

CHARACTERIZATION OF INHERENT RANDOM HETEROGENEITY OF WEATHERED GRANITE

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ABSTRACT: Soils derived from granitic rocks exhibit a complex degree of variability in space. A grid was established having 5 m intervals spanning 50 m in length and 20 m in width in order to investigate inherent random heterogeneity of areas covered with weathered granite. Six major patterns of cone resistance varies with the depth were identified. Main grid was further divided at selected locations in 1m grids and at one location in 25 cm grids spanning 1 m in both directions for better understanding of spatial variability at close proximity. The analyses revealed that the coefficient of variation of cone resistance can be presented as 20% independent of the depth. Geo-statistics has been shown to be a useful technique in the assessment of inherent random heterogeneity of weathered granitic profiles. Semi-variogram analyses showed that the Spherical Models is best fitted to represent the spatial autocorrelation and prediction of cone resistance for areas covered with weathering remnants of granitic rocks.

Keywords: Cone Resistance, Coefficient of Variation, Inherent Random Heterogeneity, Geo-statistics

1. INTRODUCTION

Geotechnical variability is a complex attribute which results from many sources of uncertainties. The three primary sources of uncertainties are inherent random heterogeneity (also known as inherent variability or spatial variability), measurement error, and transformation uncertainty. This paper deals with inherent random heterogeneity of cone resistance data collected from natural slopes having weathered granitic profiles at Hiroshima prefecture, Japan. Inherent variability is primarily due to the natural geological processes that produced and continually modify the soil mass in-situ.

Soils are inherently heterogeneous. Soils have been formed by a combination of various geological, environmental, and physical-chemical processes. Many of these properties are continuing to vary with time slowly. However, the in situ properties varying both vertically and horizontally are much important for geotechnical analyses. Several researchers have investigated inherent uncertainty and those studies such as [1], [2], [3], [4], [5], and [6] are available in the literature. Due to differential weathering processes over the years, granitic rocks profiles exhibit erratic weathering fronts with varying material properties spatially [7]. Figs.1(a) and (b) illustrate a typical weathering profile of weathered granite collected from a trench at Mt. Gagara, and the sketch of the scattered un-weathered remnants, respectively. In order to accurately model the spatial variability of in-situ strength properties of weathered granitic profiles, a large number of test data are required.

In this study, data were collected from the extensive field investigation that was carried out primarily to determine the stability of natural slopes of weathered granite at Mt. Gagara in Hiroshima prefecture, Japan [9]. Cone resistance data were collected from grid spaces 5m, 1m and 0.25m in which the in-situ tests were carried out till to the hard stratum of rock.

To analyze the inherent random heterogeneity of cone resistance of weathered granite, two main statistical approaches were used; Coefficient of variation (CV) and geo-statistics. Conventional statistics such as CV are based on basic hypotheses, and do not relate with the spatial dependence between data. In contrast, geo-statistics based on the theory of regionalized variables, and deals with deterministic values in

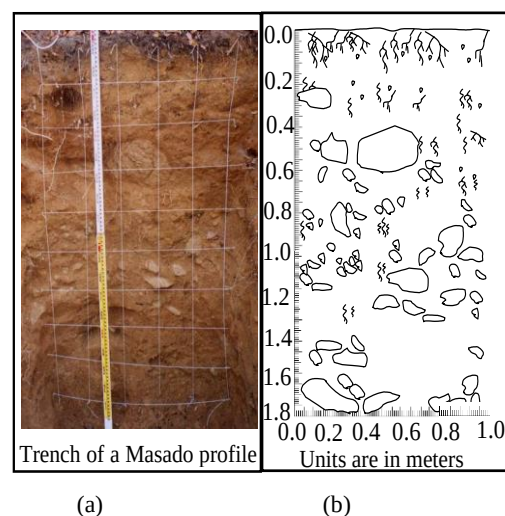


Fig.1 Typical weathering profile of granite [8]

every point in the reference domain. The prime purpose of this study was to find the degree to which cone resistance data scattered in 2D plane for a given depth. Both of above approaches were used to model the variability of cone resistance data.

