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COMPARISON BETWEEN CPT AND SDS DATA FOR SOIL CLASSIFICATION IN CHRISTCHURCH

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Abstract: A large number of civil engineering structures were damaged due to liquefaction during huge recent earthquakes in Christchurch and need to be reconstructed. Prior to reconstruction, properties of soils in different areas should be identified and, based on behavior of underlying soils, appropriate foundation for structures should be designed. Cone Penetration Test (CPT) is one of the most common in-situ tests for soil characterization. However, this test is relatively expensive and needs skilled operator. Therefore, Swedish Weight Sounding (SWS) test has become popular for ground investigation as it does not occupy large space and it is simpler and faster compared to other methods. Nevertheless, using SWS has some disadvantages such as low accuracy of soil classification and rod friction is excluded in the test results. The Screw Driver Sounding (SDS) test developed in Japan is a new operating system for SWS consisting of a machine that drills a rod into the ground at different steps of loading while being rotated. This machine can continuously measure the required torque, load, speed of penetration and rod friction during the test, so can give a better overview of the soil profile along the depth of penetration. In this paper, based on the test conducted in Christchurch adjacent to a borehole and a CPT site, a comparison of the accuracy of soil classification based on CPT and on SDS method is discussed. The results confirm the advantages of SDS over the CPT method in terms of accuracy for soil classification.

1. INTRODUCTION

It is well understood that huge earthquakes can cause severe damage to civil engineering structures. Following the devastating earthquakes in Christchurch, a significant part of the structures was either destroyed or badly damaged and need to be reconstructed. A significant part of such damage was related to ground failures associated with liquefaction. Liquefaction is a phenomenon that occurs in saturated, sandy soils during earthquakes, which results in a loss of soil strength and bearing capacity. The city of Christchurch is situated on the east coast of the South Island of New Zealand, which borders the Pacific and Indian-Australian tectonic plates. Adequate knowledge of ground conditions is very important for analyses, design and construction of geotechnical systems. For preventing similar damages in the future, physical and mechanical properties of soils in different areas should be identified prior to reconstruction and based on the behavior of underlying soils, appropriate foundation for structures should be designed.

Recently, the use of in-situ soil testing has increased in geotechnical engineering practice. This is because of the rapid development of in-situ instruments, improved understanding of soil behavior and the subsequent realization of the limitations and inadequacies of some conventional laboratory testing (Eslami, 2006). Several in-situ tests obtain direct measurements of soil properties and geotechnical parameters (AASHTO, 1988). The most common tests include: standard penetration test (SPT), cone penetration test (CPT), Piezo-cone (CPTu), Swedish weight sounding (SWS), flat dilatometer (DMT), pressure meter test (PMT), and vane shear test (VST). Each test applies specific loading patterns to measure the corresponding soil response in an attempt to evaluate material characteristics, such as strength and/or stiffness (AASHTO, 1988).

In this study after a review of CPT, SPT and SWS, a new in-situ test called Screw Driver Sounding (SDS) method is introduced and the results of soil classification by this test in Christchurch is compared to CPT-based soil classification.

2. POPULAR IN-SITU TESTS FOR SOIL CLASSIFICATION

The Standard Penetration Test (SPT) is still the most popular in-situ test (Eslami, 2006). However, plenty of problems and limitations exist for this test, with respect to performance, interpretation and repeatability. These are due to the uncertainty of the energy delivered to the rod, test procedures and operator-equipment effects. On the other hand, the Cone Penetration Test (CPT) is simple, fast, and it gives continuous records with respect to depth. The results are interpretable on both empirical and analytical basis and a variety of sensors can be incorporated by using a cone penetrometer (Eslami, 2006). However this test needs skilled operator to perform (AASHTO, 1988).

Swedish weight sounding (SWS) is another in-situ test that is popular in Japan and Nordic countries. It is estimated that about 20,000 SWS tests are carried out annually in Sweden alone (Broms and Flodin, 1988). The test has also been used in countries like Singapore, Algeria and some east European countries (Bergdahl et al., 1988). Also Habibi et al. (2006) reported the use of SWS in estimating the bearing capacity of foundation for some buildings in southern areas of Tehran, Iran. The key advantages of this test are that it is highly portable, low cost and, similar to CPT, provides a continuous profile of the soil. SWS consists of some pieces of weights (a 5kg clamp, two 10kg and three 25kg weights), a screw-shaped point, 22mm extension rods and a handle (or a motor) for rotating the rods (Habibi, 2006). Figure 1 shows a schematic view of the apparatus and its screw-shaped point.

