma_E^2 - \mu(\lambda_1 m_1 + \lambda_2 m_2 - m_0) \tag{7}$$



Ω ---ground space as a random field of $W(\mathbf{u})$

$W(\mathbf{u}_i)$ ---soil property as a random variable

$\mathbf{u}_i(x_i, y_j)$ ---location coordinates vector

$w(\mathbf{u}_i)$ ---soil property at location $\mathbf{u}_i$

$\hat{w}(\mathbf{u}_1)$ ---an estimator of $w(\mathbf{u}_1)$

Fig. 1 Concept of the Parabolic Estimation Model

The parameter λ_1, λ_2, m_0, and μ may be obtained by minimizing σ_E^2 in Eqs. (3-6) as given below:

$$\partial F/\partial\lambda_1 = 2\lambda_1 Var_1 + 2\lambda_2 C_{12} - 2C_{01} - \mu m_1 = 0 \tag{8}$$

$$\partial F/\partial\lambda_2 = 2\lambda_1 C_{12} + 2\lambda_2 Var_2 - 2C_{02} - \mu m_1 = 0 \tag{9}$$

$$\partial F/\partial m_0 = \mu = 0 \tag{10}$$

$$\partial F/\partial\mu = \lambda_1 m_1 + \lambda_2 m_2 - m_0 = 0 \tag{11}$$

Thus, from Eqs. (8-11), the authors derived the values of λ_1 and λ_2 represented by the variance and auto correlation function as follows:

$$\lambda_1 = (C_{01}Var_2 - C_{02}C_{12}) / (Var_1 Var_2 - C_{12}^2) = \sqrt{(Var_0/Var_1)}[(\rho_{01} - \rho_{02}\rho_{12}) / (1 - \rho_{12}^2)] \tag{12}$$

$$\lambda_2 = (C_{02}Var_1 - C_{01}C_{12}) / (Var_1 Var_2 - C_{12}^2) = \sqrt{(Var_0/Var_2)}[(\rho_{02} - \rho_{01}\rho_{12}) / (1 - \rho_{12}^2)] \tag{13}$$

where ρ_{ij} is the auto correlation function between points i and j ($\rho_{ij} = C_{ij}/\sqrt{Var_i Var_j}$).

Substituting back λ_1 and λ_2 into Eq. (6), the minimized square error is obtained, as follows:

$$\sigma_E^2 = Var_0 - \{(C_{02}^2 Var_1 + C_{01}^2 Var_2 - 2C_{01}C_{02}C_{12}) / (Var_1 Var_2 - C_{12}^2)\} \tag{14}$$

Which may also be written as:

$$\sigma_E^2 = Var_0\{1 - [(\rho_{01}^2 + \rho_{02}^2 - 2\rho_{01}\rho_{02}\rho_{12}) / (1 - \rho_{12}^2)]\} \tag{15}$$

Since no assumption has been made, so far, on stationarity for auto correlation function while deriving the above equations, it follows that Eq. (14) and Eq. (15) can be applied to non-stationary space such as, for example, in case where the correlation function are location-dependent.

Previous studies (Alonso and Krizek, 1975; Matuo and Asaoka, 1977; Vanmarcke, 1977; Tang, 1979; and Bergado, 1994) have shown that empirical auto correlation function of soil properties usually can be idealized by using an exponential decay function of the form given below:

$$\rho(\Delta h) = \exp\{-(\Delta h/a)^m\} \tag{16}$$

where, $\rho(\Delta h)$ is stationary auto correlation function of soil properties, (Δh) is distance vector between any two points, and m and a are decay parameters.

Taking advantage of the stationary form of $\rho(\Delta h)$ in Eq. (16), and substituting it into Eq. (15), another form of the minimized square error σ_E^2 is obtained, as follows:

$$\sigma_E^2 / Var_0 = [1 - \exp\{-2A\} - \exp\{-2nA\} + \exp\{-2(1+n)A\}] / [1 - \exp\{-2(1+n)A\}] \quad (m = 1) \tag{17}$$

$$\sigma_E^2 / Var_0 = 1 - ([\exp\{-2A^2\} + \exp\{-2n^2A^2\} - 2\exp\{-2(1+n+n^2)A^2\}] / [1 - \exp\{-2(1+n)^2A^2\}]) \quad (m = 2) \tag{18}$$

where $A = \Delta h_{01}/a$ and $n = \Delta h_{02}/\Delta h_{01}$ (Fig. 1).

When $\Delta h_{02}/a \rightarrow \infty$ $(n \rightarrow \infty)$, the square error becomes:

$$\sigma_E^2 / Var_0 = 1 - \exp[-2(\Delta h_{01}/a)^m] \tag{19}$$

Equation (19) simply links the minimized square error σ_E^2 to interval Δh_{01} between points 0 and 1. Suppose point 1 is the sampled location in previous step of investigation, and point 0 is the unsampled location needed to be investigated in the next step, then Δh_{01} is the spacing of exploration (or bore hole spacing) in the next step of investigation corresponding to the required square error σ_E^2. The spacing of exploration Δh_{01} can be easily derived from Eq. (19) as follows:

$$\Delta h_{01} = a\,[\,(1/2)\ \ln\{Var_0/(Var_0 - \sigma_E^2)\}]^{1/m} \tag{20}$$

At estimated location, Var_0 is a priori unknown value and needs to be estimated. For stationary processes that the mean is an unknown constant, according to the intrinsic hypothesis made in most geostatistical procedures (Journel and Huijbregts, 1978), by definition, Var_0 is constant over the ground and equal to $C(0)$ (the value of the covariance C_{ij} when $i = j$).