2. SITE INVESTIGATION

The field investigation was carried out at Ikeno-ue situated on the northern slope of Mt. Gagara as shown in Fig.2. It is located about 800 m east of the academic area of Hiroshima University, Japan. An area of 20 m x 50 m was selected between the ridge and the middle slope, and divided the area into 5 m x 5 m grids as shown in Fig. 5. The slope angle at the selected site varies between 10° to 30° and the area is covered by weathered remnants of granites. This area was subjected to a landslide in year 1999 owing to heavy rainfall and the present study location is about 50 m away from the failure area. Lightweight dynamic cone penetration tests (LWDCPTs) were conducted at each of 55 grid nodes (from a-1 to e-11) to examine the variability of cone resistance in 5 m grids. Also, in-situ tests were conducted at nodes of 1m (40 tests), and 0.25 m (25 tests) grid spaces within the main grid. Fig. 5 illustrates the locations of 1 m, and 0.25 m grids within the main grid. Fig.6 shows the sketch of 0.25 m grid. At each grid node, three tests were conducted until the cone resistance becomes to 10 MPa, which is good enough to determine the hard stratum of the soil profile.



Fig.2 Location of the site and Ikeno-ue landslide

LWDCPT apparatus is shown in Fig.3. It has

been designed and developed in France since 1991 [10]. The total weight of all parts including the carrying case of the device is 20 kg. It mainly consists of an anvil with a strain gauge bridge, Central Acquisition Unit (CAU), and a Dialogue Terminal (DT). The hammer is a non-rebound type and weighs 1.73 kg. The stainless steel rods are 14 mm in diameter and 0.5 m in length. Cones having horizontal sectional area 2, 4, and 10 cm² are available, and a cone holder is used to fix the 4, and 10 cm² cones to the rod. In this study, 2cm² cone was used for in-situ tests as the cone can be extracted after completion of a particular test. However, 4 or 10 cm² cones cannot be extracted after a test.

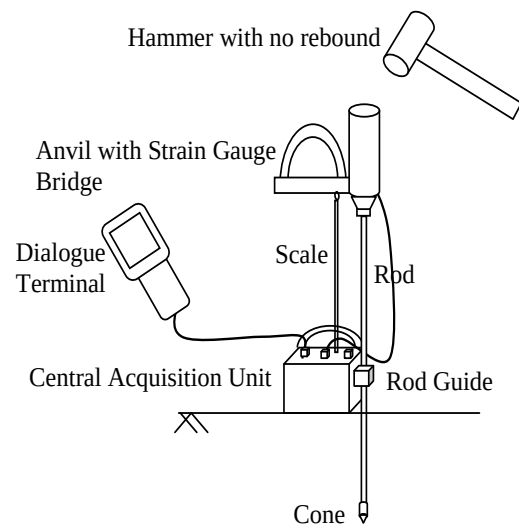


Fig.3 Lightweight Dynamic Cone Penetrometer

The blow from the hammer to the anvil provides energy input, and a unique microprocessor records the speed of the hammer and depth of penetration. The dynamic cone resistance (q_d) is calculated from the modified form of Dutch Formula [11], [12] as shown in Eq. (1). On the screen, dialogue terminal displays not only real time data both graphically and in tabular form but also dynamic cone resistance and penetration depth.

$$q_d = \frac{1}{A} \cdot \frac{\frac{1}{2} M \cdot V^2}{1 + \frac{P}{M}} \cdot \frac{1}{x_{90^\circ}} \quad (1)$$

Where:

x_{90° = penetration due to one blow of the hammer by 90° cone (m),
 A = area of the cone (m²),
 M = weight of the striking mass (kg),
 P = weight of the struck mass (kg), and
 V = speed of the impact of the hammer (m/s).

2.1 Preliminary Data Analysis

LWDCPTs data collected from main grid nodes were statistically analyzed, and the penetrograms (soundings) of each location were plotted. Further analyses were carried out to examine the possible similarities within the soundings. It was found that, most of the soundings could be grouped into six trends (patterns) according to the cone resistance varies with profile depth as shown in Fig.4. The areas covered by each pattern are marked in Fig. 5. The characteristics of the patterns are shown in Table 1.