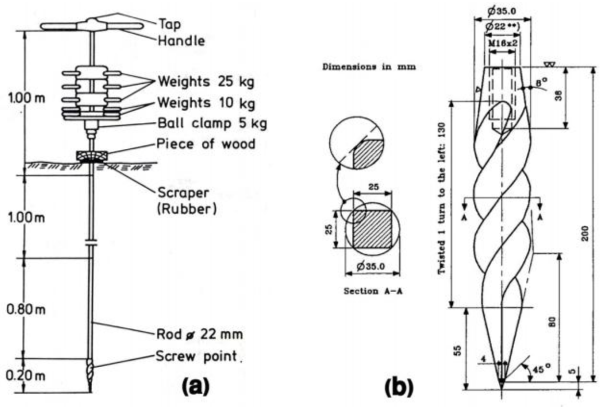

Figure 1 Swedish weight sounding equipment: (a) schematic view of apparatus (Bergdahl et al., 1977); (b) screw-shaped point (ENV19 97:3, 2000).

The penetration resistance of soil can be estimated ether by measuring the required load or the number of half-turns that the screw point is rotated to penetrate to a planned depth. When sounding is performed in soft soil, the penetration resistance is typically measured only through the weight required for penetration of the rods. This means that the weight is increased up to the weight which could penetrate the soil. The levels of static loading used in the test are 0, 5, 25, 50, 75 and 100kg. If the penetration does not occur with 100kg loading, the rod is rotated by using a handle. Although the SWS test is highly portable and simpler than other sounding tests, this test has some disadvantages such as low accuracy in classifying soils. As SWS is usually conducted without soil sampling, soil classification is estimated from the test results, local circumstances at the site and experience of operator. Furthermore, SWS cannot penetrate into very dense soils and the usual depth of penetration is limited to 10-15 m. The other problem associated with the SWS test is that the result is fairly influenced by rod friction, which may affect the measured results. Especially, in case where the soil contains gravel, the required load to penetrate, number of half-turns and consequently soil resistance from the SWS tends to be over-estimated as the rod friction becomes large.

3 SCREW DRIVER SOUNDING TEST

3.1 Background and test procedure

A new operation system for the SWS, the Screw Driver Sounding test, called as SDS, has been recently developed in Japan to minimize the disadvantages of the SWS as well as to incorporate a procedure to measure the rod friction. The machine originally used for the SWS test has been improved to be suitable for the SDS test. In the usual SWS test, there are two loading stages. In the first stage, a vertical load (W_{sw}) is applied to the rod in 4 incremental steps up to a load of 1kN. If the settlement of the rod does not reach 25cm depth, the rod is penetrated by rotating the rod into the soil in the second stage. In the SDS test, on the other hand, a static loading system is used and the number of load steps is increased to 7, while the rod is always rotated at a constant rate during the test. The step loads are 0.25, 0.38, 0.5, 0.63, 0.75, 0.88, 1kN in this order and the load is increased at every complete rotation of the rod. Measured items in the test are maximum torque (Max.T), average torque (Av.T), minimum torque of rod (Min.T), penetration length (L), penetration velocity (V) and number of rotations of rod (N). The data are measured at every complete rotation of the rod. In the SDS as well as the SWS, a set of loading is conducted at every 25cm for penetration and after each 25cm penetration, the rod is lifted up by a few centimeters and then rotated to measure the rod friction. Figure 2 shows the SDS machine during testing in Christchurch.

Figure 2 SDS machine during operation

3.2 Plasticity model for the SDS test

To clarify the interaction between the torque and the vertical force, a plasticity theory analogy model for the Swedish weight sounding by using the results of a SWS miniature test was proposed by Suemasa et al (2005). The summary of the model is described below for better understanding of the SDS result. Further details are provided by Suemasa et al (2005).

An incremental work done by torque and vertical force is given by

$$\delta E = \pi T \delta n_{ht} + W \delta s_t \tag{1}$$

where T is the required torque to rotate the screw point, W is the required vertical load, δn_{ht} is the number of incremental half turns and δs_t is the incremental settlement caused by the load. The penetration load, W_p, is defined as a the load by which the screw point is penetrated into ground without rotation. The incremental work is normalized by the penetration load as shown in equation 2.

$$\frac{\delta E}{W_p D} = \frac{\pi T}{W_p D}\delta n_{ht} + \frac{W}{W_p}\frac{\delta s_t}{D} = T_n \delta n_{ht} + W_n \frac{\delta s_t}{D} \tag{2}$$