To estimate $C(0)$, the preferred tool is the semi-variogram $\gamma(\Delta h)$. Since $C(0) = \gamma(\infty)$, in practice, when $\gamma(\Delta h)$ becomes asymptotic after a Δh, $C(0)$ can be determined by the corresponding $\gamma(\Delta h)$.

For a non-stationary process, $W(u)$ is usually separated into a mathematical trend part $m(u)$ and a zero mean random part $R(u)$ as follows:

$$W(u) = m(u) + R(u) \tag{21}$$

Since $E\{R(u)\} = 0$ and $Var[R(u)] = E\{[R(u)]^2\} = C_R(0)$ = a constant quantity, Var_0 can be estimated as follows:

$$Var_0 = E\{[w(u) - m(u)]^2\} = E\{[R(u)]^2\} = C_R(0)\ \ (=\text{constant}) \tag{22}$$

where, $C_R(0)$ is the variance of $R(u)$.

Thus even in non-stationary processes Var_0 can be estimated by the constant variance of the zero mean random part $R(u)$. $C_R(0)$ can be also estimated from $\gamma(\Delta h)$ of $W(u)$, since by definition, $\gamma(\Delta h)$ filters the trend part.

When a finite variance $C_R(0)$ exists, from Eq. 6, λ_1 and λ_2 are obtained as follows:

$$\lambda_1 = [\rho(\Delta h_{01}) - \rho(\Delta h_{02})\rho(\Delta h_{12})] / [1 - \rho^2(\Delta h_{12})] \tag{23}$$

$$\lambda_2 = [\rho(\Delta h_{02}) - \rho(\Delta h_{01})\rho(\Delta h_{12})] / [1 - \rho^2(\Delta h_{12})] \tag{24}$$

Substituting the λ_1 and λ_2 into Eq. 1 and Eq. 2, the mean m_0 and the estimate $\hat{w}_0$ can be calculated.

According to Eqs. (17-18), the relationship between σ_E^2/Var_0 and $\Delta h_{01}/a$ for different n-values ($=\Delta h_{02}/\Delta h_{01}$) are plotted in Fig. 2(a) and Fig. 2(b), when $m = 1$ and 2, respectively. From these figures, it is clear that if the square error of estimation $(\sigma_E)^2$ and correlation distance a are given, the curve of $n \to \infty$ can be used to determine the minimum spacing of exploration in the direction of h_0. It may be noted that a is the correlation distance along the same direction.

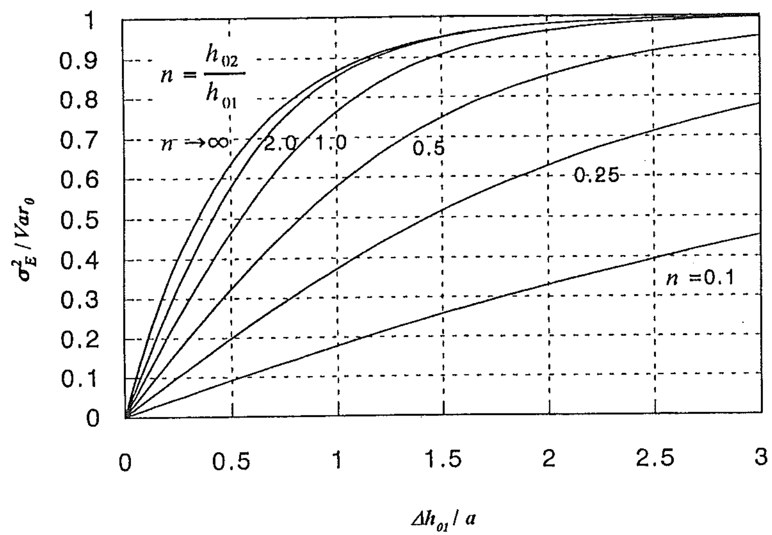
It is emphasized that to use the suggested model to evaluate the spacing of exploration, prior knowledge of the parameters, such as correlation distance a, variance $C(0)$, etc. is needed.