Table 1 Characteristics of the patterns

Pattern	Characteristics
A	A gradual increase of penetration resistance with depth and shows a comparatively thick weathering front over the bed rock.
B	Gradual increase of penetration resistance with depth. However, penetration resistance is higher than that of pattern A. This group also shows thick weathering front.
C	This class shows considerably shallow profiles than those of patterns A and B. Gradual increase of cone resistance with the depth with greater increment ratio.
D	Although the profile thickness is similar to that of pattern C, the trend of increases the cone resistance with depth is quite low; shows very low values of penetration resistance, about 1 MPa, almost up to 2.0 m. This soil is mostly the colluvium.
E	The trend of increase in cone resistance is similar to that of pattern D. However, the profile thickness is less: about 1.2 m.
F	This group shows the shallowest profiles (total depth is about 0.5 m) and exhibits higher increment ratio of penetration resistance.

3. STATISTICAL ANALYSIS TO MODEL THE INHERANT HECTEROGENEITY

Classical statistical methods are basically a spatial and a temporal methods where the spatial and temporal coordinates are ignored. In this study, one of the classical method, coefficient of variation (CV) was used to find the random heterogeneity of the cone resistance data. CV

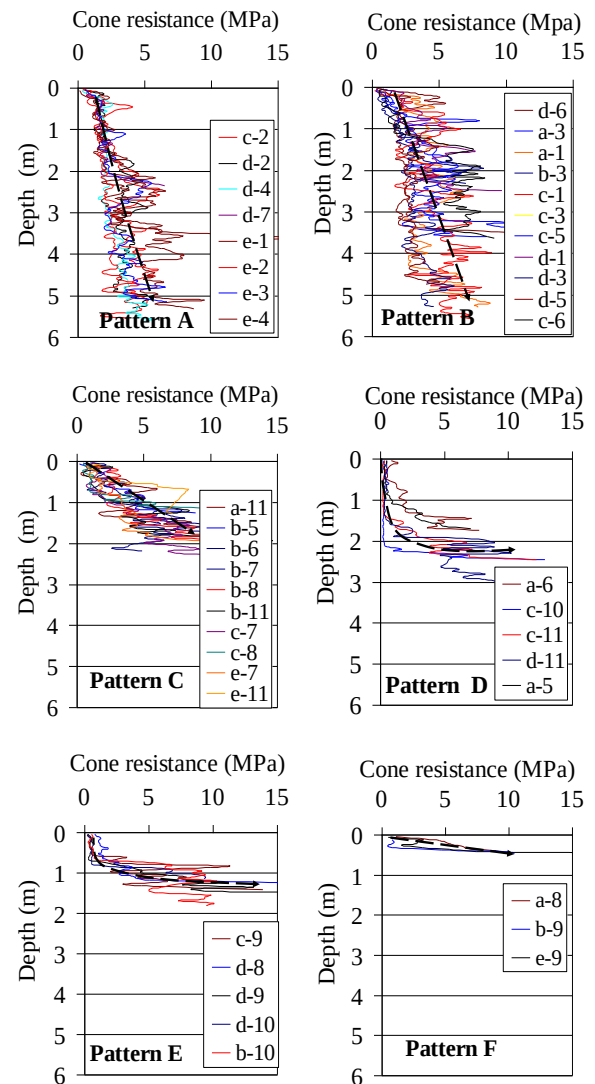


Fig.4 Variation of cone resistance with depth

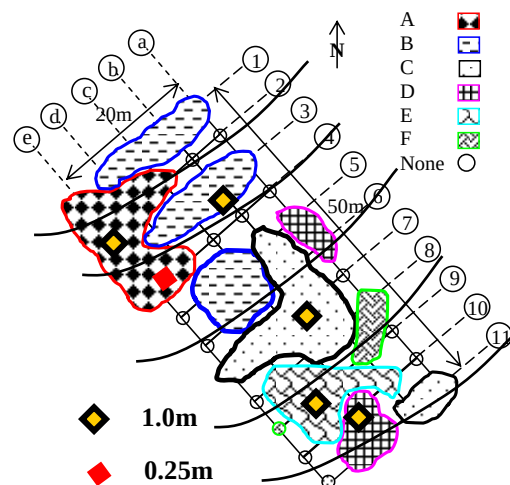


Fig.5 Location of in-situ test grids and areas of patterns

measures the degree into which the set of data varies and often refers as relative standard deviation. The mathematical formula to calculate CV is shown in Eq. (2).

$$CV = \frac{\sigma}{\bar{X}} * 100\% \quad (2)$$

Where:

σ is standard deviation, and $\bar{X}$ is the mean.