In the above equation, D is diameter of the screw point, and T_n and W_n are the normalized T and W, respectively. From the observations of the test results, an elliptical yield locus centered on the origin is assumed in this model, i.e.

$$c_y T_n^2 + W_n^2 = 1 \tag{3}$$

where c_y is the coefficient of yield locus. A function of plastic displacement potential is also assumed to be elliptical, i.e.

$$c_p T_n^2 + W_n^2 = 1 \tag{4}$$

where c_p is a coefficient of plastic potential. If the associative flow rule is adopted, c_p must be equal to c_y. Differentiating this plastic potential function gives the displacement incremental vector as

$$N_{sw} D = \frac{\delta n_{ht}}{\delta s_t / D} = c_p \frac{\pi T}{WD} \tag{5}$$

where $N_{sw}D$ is the number of normalized half turns. From these results, it is found that each soil category has different values of c_p. Thus, by measuring the applied torque in SWS, soils can be classified by using the theory developed for SWS (Tanaka, 2012).

3.3 Estimation of rod friction

Due to the effects of rod friction during penetration, the measured load and torque for penetration are more than the required ones at screw point. The rod friction can be divided into a vertical component (W_f) and a horizontal component (T_f) as the rod is rotated and penetrated into the ground (Tanaka, 2012).

The applied load (W_a) and applied torque (T_a) by the SDS machine are defined as follows:

$$W_a = W_f + W \tag{6}$$

$$T_a = T_f + T \tag{7}$$

where W and T are load and torque at the screw point, respectively. The maximum shear stress acting on the rod surface is computed as,

$$\tau_{\max} = \frac{T_m}{2\pi r^2 \cdot L} \tag{8}$$

where T_m is the torque resisting the rod friction measured at the end of a loading set, r is a radius of the rod and L is a total penetrated length. Assuming that the direction of rotation velocity (V_θ) and of settlement velocity (V_z) are equal to those for horizontal shear stress (τ_θ) and vertical shear stress (τ_z) on rod surface, respectively, the formulas can be given as follows:

$$\tau_\theta = \tau_{\max}.\sin\theta \tag{9}$$

$$\tau_z = \tau_{\max}.\cos\theta \tag{10}$$

By substituting eq. (8) into eqs. (9) and (10), the vertical and the horizontal components of the rod friction are obtained as

$$\tau_f = 2\pi r^2 L \frac{v_\theta}{\sqrt{v_v^2 + v_\theta^2}} . \frac{T_m}{2\pi^2 L} \tag{11}$$

$$W_f = 2\pi r L \frac{v_v}{\sqrt{v_v^2 + v_\theta^2}} . \frac{T_m}{2\pi^2 L} \tag{12}$$

4. SOIL CLASSIFICATION USING SDS DATA IN JAPAN

Soils can be classified in different ways using SDS data. For instance, changes in measured torque which are caused by increasing the applied load are not equal for different types of soils. Per the classification proposed by Tanaka et al. (2012), the slope of the corrected torque against corrected load graph (*dT/dW*) tends to have a positive value for sand or loam, and a negative value or zero for clay and silt. Depending on the density and soil friction, the slope would change. Denser materials with more friction show higher value of *dT/dW*. For peat or organic soil, as well as other frictional soil, the corrected load is very small and the corrected torque increases as the corrected load increases. As these types of soils include plant roots and leaves that can be entangled at the screw point, the corrected torque has a tendency to increase. For tuff clay, the corrected torque tends to be constant or to decrease while the corrected load is increased. Tuff clay is compressible and shows brittle response in shear due to the many large gaps inside it. In the tuff clay, even with high SPT N value, it is thought that the corrected torque would be small due to the changes in soil fabric by the rotation of the screw point.

The slope of an approximate line obtained from the relationship between the number of normalized half turns ($N_{sw}D$) and normalized torque ($\pi T/WD$) is the coefficient of plastic potential (c_p). The relationship between c_p and dT/dW is shown in Figure 3 for different types of soils. The values of c_p for loam, loamy clay and tuff clay categorized as diluvial layer is more than 1 (Section A). On the other hand, for silt, this parameter changes between 0.3 and 1 (Section B). c_p for peat and organic soil is less than 0.3 (Section C). For diluvial layer, c_p is more than 1 and dT/dW is positive; c_p is less than 1 for alluvial layer and less than 0.3 for peat layer (Tanaka, 2012).

