Assessment of natural slopes susceptible to failure in heavy rainfall based on in-situ cone resistance data

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Assessment of natural slopes susceptible to failure in heavy rainfall based on in-situ cone resistance data

A.M.R.G. Athapaththu[i)] and Takashi Tsuchida [ii)]

i) Assistant Professor, Department of Civil and Environmental Engineering, Hiroshima University, Higashi-Hiroshima, Japan.
ii) Professor, Department of Civil and Environmental Engineering, Hiroshima University, Higashi-Hiroshima, Japan.

ABSTRACT

Slope failures are major natural disasters in Hiroshima prefecture, Japan under intense rainfall conditions. Both people and property were affected severely due to these disastrous events during past few decades. 32,000 planar slopes and valleys were susceptible to failure in Hiroshima prefecture, Japan have been identified by Hiroshima prefectural government and was developed a hazard assessment system thoroughly based on rainfall and past records of the data. However, the developed system can only be accommodated in a large area 5 km x 5km grid, and not be possible to predict the individual slope failure in the region. Geotechnical investigation of natural slopes is challengeable especially when natural slopes having higher gradients and access is difficult and also to estimate shear strength parameters spatially. Recently, authors have conducted a series of in-situ investigations based on the newly developed lightweight dynamic cone penetrometer to examine its applicability in analyzing the slopes covered with weathering remnants of granitic rocks. Six patterns were identified based on the penetration resistance varying with the depth. Semi-variogram analysis showed that the correlated distance of cone resistance varies with 11 to 30 m depending on the depth. A series of laboratory calibration tests based on the lightweight dynamic cone penetration tests, and direct shear tests were conducted at different void ratios and degrees of saturation. Based on the laboratory calibration test results, a method of determining void ratio, e from the data of q_d was presented. Based on this, two formulas to evaluate shear strength parameters, cohesion and friction angle, were established with the cone resistance and the degree of saturation. As a whole proposed method can be successfully applied to individual slopes to determine the profile thickness, and to evaluate the shear strength parameters spatially. Based on this, hazard assessment of individual slopes can be made.

Keywords: cone resistance, shear strength, geo-statistics

1. INTRODUCTION

Majority of slope failures in Japan are trigged by rainfalls in monsoon seasons. These failures are not only put loss of human lives but also cause lot of damages to the existing infrastructures. At present, nearly 32,000 natural slopes and valleys are found to be susceptible to failures in Hiroshima Prefecture, the highest among any prefecture in Japan, (Hiroshima Prefecture, 2011). The regional hazard assessment system utilized by Hiroshima Prefectural government is thoroughly based on the recorded rainfall and the rainfall-failure relationship in each 5 km×5 km area obtained from the past records of landslide disasters. In this system, the failure of slope/s and evacuation orders can be given for an area of 5 km×5 km, and the hazard of an individual slope cannot be predicted. This is an empirical system, and is not adequate for more accurate assessment of individual slopes as any reliable slope stability analyses had not been conducted by incorporating proper geotechnical inputs in developing the system. It is well known that the shear strength parameters, cohesion, and internal angle of friction, play a major role in the stability of slopes. Slope angle, thickness of soil layers, water table fluctuations and change of degree of saturation with time depending on intensity of rainfall are other triggering factors that need to be considered in the stability analysis. Therefore, the authors have taken initiatives to develop a sound methodology explore the natural slopes covered with weathered granite and to analysis the stability of slopes in the region. The developed method is based on lightweight dynamic cone penetrometer which was developed in France since 1990.

1.1 Lightweight dynamic cone penetrometer

Lightweight Dynamic Cone Penetration Test (LWDCPT) device has been designed and developed in France since 1991 (Langton, 1999). The schematic view of LWDCPT device is shown in Fig 1(a). 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 rebound type and weighs 1.73 kg. The stainless steel rods are 14 mm in diameter and 0.5 m in length. Cones of 2, 4, and 10 cm^2 in area are available, and a cone holder is used to fix the 2 cm^2 cone to the rod. The device can be operated by one person at almost any location to a depth of 6 m.