CASE STUDY IN THE SOFT GROUND OF SAGA PLAIN

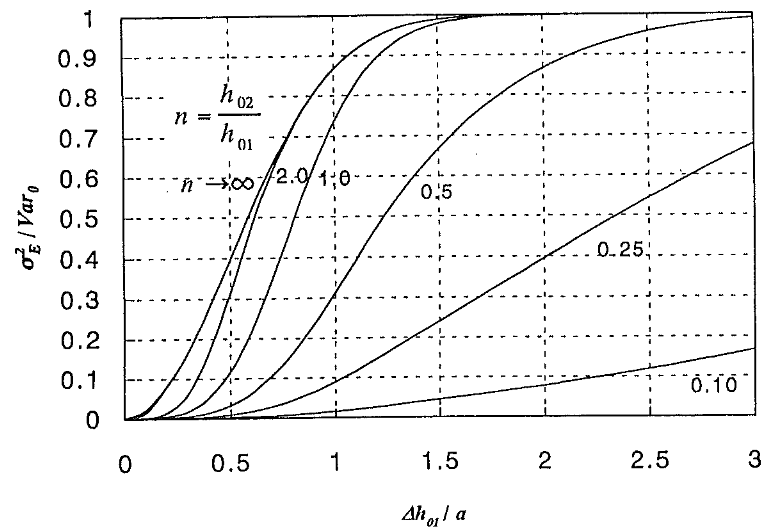
Site Description

Saga plain, a lowland in north Ariake Bay, Japan, is underlain by soft recent deposits of thickness varying from 10 m to 30 m. Low strength, high sensitivity and high compressibility of these deposits have led to widespread geotechnical problems (Miura, et al., 1997). So far, numerous soil investigations on geotechnical characteristics of these deposits are performed. A database system for information of the ground (DIG) has been established in the Institute of Lowland Technology, Saga University. Data from around 1750 borings in Saga plain are stored in the database.

Figure 3 is the surface distribution of the soft deposits in Saga plain (Simoyama, et al., 1994). The ground profile along the north-south profile, A-A', as marked in Fig. 3 is shown in Fig. 4. This soil profile can be divided into four distinct groups based on their geotechnical characteristics and the process of formation. The lowest layer (D_n) consists of 30 m thick clastic sediments of stiff clay, intermixed with seams of dense sand and gravel. This layer appears to be of terrestrial origin. The overlying layer (C) consists of grey or dark brown sedimentary soils of volcanic



(a) $m = 1$



(b) $m = 2$

Fig. 2 σ_E^2/Var_0 vs. $\Delta h_{01}/a$

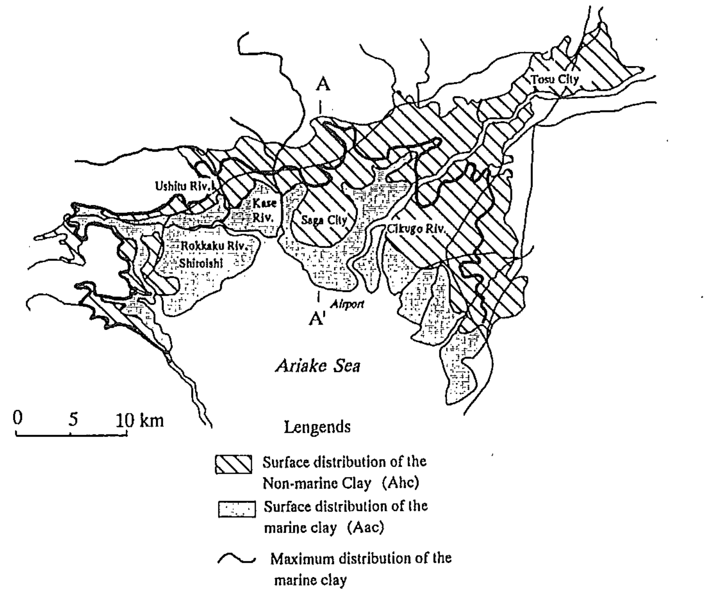


Fig. 3 Map of the Distribution of the Marine Clay and Non-Marine Clay in Saga Plain

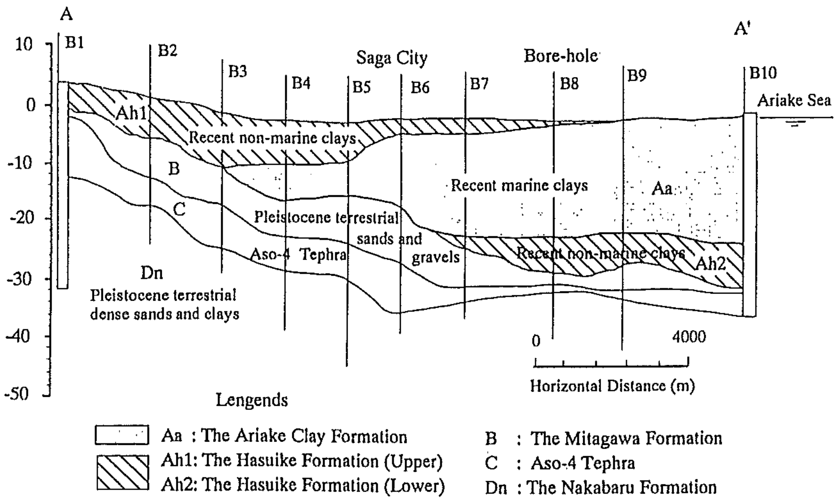


Fig. 4 The North-South Profile of Saga Plain (*A-A'*)

origin with thin seams of volcanic sand and pumice. Overlying layer *C*, a 10 m thick layer (*B*) is present that consists of light grey to dark grey color dense sand mixed with gravel.