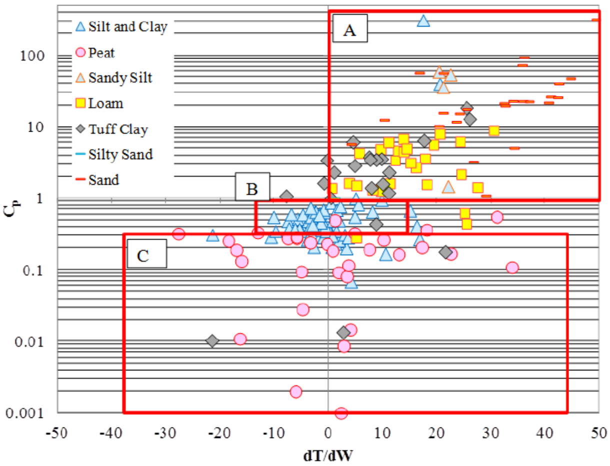

Figure 3. Relationship between c_p and dT/dW defining soil types (Tanaka, 2012).

5. SOIL CLASSIFICATION USING SDS DATA IN CHRISTCHURCH

A SDS test was conducted in Christchurch near a CPT site and borehole in order to make a comparison between the results of soil classification from these two tests. The selected site was located in Avonside Drive. This area liquefied during 2010 earthquake in Christchurch. Figure 4 shows the location of the selected site. The SDS test was conducted within a two meter distance from the CPT test and borehole. The borehole and CPT data was obtained from the Canterbury Geotechnical Database.

Figure 5 illustrates the CPT profile of the soil and the changes in SDS parameters along the depth. Based on Japanese data which has been presented in Section 3, soils can be classified by using dT/dW, average required torque and c_p. As shown in Figure 5, dT/dW is positive along the soil profile which means the soil is coarse-grained. From a depth of 1.0-2.75m, the average values of corrected torque and c_p are around 20 and 3, respectively; because of these low values, the soil in this region can be classified as sandy silt. Below 2.75m, the value of dT/dW gradually increases and this trend continues until 4m. Similarly, the average required torque for penetration increased from 35Nm to 45Nm, indicating an increase in soil friction or density. In

Figure 4 Location of test site in Christchurch.

this region, the value of c_p also gradual increased from 3 to 13. It can be predicted that between 2.75m and 4m, the percentage of fines in sand dropped or the soil becomes more frictional. From 4m to 5m, dT/dW increased gradually. The required torque for penetration in this part of the deposit was approximately 50Nm and average value for c_p was around 8. An increase in dT/dW in this section of the soil profile indicates a soil type with medium sand profile. There was a drop in dT/dW between 5 and 6 m referring to an increase in percentage of fines which reduced the friction of the soil. Below depth of 6m, an upward trend for dT/dW and c_p again continued, indicating a reduction in percentage of fines. Soil in this section of the profile can be classified as fine to medium sand.

The obtained soil classification from SDS is next compared to that obtained from CPT. For this purpose, the CPT soil behavior type classification used in this study is based on Robertson (1990) soil behavior type chart. Note that the CPT-based charts are for soil behaviour type (SBT), since the cone responds to the in-situ mechanical behavior of the soil and not directly to soil classification criteria based on grain-size distribution and soil plasticity. Robertson (1990) proposed using normalized (and dimensionless) cone parameters, Q_{t1}, F_r, and B_q, where

$$Q_{t1} = (q_t - \sigma_{vo}) / \sigma'_{vo} \quad (13)$$

$$F_r = [f_s / (q_t - \sigma_{vo})]100\% \quad (14)$$

$$B_q = (u_2 - u_0)/(q_t - \sigma_{v0}) = \Delta u / (q_t - \sigma_{v0}) \quad (15)$$

where σ_{v0} is the in situ total vertical stress; σ'_{v0} is the in situ effective vertical stress; u_0 is the in situ equilibrium water pressure; u_2 is the pore pressure measured at cone shoulder; Δu is the excess penetration pore pressure and q_t is cone resistance corrected for pore water pressure on cone shoulder. In the original paper by Robertson (1990), the normalized cone resistance was defined using the term Q_t. The term Q_{t1} is used here to show that the cone resistance is the corrected cone resistance, and the stress exponent for stress normalization is 1.0.