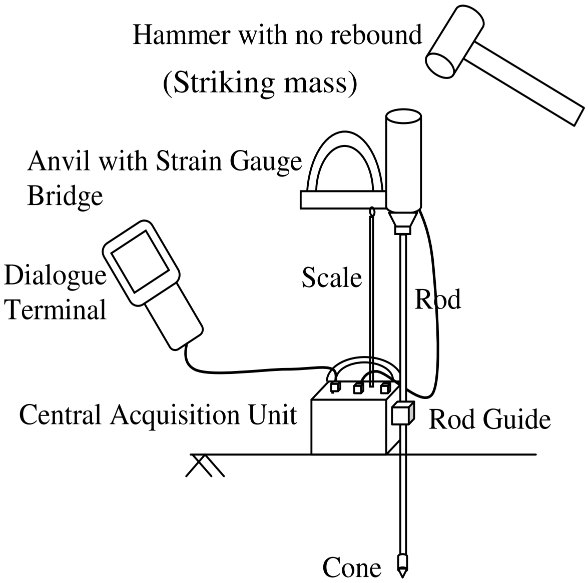


Fig. 1. Lightweight Dynamic Cone Penetrometer.

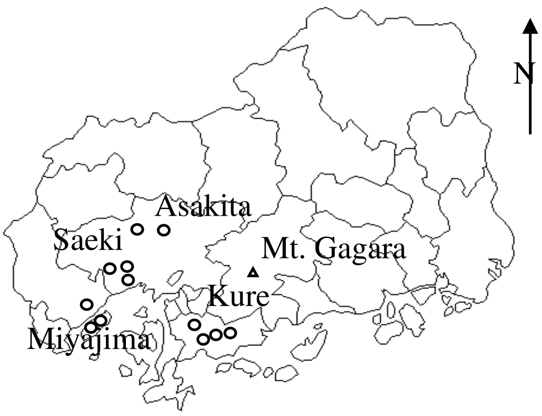
2 SITE INVESTIGATION AND ANALYSIS OF SITE DATA

The base investigation was carried out at Ikeno-ue situated on the northern slope of Gagara Mountain (Fig 2) 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 2(c). LWDCPTs were conducted at each of 55 grid nodes. At each 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. Further in- situ tests were conducted at 2.5m, 1 m, and 0.25 m intervals at the designated area marked in Fig 2 (c) to examine the variation of cone resistance at different proximities. Later theses data were used for geo-statistical analysis.

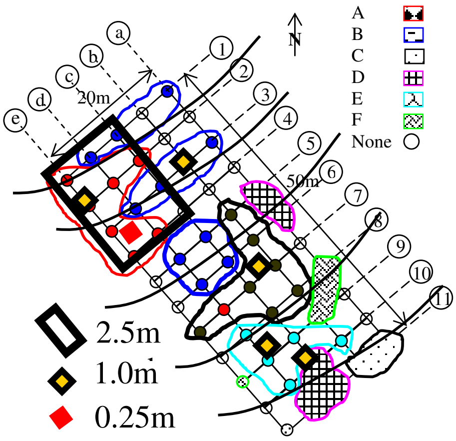
2.1 Analysis of cone resistance data for Classification

The data of LWDCPTs collected from 55 nodes of Mt. Gagara were statistically analyzed, and the average cone resistance in 50 mm intervals was calculated. The penetrograms (soundings) of each location were graphically presented and further analysis was carried out to examine the possible similarities within soundings. Observations were made as the most of the soundings could be fitted into six patterns based on the trend of variation in cone resistance with depth as shown in Fig. 3. The characteristics of patterns are given in Table 1 (Athapaththu et. al, 2007).

(a) Site locations in Japan and South Korea



(b) Site locations in Hiroshima prefecture



(c) Areas of Patterns and Grid Arrangements

Fig. 2. Site locations and grid arrangements.

2.2 Classifications of soundings of other sites

The LWDCPTs carried out at two locations in Mt. Gagara, Hiroshima Prefecture, Japan and two slopes in Mt. Rokko in Kobe, Japan were classified and are shown in Table 2. Pattern D is dominated in Mt. Gagara and shallow profiles were observed in the Mt. Rokko. The in-situ investigation was carried out at southern part of South Korea ; Namwon, Daegok, and Dam yang recently. These sites covered with remnants of weathered granitic rocks. The data collected from South Korea were analyzed based on the classification developed for Mr. Gagara (Athapaththu et. al, 2014). Table 1 summarized the distribution of pattern in these investigated locations. Major portion of soundings at Namwon was identified as Patterns D and E which have the low cone resistance.