Soils overlying the dense sand layer (*B*) are soft recent formations that constitute the Saga plain. These soil groups can be divided into a 20 m thick marine clay formation called Ariake Clay Formation (A_a) and a non-marine clay formation called Hasuike Formation (A_h). The Hasuike Formation can be further divided into an upper layer formation (A_{h1}) and a lower layer formation (A_{h2}) separated by the thick marine formation (Fig. 3). Deposition of the marine and non-marine formations has occurred continuously during the sea advance (known as Jomon Transgression in Japan) roughly 10000-6000 years ago and during the retreat of the sea to its present position. While the formation A_a mainly consists of a marine clay (A_{ac}) which is a dark grey or dark blue color, soft, silty clay with shell fragment, layers A_{h1} and A_{h2} consist of dark-blue color soft, silty clay (A_{hc}) deposited in brackish or fresh water condition. Within the soft ground, several discontinuous seams of sandy soil of 0.5 m to 1.0 m thickness are erratically distributed, especially at the coastal area and river mouths. The organic life, plants and vegetation which remain contained in the clay A_{hc} are always good markers of non-marine condition, while the shell fragments in the clay A_{ac} are an indication of marine condition.

The statistics of the geotechnical properties of clay formations A_{ac} and A_{hc} in the *a5* area (Fig. 5) are given in Table 1 and Table 2, which were calculated using the database system for information of the ground at the Institute of Lowland Technology. As the marine formation A_c constitutes most parts of the soft ground and the clay A_{ac} is the dominant constituent of this formation, the statistical characterization of geotechnical properties of the clay A_{ac} will be focused in future discussion.

As the suggested model requires data input in form of correlation distance and variance, the next two subsections evaluate these statistical parameters for two important soil characteristics, namely, a layer thickness and an undrained shear strength.

Correlation Distance and Variance of Layer Thickness

Figure 5 shows the bore-holes in Saga Plain, from which the layer thicknesses were obtained. The layer thickness increases towards the sea and decreases towards the inland (Fig. 3 and Fig. 4). The deep valley of the layer thickness of the soft ground shown in Fig. 6 coincides with the riverbed of the Chikugo River, the largest river in Kyushu island, which flows through the plain along the northeast direction at upstream and towards the south at river mouth into the sea (Fig. 3). Figure 7 is the histogram of the layer thickness of the soft ground. The average thickness of the soft ground is 11.2 m. The standard deviation of the layer thickness is as large as 5.9 m.

Because of the different depositional environments caused by the river flow and the tidal current of the sea, the thickness of the soft ground at or near riverbed tends to be thicker than that at other locations. As a consequence, the correlation distance (or variance) may have larger value along certain direction and smaller value along other directions. To determine exploration spacing in the soft ground, anisotropy of correlation structures should be taken into account.

Because the data points are irregularly sampled in the soft ground (Fig. 5), a computer program developed by Deutsch and Journel (1998) for irregularly spaced data will be used to calculate the correlation structures such as semi-variogram and correlogram (auto correlation function) of the layer thickness.

Figure 8 and Fig. 9 are correlograms and semi-variograms with respect to different directions ($\theta = 0 - 180^{\circ}$) for the layer thickness, in which θ was defined by an angle from x axis (West -East) to the direction of correlation distance anti-clockwise as shown in Fig. 1.

Figure 10 shows the relationship between the correlation distance a and θ obtained from the correlograms in Fig. 8. The direction of the largest correlation distance (a = 1867 m) is near the northeast direction ($\theta = 60^{\circ}$), which almost coincides with the direction of the riverbed of the Chikugo River. Fig. 11 shows the relationship between variance $C(0)$ and θ obtained from the semi-variograms in Fig. 9. Along the east-west direction ($\theta = 0^{\circ}$ or 180°) $C(0)$ takes the largest value of 28 m^2.

The exploration spacing corresponding to different given estimation errors are listed in Table 3. It is interesting to note that for an estimation error of around 1.0 m in layer thickness, which corresponds to $\sigma_E = 0.5\sqrt{C(0)}$ in Table 3, a sample spacing of less than 100 m is required. This exploration spacing agrees with the exploration spacing suggested by Fujikawa, et al. (1996) for optimal design of embankment road on the soft ground.

Table 1 Representative Values of Physical Properties of A_{ac} and A_{hc}

	A_{ac} (marine clay)				A_{hc} (non-marine clay)			
	min-max	mean	cov	n	min-max	mean	cov	n
Specific gravity, Gs	2.50 - 2.75	2.613	0.016	194	2.45 - 2.71	2.604	00.2	148
Unit dry weight, γ_t (kN/m^3)	12.7 - 16.7	14.7	0.052	242	12.5 - 18.7	14.7	0.087	179
Natural void ratio, e	1.16 - 4.5	2.26	0.216	182	0.90 - 4.31	2.44	0.263	175
Natural water content, W_n (%)	43.9 - 178.6	87.2	0.214	243	32 - 199	88.75	0.315	143
Liquid limit, LL (%)	41.7 - 130.8	81.6	0.21	174	32.7 - 135.7	82.3	0.23	129
Plastic limit, W_p (%)	22.2 - 57.4	38.7	0.16	174	18.3 - 57.2	39.8	0.19	129
Liquidity index, I_L	0.4 - 2.8	1.1	0.34	174	0.2 - 2.2	1.3	0.32	129
Plasticity indes, I_p (%)	12.2 - 85.7	42.9	0.31	174	11.3 - 79.8	42.5	0.32	129
Clay (d<5μm), Cf (%)	16.0 - 75	42.5	0.268	166	11 - 65	42.5	0.27	122
Silt (5μm<d<μm), Si (%)	17.0 - 67	43.1	0.234	166	24 - 74	45.4	0.21	122