Data, which belong to each pattern as demonstrated in Fig. 4, were statistically analyzed based on Eq. (2) in order to find the variability of cone resistance varies along the depth and within the each pattern. Fig.7 illustrates the variability of cone resistance within each pattern. CV of pattern A is about 20% throughout the profile depth and the rest of patterns show slightly higher variability. Pattern B shows the highest variation of CV (up to 40%), may be due to high variability of cone resistance varies within the small range of depth. In a similar manner, data of soundings collected at 1.0 m, and 0.25 m grid spaces were analyzed based on Eq. 2 irrespective of patterns. Fig. 8 shows the CV varies along the depth for 0.25, 1.0 and 5 m grid spaces. It can be observed that the CV varies along the depth for all grid spaces.

Comparison of data revealed that the CV varies from 10% to 30% in general for all range of depths. This may be due to the incomplete weathering patterns of granitic rocks along the profiles. However, significant variations are observed near shallow depths (<0.5 m) and greater depths (>2.5 m). This may be due to the differential weathering at depths more than 2.5 m and presence of unweathered remnants at shallow depths. Fig. 9 shows the CV varies with different grid spaces for selected depths, 0.1, 0.5, 1.0, 1.5, 2.0, and 2.5 m. The depth was measured from the ground surface and the assumption was made as the soil profile is parallel to the bed rock.

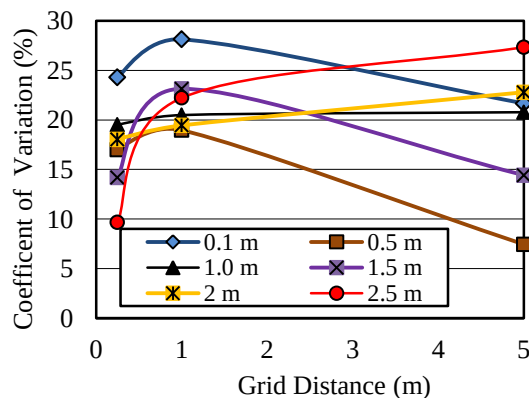


Fig.9 CV with grid spaces for selected depths

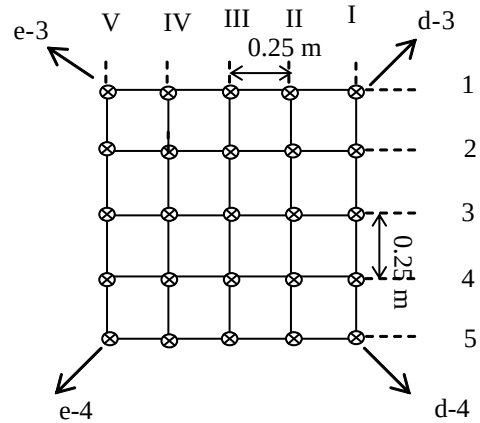


Fig.6 Numbering of .25 m grids

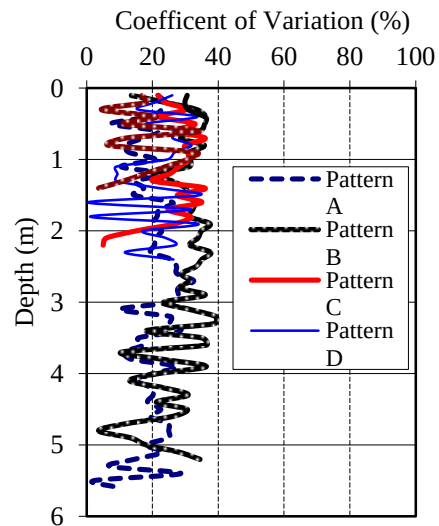


Fig.7 CV for different patterns

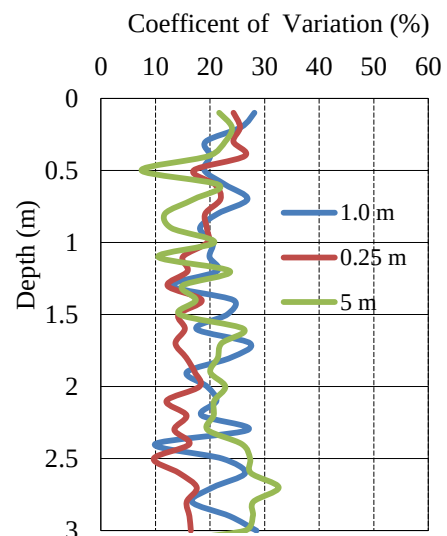


Fig.8 CV varies with depth for grid spaces

The graphs reveal that the CV varies from 0 %

to 30 % for all range of cone resistance data collected at different grid spaces and depth. In general, averagely, CV of cone resistance can be presented about 20% throughout the depths of weathering remnants of decomposed granite profiles. This is almost similar in presenting typical geotechnical engineering parameters.