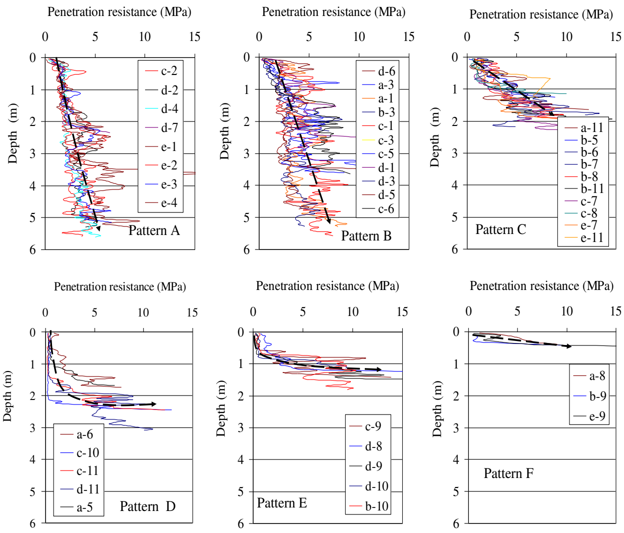


Fig. 3. Six patterns of soundings

Table 1. Characteristics of the patterns

Pattern	Characteristics
A	A gradual increase of penetration resistance with depth. These profiles show a comparatively thick weathering front over the bed rock.
B	Gradual increase of penetration resistance with depth. However increment ratio is greater 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 increment ratio of higher penetration resistance.

Table 2. Distribution of the patterns.

Location	No. of data	Percentage of patterns (%)					
		A	B	C	D	E	F
Mt. Gagara I	24	39.0	13.0	-	48.0	-	-
Mt. Gagara II	26	-	14.0	-	50.0	29.0	7.0
Mt. Rokko, Kobe I	19	25.0	-	-	38.0	25.0	12.0
Mt. Rokko, Kobe II	9	20.0	5.0	5.0	21.0	24.0	25.0
Namwon-I	15	-	6.7	-	33.3	33.3	26.7
Daegok	10	30.0	20.0	20.0	-	20.0	10.0
Dam yang	6	-	-	50.0	16.7	16.7	16.6

2.3 Use of geo-statistics to determine the spatial variability of cone resistance

Geo-statistics, and particularly the semi-variograms, have been shown to be a useful technique in recent studies to examine the spatial distribution and hence applied it for the present study. 2D kriging was adopted for the current analysis of cone resistance data. 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 meters. The data were collected from the intensive in-situ investigations conducted at Mt. Gagara as shown in Fig 2 (c). The depth was measured from the ground surface and the assumption was made as the soil profile is parallel to the bed rock. Fig.4 illustrates the finding of the analyses and it was found that correlated distance of cone resistance varies from 11 m to 30 m depending on the depth (Athapaththu et. al, 2007). Further it was observed that correlated distance increases with the depth. This analysis is helpful to determine the spacing between in-situ tests locations within a site for future investigations.

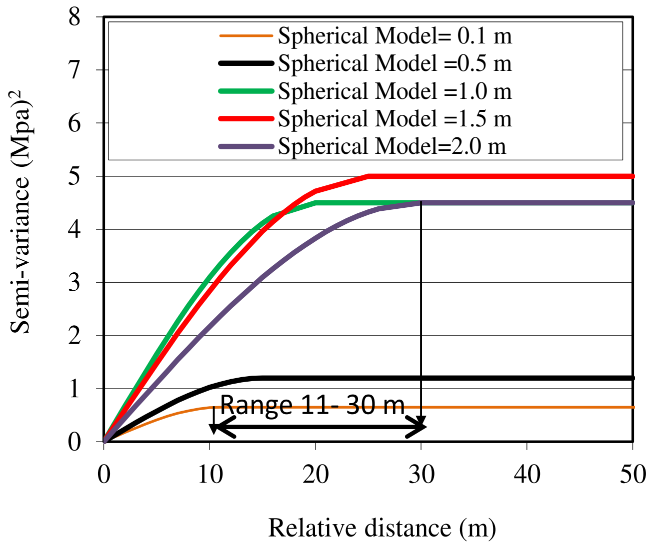
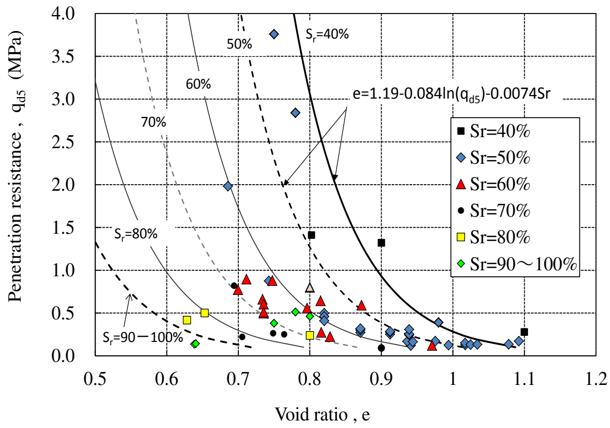