cov = coefficient of variation; n = number of data

Table 2 Representative Values of Mechanical Properties of A_{ac} and A_{hc}

	A_{ac} (marine clay)				A_{hc} (non-marine clay)			
	min-max	mean	cov	n	min-max	mean	cov	n
Compression index, C_c	0.32 - 1.32	0.98	0.42	96	0.2 - 2.32	1.01	0.48	64
Coefficient of consolidation, C_v (cm^2/sec) x 10^{-4}	9.66 - 149.4	50.7	0.85	22	3.17 - 206.5	48.9	0.95	50
Consolidation yield stress, P_c (kPa)	26.0 + 5.79Z		0.24	95	40.0 + 5.69Z		0.44	64
Undrained shear strength, c_u (kPa)	8.92 + 1.57Z		0.33	219	11.3 + 1.57Z		0.44	156

cov = coefficient of variation; n = number of data; Z = depth (m)

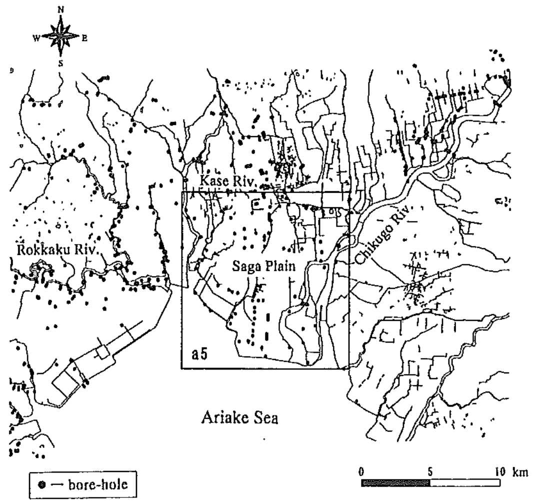


Fig. 5 Location of Boreholes in Saga Plain

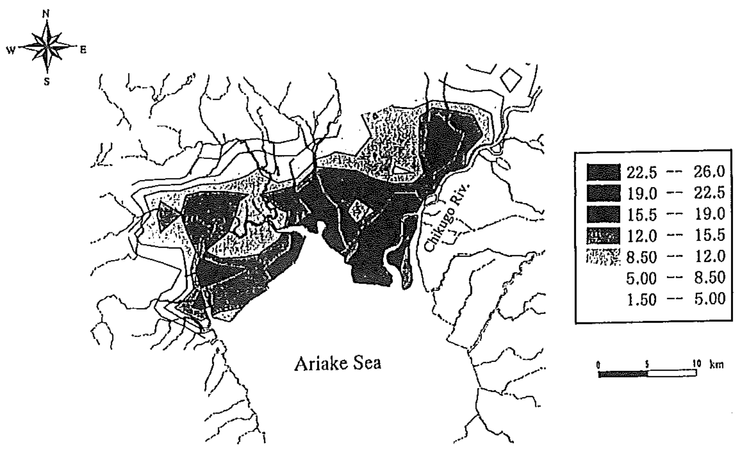


Fig. 6 The Layer of Thickness of Soft Ground in Saga Plain

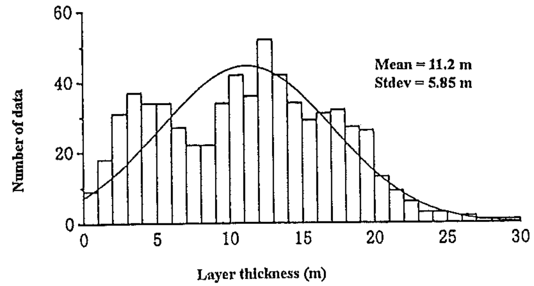


Fig. 7 Histogram of Layer Thickness of the Soft Ground in Saga Plain

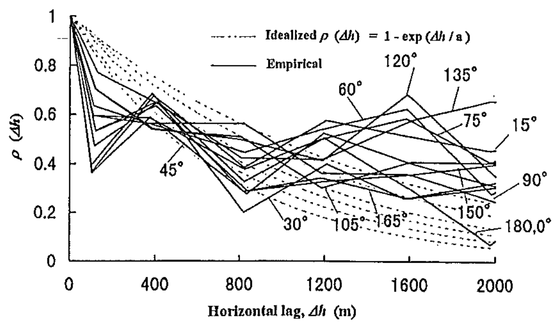


Fig. 8 Correlograms of the Layer Thickness with Respect to Different Horizontal Directions