4. GEO-STSTATISTICAL ANALYSIS OF CONE RESISTANCE DATA

Geo-statistics is a collection of statistical methods which were traditionally used in geo-sciences. These methods describe spatial autocorrelation among sample data and use it in various types of spatial models. Geo-statistics relies on both statistical and mathematical methods, which can be used to predict unknowns to a reasonable accuracy from the stochastic interpolation technique which is based upon establishing the autocorrelation between observation data [1],[13],[14]. It is obvious that properties of sample points close together have less variation than points farther apart. This is the fundamental geographic principal used in geo-statistics. To account for the distance relationship, the values of closer points are weighted more heavily than those farther away. That is the weight of a value decreases as the distance increases from the prediction location.

2D kriging was adopted for the current analysis of cone resistance data. The cone resistance, q_d at an unknown location of interest in XY plane with selected Z coordinate from the 'n' number of data can be written as in Eq. (3) below.

$$q_d(i^*) = \sum_{i=1}^n w_i * q_d(i) \quad (3)$$

Where:

$q_d(i^*)$ is the cone resistance at unknown location,
 $q_d(i)$ is the measured cone resistance at the i^{th} location,

w_i is an unknown weight for the measured value at the i^{th} location, and the summation of w_i must be made equal to one to avoid biasness of the predictor.

The observed values and the predicted values of cone resistance are made as small as possible in order to minimize the statistical expectations of the following formula, from which the parameters of semi-variograms were obtained as shown in Eq. (4).

$$\min \left\{ \sum_{i=1}^n [\gamma(h)_{ij-\text{measured}} - \gamma(h)_{ij-\text{calculated}}]^2 \right\} \quad (4)$$

The measured semi-variance of i^{th} and j^{th} locations, $\gamma(h)_{ij}$, can be calculated from the basic formula shown in Eq. (5).

$$\gamma(h)_{ij} = \frac{1}{2} (q_d^i - q_d^j)^2 \quad (5)$$

Where:

q_d^i is the cone resistance at i^{th} location

q_d^j is the cone resistance at j^{th} location

The solution to the minimization, constrained by un-biasedness, gives the kriging equations in a matrix form as in Eq. (6).

$$\begin{pmatrix} \gamma_{11} & \cdot & \cdot & \gamma_{1n} & 1 \\ \cdot & & & \cdot & \cdot \\ \cdot & \cdot & & \cdot & \cdot \\ \cdot & & & \cdot & \cdot \\ \gamma_{n1} & \cdot & \cdot & \gamma_{nn} & 1 \\ 1 & \cdot & \cdot & 1 & 0 \end{pmatrix} * \begin{pmatrix} w_1 \\ \cdot \\ \cdot \\ \cdot \\ w_n \\ m \end{pmatrix} = \begin{pmatrix} \gamma_{1p} \\ \cdot \\ \cdot \\ \cdot \\ \gamma_{np} \\ 1 \end{pmatrix} \quad (6)$$

Where:

γ_{ij} denotes the modeled semi-variogram values between all pairs of observed q_d values,

γ_{ip} denotes the modeled semi-variogram values based on the distance between the i^{th} location and the prediction location,

m (in the weight matrix) is an unknown constant, which arises because of the un-biasedness constraint and can be determined through the calculation process. Solving the matrix as shown in Eq. (6), w_i can be determined and the solution for unknown q_d for location 'p' can be calculated from Eq. (3). In this study, two semi-variogram models i.e Spherical and the Power models were used. Table 2 shows the mathematical formulation of the semi-variograms. Fig. 10 illustrates a sketch of a typical Spherical model.