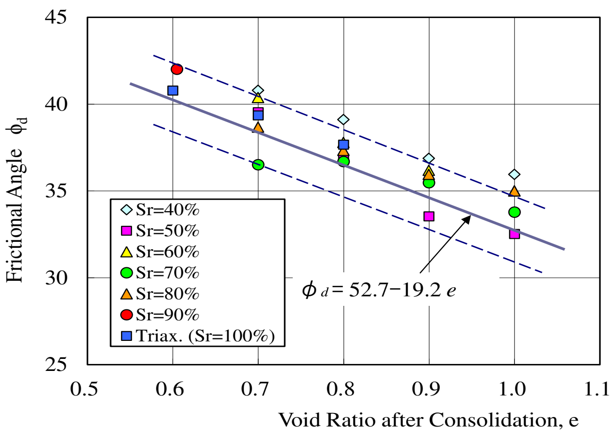
Fig. 4. Correlated distance of cone resistance.

3 RESULTS OF DIRECT SHEAR AND CALIBRATION TESTS

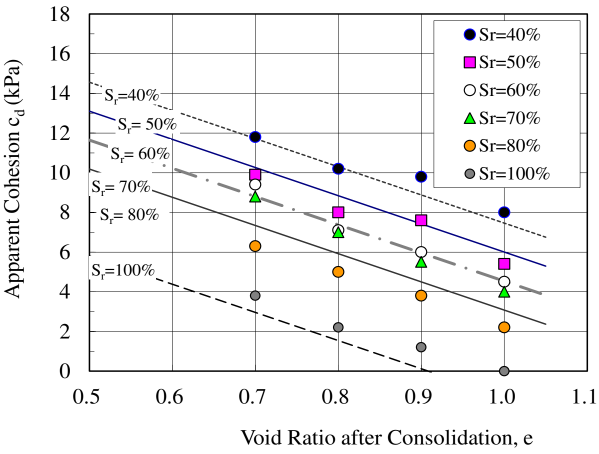
The main objective of this part of research was to establish sound relationship with shear strength parameters, ϕ_d and c_d with cone resistance, q_d under different void ratios and degrees of saturation. To fulfil this task, a series of laboratory direct shear tests were carried out varying void ratios and degrees of saturation. Also, laboratory scale calibration tests were conducted based on LWDCPT for different void ratios and degrees of saturation. The testing program consisted of (i) consolidated drained direct shear box tests conducted at void ratios ranging from 0.7 to 1.0 in 0.1 increments at a constant degree of saturation (ii) Repeat of (i) at different degrees of saturation varying from 40% to 100%. Laboratory scale calibration tests were conducted on weathered granitic soil prepared in soil columns for different degrees of saturation and void ratio as mentioned above. Fig 5(a) illustrates the relationships between cone resistance and void ratios for different degrees of saturation. The cohesion c_d, and the friction angle, ϕ_d varying with void ratios under different degrees of saturation are shown in Figs. 5 (b) and (c).



(a) Cone resistance varies with void ratio, *e*.



(b) Friction angle varies with void ratio, *e*.



(c) Apparent cohesion varies with void ratio, *e*.

Fig.5 Relationships of shear strength parameters with *e*, and S_r.

Equations (1) and (2) were derived based on the Fig. 5, and can be used to calculate shear strength parameters for soils derived from weathered granite (Tsuchida et.al,2011; Tsuchida et. al, 2014). Here S_r is the degree of saturation at the time of conducting the in-situ tests and qd_5 is the cone resistance for 5kPa overburden stress. Once the friction angle is determined from Equation (1), c_d can be calculated based on Equation (3).

$$\phi_d = 29.9 + 1.61\ln(q_{d5}) + 0.142 S_r \quad (1)$$

$$c_d = 10.6 + 1.19\ln(q_{d5}) - 0.041 S_r \quad (2)$$

$$c_d = \frac{\phi_d}{1.35} - 11.6 - 0.146 S_r \quad (3)$$

4 APPLICATIONS OF FINDINGS TO GEOTECHNICAL INVESTIGATION AND DISCUSSIONS

In this study, in situ investigation of natural slopes and shear strength parameters required for the analysis were thoroughly discussed. A typical procedure for the investigation of a slope is summarized below.

1) Gather the geological and topographical maps of the area of interest (susceptible valley of interest).
2) The in-situ testing points are determined at both sides of the valley center from top to the foot at 20 m intervals.
3) At each testing point, the gradient of slope need to be measured and the LWDCPTs are to be carried out. The soil samples will be taken at 30 cm depth for permeability tests, and other laboratory tests.

Fig. 6 shows an example of investigation carried out at a valley in Mt. Gagara. Along the lines A, and B, LWDCPTs and soil sampling were carried out. Based on the developed relationships, shear strength parameters were determined and are illustrated in the cross sections of lines A and B as drawn in Figs 7 (a) and (b).