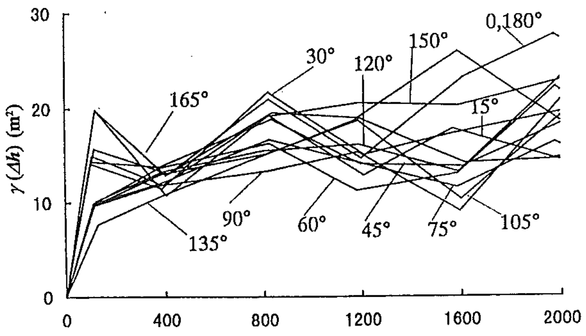


Fig. 9 Semi-Variograms of the Layer Thickness with Respect to Different Horizontal Directions

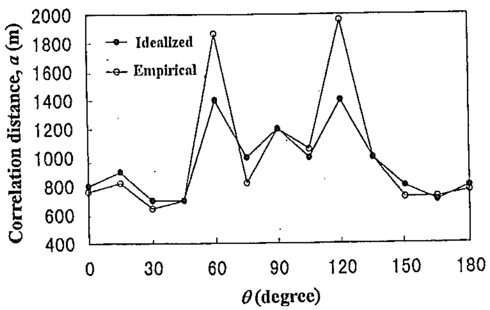


Fig. 10 The Relationship Between a and θ of Layer Thickness

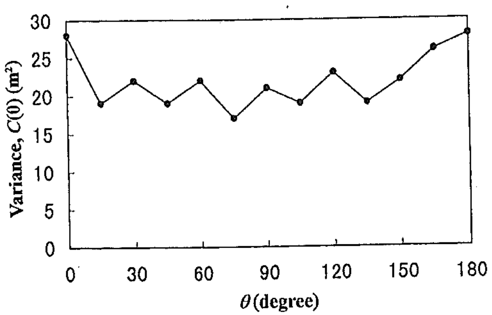


Fig. 11 The Relationship Between $C(0)$ and θ of Layer Thickness

Table 3 Exploration Spacing for Layer Thickness

Estimation error σ_E (kPa) / θ (degree)	Horizontal exploration spacing, Δh (m)			
	$0.25\ C(0)^{0.5}$	$0.50\ C(0)^{0.5}$	$0.75\ C(0)^{0.5}$	$0.95\ C(0)^{0.5}$
0°	26	115	331	931
15°	29	129	372	1048
30°	23	101	289	815
45°	23	101	289	815
60°	45	201	579	1630
75°	32	144	413	1164
90°	39	173	496	1397
105°	32	144	413	1164
120°	45	201	579	1630
135°	32	144	413	1164
150°	26	115	331	931
165°	23	101	289	815
180°	26	115	331	931

Correlation Distance and Variance of Undrained Shear Strength

The undrained shear strength c_u was calculated from the unconfined compressive strength q_u ($c_u = 0.5\,q_u$) and is the main soil parameter for stability analysis of embankment on the soft ground.

The variation of c_u along depth is shown in Fig. 12. As expected, the undrained shear strength of the soft ground also increases with depth. A simple linear regression analysis of the data results into the following equation:

$$\bar{c}_u = 8.92 + 1.57z \tag{25}$$

where, $\bar{c}_u$ is the mean of c_u and z is the depth from ground surface. A constant standard deviation of as large as 6.17 kPa was obtained.

Asaoka, et al. (1982) suggested a model to calculate the mean and standard deviation of undrained shear strength of a soil profile. In the model the standard deviation was modeled in the manner increasing with depth. However, from the data of the whole ground, a constant standard deviation of as large as 6.17 kPa was obtained by linear regression. This suggests that it is better to model the standard deviation as a constant with depth for the soft ground.

It must be emphasized here that the overall trend given by Eq. (25) does not represent the values at any local borehole. In fact, the value of c_u also varies with the location of horizontal plane. This makes it possible to calculate both the horizontal and vertical correlation of c_u. Because sampling data are irregularly spaced with the soft ground, the computer program for irregularly spaced data will be used to calculate its correlation structures. As mentioned in former subsection, because of the differences in the depositional environment, the soft ground deposits exhibit variation both in vertical and horizontal plane direction. As a consequence, the correlation structures of c_u, such as correlogram and variogram, in different directions would be different. To evaluate the exploration spacing along a certain direction in horizontal plane, the correlation distance a and the variance $C(0)$ corresponding to that parameter direction should be used.

Figure 13 and Fig. 14 are correlograms and semi-variograms along vertical direction (z), respectively. The vertical correlation distance a of the clay in the soft ground of Saga Plain is 3 m, which is larger than that of soft Bangkok clay (Bergado, et al., 1994).