Table 2 Model semi-variograms

Model	Mathematical Formulation	Remarks
Spherical	$h < a$ $\gamma(h) = C \left(\frac{3h}{2a} - \frac{1}{2} \left(\frac{h}{a} \right)^3 \right) + C_0$ $h > a$ $\gamma(h) = C + C_0$	$C + C_0$ = Sill C_0 = Nugget a = Range h = horizontal distance
Power	$0 \leq \alpha < 2$ $\gamma(h) = \rho h^\alpha + C_0$	ρ = Gradient α = power C_0 = Nugget h = horizontal distance

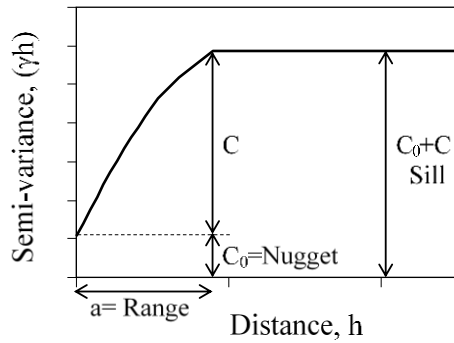


Fig.10 The Spherical Model

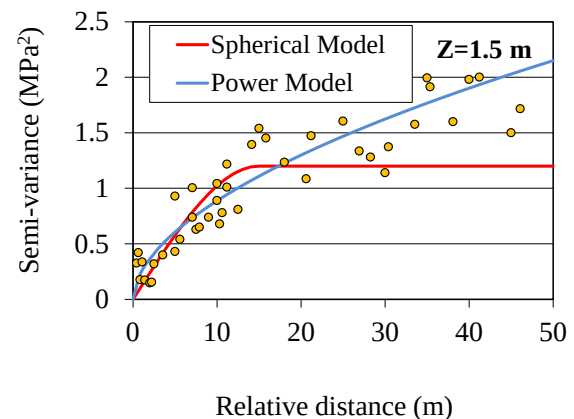
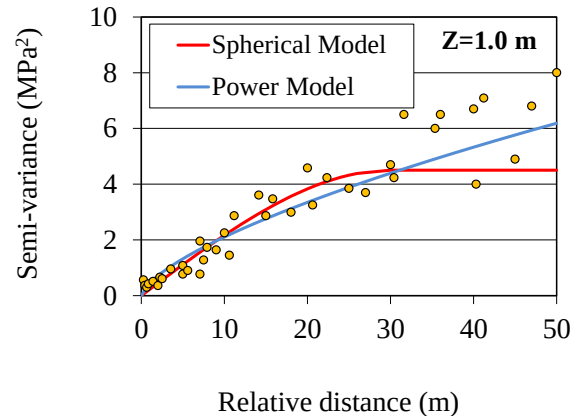
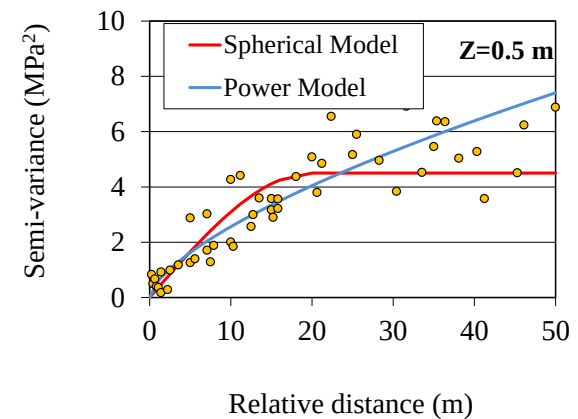
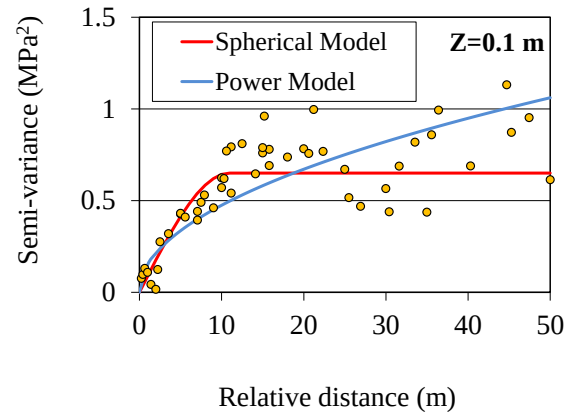
4.1 Analysis of the semi-variograms