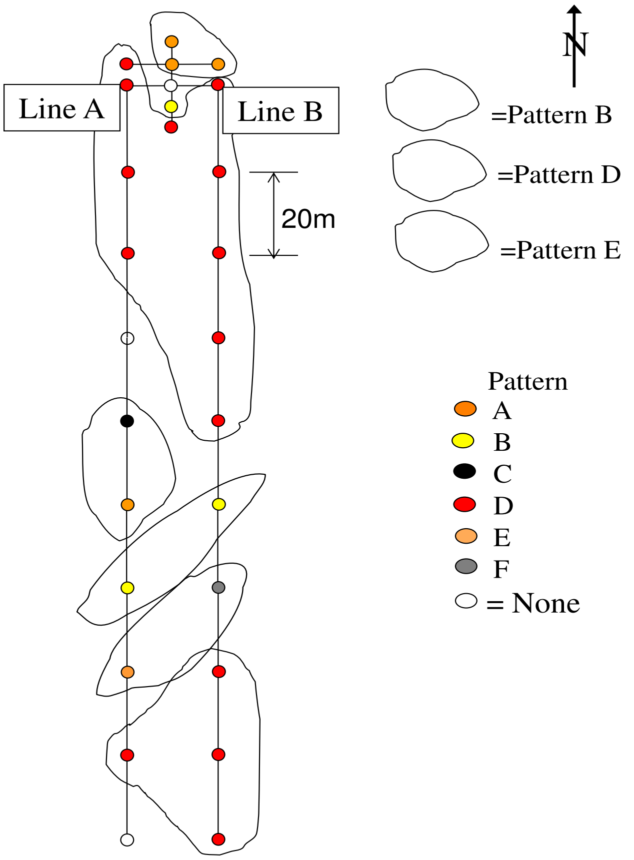
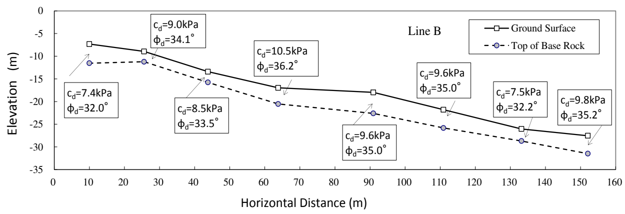
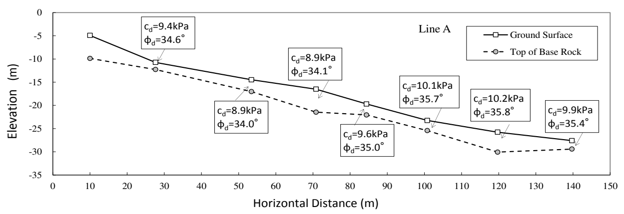


Fig.6 Pattern categorization.



(a) Line A



(b) Line B

Fig.7 Cross section and shear strength parameters for stability analyses.

Using this information, it is now possible to analyses the slope for the measured or predicted rainfall data for known degree of saturation at the time of interest. The rest of the slopes which is susceptible to failure can be well assessed through the proposed methodology. However, collecting the information of individual slopes is challengeable as the number of susceptible slopes/valleys is very high in Hiroshima prefecture, Japan. A day is required to investigate and carryout the in-situ tests at a given site.

5 CONCLUSIONS

This study was focused to find an effective method for site investigation and analysis of slopes susceptible to failure in weathered granitic rocks in Hiroshima prefecture, Japan. Based on the outcomes of this research following conclusions were drawn.

1. Six patterns of cone resistance varying along the depth were identified in the weathered granitic profiles. The proposed six patterns were successfully applied for the different locations and found that most of the soundings can be fitted into one of the pattern. Therefore, proposed classification can be successfully applied to the terrains having weathered granite.

2. The Spherical Model was found to be the best-fitted semi-variogram for the granitic profiles and hence can be applied to evaluate the cone resistance at unknown location. The correlated distance varies from 11 m to 30 m with the depth increases 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 of weathered granite.

3. Based on the cone resistance data, q_d, relationships were developed to calculate shear strength parameters in terms of degrees of saturation as;

$$\phi_d = 29.9 + 1.61\ln(q_{d5}) + 0.142S_r$$

$$c_d = \frac{\phi_d}{1.35} - 11.6 - 0.146S_r$$

4. A sound method was established to assess the slopes vulnerable to failure in the region. This includes site investigation and parameters required for stability analysis. It is possible to carryout stability analyses continuously with the change of degree of saturation and water table fluctuations due to rainfall.

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