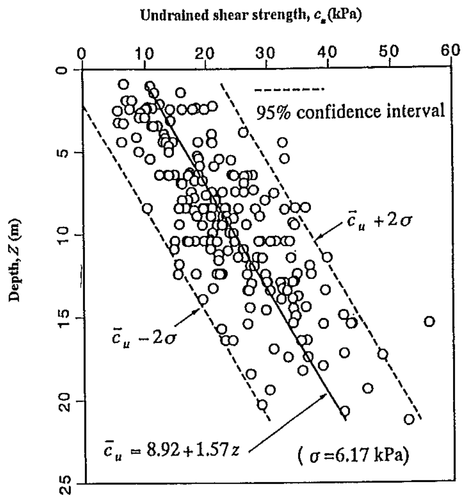


Fig. 12 Variation of Undrained Shear Strength of the Marine Clay in Saga Plain with Depth

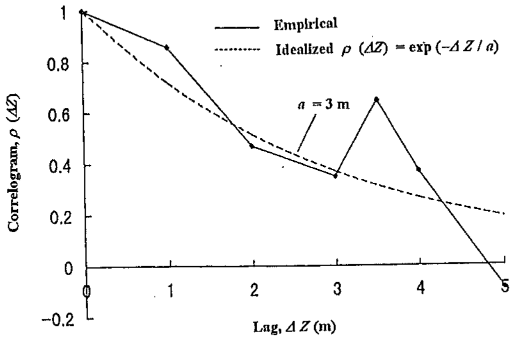


Fig. 13 Correlograms of Undrained Shear Strength along Vertical Direction

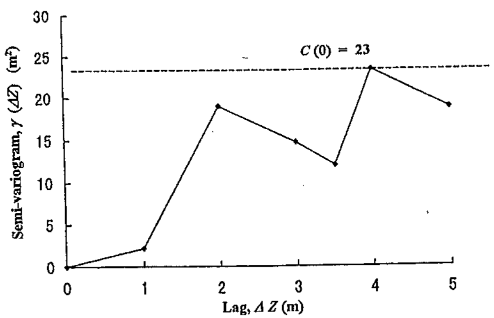


Fig. 14 Semi-Variograms of Undrained Shear Strength along Vertical Direction

Figure 15 and Fig. 16 are correlograms and semi-variograms along different directions ($\theta = 0^\circ$ or 180°) in horizontal plane (x-y), respectively. The longest correlation distance (a = 526 m) is the one in south-north direction ($\theta = 90^\circ$). The relationship between the correlation distance a and the angle of direction θ in horizontal plane is shown in Fig. 17. The average of these correlation distances in horizontal plane is about 350 m, which is larger than the horizontal correlation distance of soft Bangkok clay (Bergado, et al., 1994). The relationship between $C(0)$ and a are shown in Fig. 18, where $C(0)$ has the largest in north-south direction.

Based on Fig. 18, the exploration spacing in different directions for different given estimation errors is listed in Table 4.

COMPARISON BETWEEN THE ESTIMATION ERROR OF THE SUGGESTED MODEL AND KRIGING ERROR

The procedure used by the authors to derive the simple model of estimation error in the preceding chapter is similar to that in conventional kriging approaches. However, by using the nearest pair of data (points 1 and 2 in Fig. 19) to estimate the value at unsample point 0, a simpler form of estimation error has been obtained (Eqs. 17-18). Herein, the authors will constitute a data cluster at another points (5', 4', 3', 2', 3, 4, 5) except 1 and 2, along the line in Fig. 19, and will use the cluster data to calculate the kriging error at point 0 and then compare it with the estimation error calculated by the suggested model. The variance $C(0)$ and the correlation distance of the data cluster are assumed as 1.0 and 0.1, respectively. The distance between point 1 and 2, Δh_{12}, is equal to 10, which is larger than the correlation distance a (= 0.1). Δh_{02} is the distance between point 1 and the point 0. In Fig. 20 the estimation error at point 0 calculated by the suggested model (Eqs. 17-18, when m = 1) from point 1 and 2 are compared with the kriging error at point 0, which has been calculated from all the data (5', 4', 3', 2', 3, 4, 5) in the kriging procedure (ordinary kriging). It is evident that the estimation error of the suggested model has a good agreement with the kriging error and is the estimation error in the safe side.

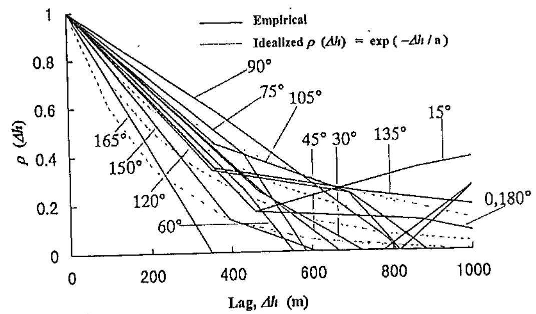


Fig. 15 Correlograms of Undrained Shear Strength along Different Horizontal Direction

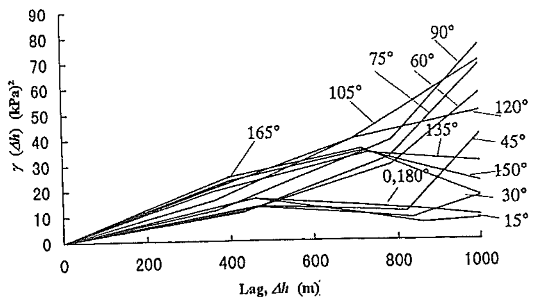


Fig. 16 Semi-Variograms of Undrained Shear Strength along Different Horizontal Direction