All data of in-situ tests except a few data which were kept for verification purpose were used to analyse the semi-variograms. Semi-variograms for the Spherical and the Power Models were calculated for six different depths at $Z=0.1, 0.5, 1.0, 1.5, 2.0$, and 2.5 m. Fig. 11 demonstrates the Spherical and the Power models calculated for above depth intervals. Table 3 shows the parameters of the Spherical and Power models. It was found that the correlated distance increases along the profile depth except for $Z=2.5$ m. The sill ranges from 0.65 to 5.5. Smaller values of sill are observed at shallow depths. Different values of range and sill indicate the inherent random heterogeneity of cone resistance varies with space and also with depth. However, close investigation of the Spherical models for the depth ranges from 1 m to 2.5 m reveals that the parameters “C” and “a” are fairly similar in values and hence there may be a possibility of developing a single semi-variogram model to represent the ranges of depth. Also, it can be observed that the Spherical Model represents the cone resistance data better than the Power model especially the points far away.

Table 3 Parameters for semi-variograms

Depth/ m	Parameters			
	Spherical		Power	
	C	a	ρ	α
0.1	0.65	11	0.15	0.50
0.5	1.2	15	0.25	0.55
1.0	4.5	20	0.56	0.66
1.5	5.0	25	0.3	0.84
2.0	4.5	30	0.45	0.67
2.5	5.5	25	0.60	0.64

The Spherical Model was found to be the best-fitted semi-variogram for the Masado profiles. The Power Model also showed reasonable agreement with the observed data. Therefore, these models can be applied to evaluate the cone



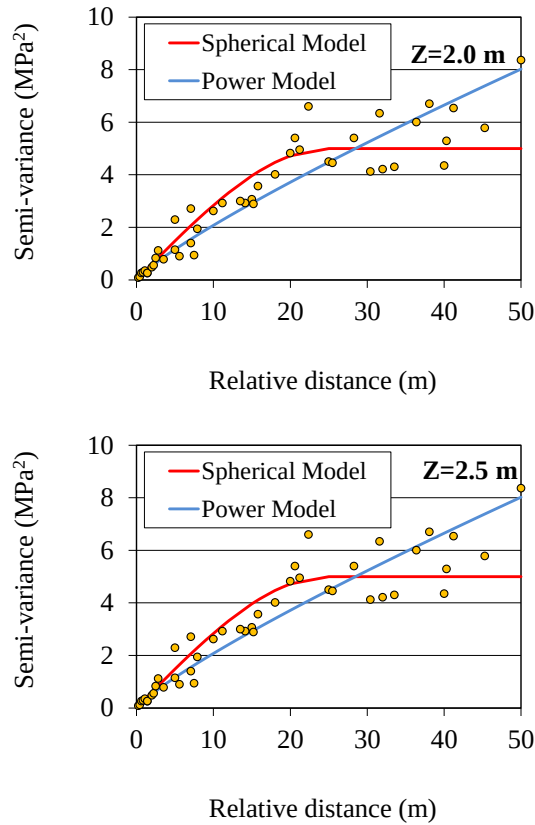


Fig.11 Modeled semi-variograms

resistance in an unknown location of interest.

The range of influence of weathered granitic profiles was found to be varied with the profile depth. This is graphically presented in Fig. 12 for selected depths. The correlated distance (range as in Table 3) varies from 11 m to 30 m with the depth ranges from 0.1 m to 2.5 m. This gives some idea for determination of grid spaces in carrying out in-situ investigation of natural slopes having weathering remnants of decomposed granite.