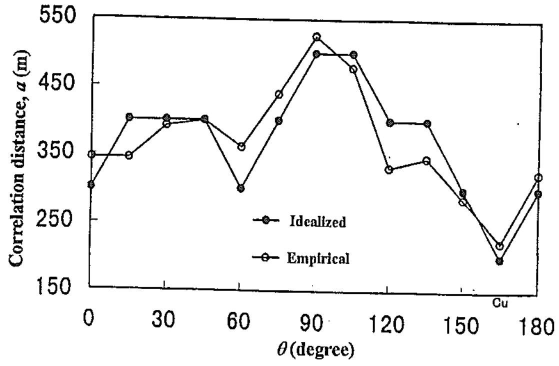


Fig. 17 The Relationship Between a and θ of Undrained Shear Strength

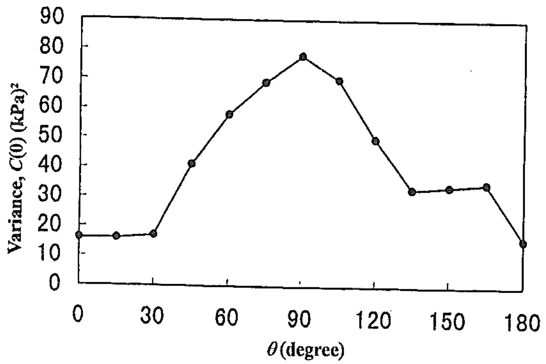


Fig. 18 The Relationship Between $C(0)$ and θ of Undrained Shear Strength

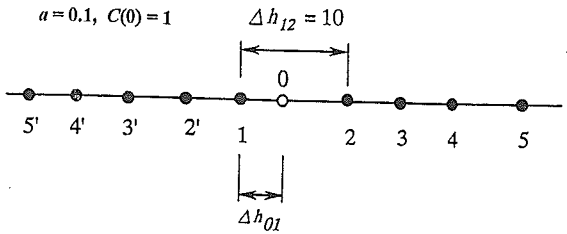


Fig. 19 The Locations of the Cluster Data (1, 2,... 5, 2', 3',... 5') Used to estimate point 0 by ordinary Kriging procedure. The correlation distance a of the cluster data is 0.1 and the constance variance $C(0)$ is 1. The simple model proposed by the authors in this paper uses only the nearest points 1 and 2 to estimate the point 0.

Table 4 Exploration Spacing for Undrained Shear Strength

Estimation error σ_E (kPa) / θ (degree)	Horizontal exploration spacing, Δh (kPa)			
	0.25 C $(0)^{0.5}$	0.50 C $(0)^{0.5}$	0.75 C$(0)^{0.5}$	0.95 C$(0)^{0.5}$
0°	10	43	124	349
15°	13	58	165	466
30°	13	58	165	466
45°	13	58	165	466
60°	10	43	124	349
75°	13	58	165	466
90°	16	72	207	582
105°	16	72	207	582
120°	13	58	165	466
135°	13	58	165	466
150°	10	43	124	349
165°	6	29	83	233
180°	10	43	124	349

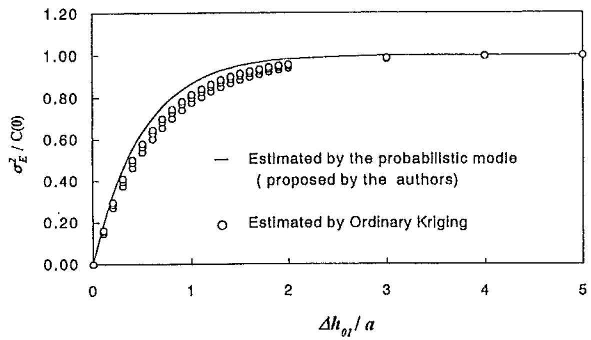


Fig. 20 Comparison of the Estimation Error Between the Proposed Probabilistic Estimation Model and Ordinary Kriging Approach (when Δh_{12} >> a)

SUMMARY AND CONCLUSIONS

A probabilistic model has been presented in this paper to determine the sample spacing during site exploration. The correlation distance, variance, and other statistical characteristics of soil properties such as undrained shear strength, soil layer thickness, have been established by a geotechnical database system for ground information for Saga Plain, Japan. The following conclusions can be drawn from this study:

1. The probabilistic model evaluates spacing of exploration, according to the estimation error or uncertainty of soil properties, which may be later used for a reliability-based design.

2. To obtain the borehole spacing during investigation using the suggested model, a priori knowledge of the statistical parameters such as correlation distance a, variance $C(0)$, etc., is required. The use of database appears the best way to obtain these statistical parameters for a ground.

3. For an estimation error of less than 2.5 m in layer thickness, an exploration spacing of less than 100 m in horizontal plane is required for site exploration in Saga Plain.

4. The correlation distance *a* of layer thickness and undrained shear strength varies in different directions within the soft ground of Saga Plain. This is a characteristic feature of the soft ground in Saga Plain. The direction of the largest correlation distance (a = 1867 m) of the layer thickness is near the northeast direction ($\theta = 60^\circ$), which almost coincides with the direction of the riverbed of the Chikugo River. The vertical correlation distance of undrained shear strength is 3 m, while the longest correlation distance (a = 526 m) in horizontal plane is the one in south-north direction ($\theta = 90^\circ$) of the plain.

5. It is evident that the estimation error of the suggested model has a good agreement with the kriging error and is the estimation error in the safe side.

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