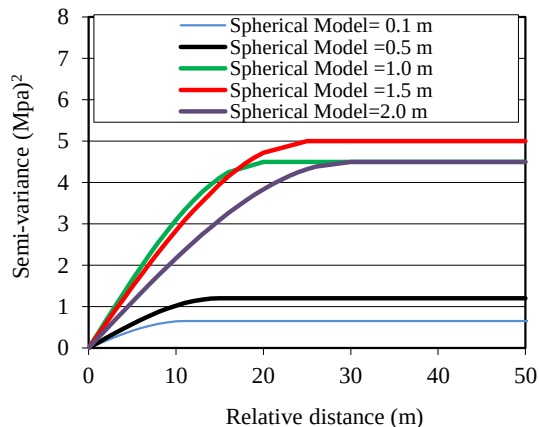


Fig.12 Correlated distance of cone resistance

4.2 Comparison of observed and predicted soundings

Six data points of 0.25 m grids, which were not considered in developing the semi-variogram models, were used for the prediction of cone resistance at several depths. The predicted data were then compared with the measured data. Fig. 13 demonstrates the observed and predicted soundings of I-3, I-5, III-4, IV-3, V-1, and V-5 locations of 0.25 m grid as shown in Fig. 6. It can be seen that the observed values agreed well with the predicted values of both Spherical and Power models. This implies that the developed semi-variogram models can be successfully applied for weathered granitic profiles.

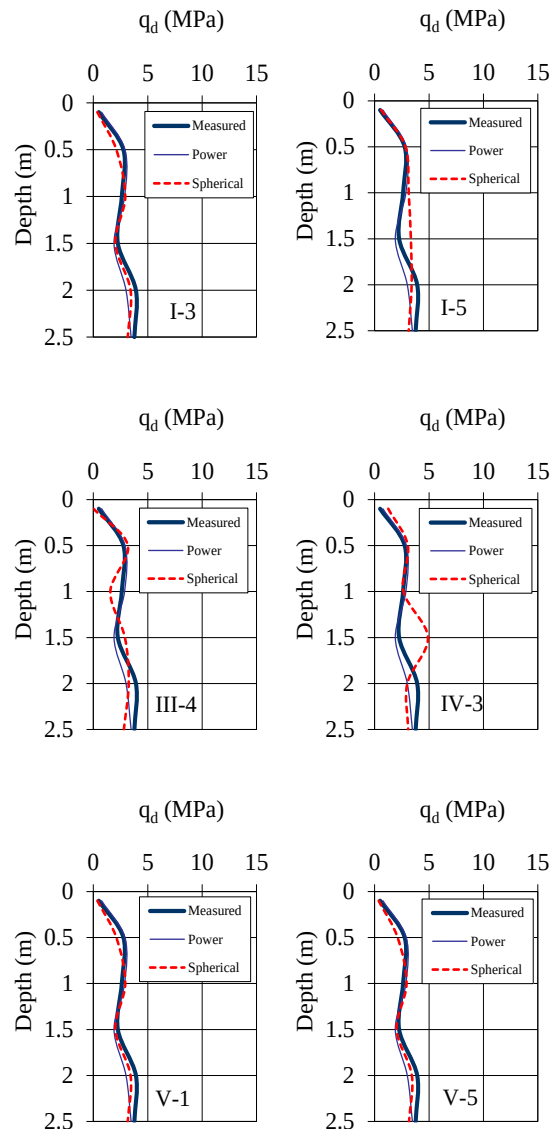


Fig.13 Observed and predicted soundings in close proximity

5. CONCLUSIONS

This paper was focused in presenting the inherent random heterogeneity of weathered granitic profiles found in Hiroshima prefecture, Japan. Two approaches were used to model the variability of cone resistance varies spatially. Following conclusions were drawn from the light of this study.

1. Six major patterns, patterns A to F, of cone resistance varies along the depth were identified in weathered granitic profiles. This classification was based on the trend of change of cone resistance with the depth. Patterns A and B show comparatively thicker profiles. Patterns D and E show very low cone resistance at shallow depths.
2. The inherent random heterogeneity of weathered granitic profiles was studied based on the coefficient of variation, CV. The cone resistance data collected at 5 m, 1 m, and 0.25 m grid spaces were quantitatively analyzed and found that CV varies from 0 % to 40 % for all range of data. In general, on average, CV for cone resistance can be presented as 20% throughout the depths of weathered granitic profiles. This variance is almost similar in presenting typical geotechnical engineering parameters.
3. Geo-statistics, and particularly the semi-variogram, has been shown to be a useful technique in predicating cone resistance of areas covered with weathered granitic remnants. The Spherical Model was found to be the best-fitted semi-variogram. The Power Model also showed reasonable agreement with the observed data.
4. The range of influence of cone resistance was found to be varied with the profile depth. The correlated distance varies from 11 m to 30 m with the depth ranges from 0.1 m to 2.5 m. These outcomes facilitate to determine the grid spaces in carrying out a typical site investigation in natural slopes having weathered granitic profiles in future.

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