Jefferies and Davies (1993) identified that a soil behavior type index, I_c, could represent the SBT in zones in the Q_{t1}–F_r

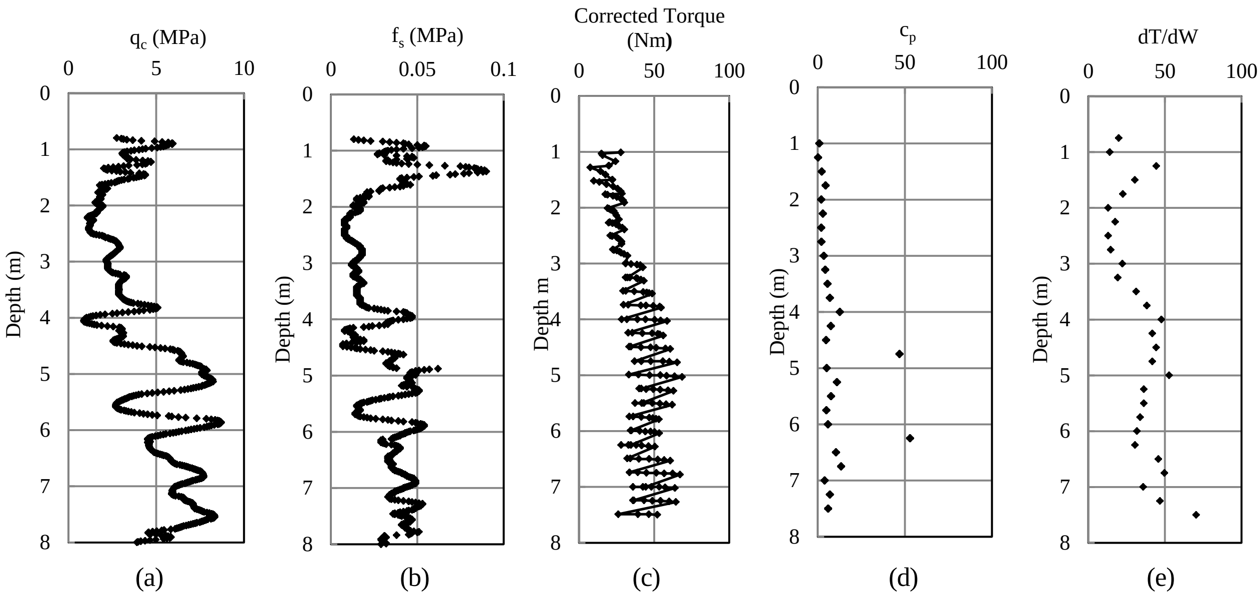

Figure 5 Variation with depth of: (a) cone resistance of CPT; (b) sleeve friction of CPT; (c) changes in corrected torque in SDS; (d) changes in c_p in SDS; (e) changes in *dT/dW* in SDS.

chart, where I_c is essentially the radius of concentric circles that define the boundaries of soil type. Robertson and Wride (1998) modified the definition of I_c to apply to the Robertson (1990) Q_{t1}–F_r chart as defined by,

$$I_c = [(3.47 - \log Q_{t1})^2 + (\log F_r + 1.22)^2]^{0.5} \qquad (16)$$

Contours of I_c on the Q_{t1}–F_r chart are shown in Fig. 6. The contours can be used to approximate the SBT boundaries. The chart identifies numbered areas that separate the soil types in twelve zones, as shown in table 1.

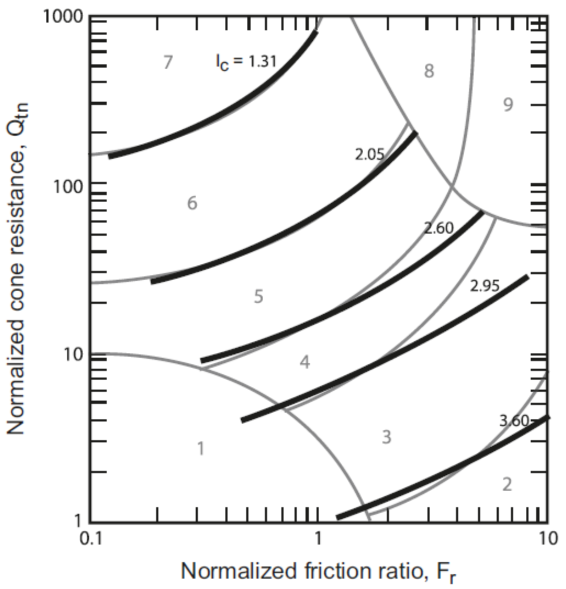

Figure 6 Contours of soil behavior type index, I_c (thick lines), on normalized SBTn Q_{t1}–F_r chart (SBT zones based on Robertson, 1990).

Table 1 Profiling chart for use in soil classification (Robertson 1990)

Zone	**Soil Behaviour Type (SBT)**
1	Sensitive fine-grained
2	Clay - organic soil
3	Clays: clay to silty clay
4	Silt mixtures: clayey silt & silty clay
5	Sand mixtures: silty sand to sandy silt
6	Sands: clean sands to silty sands
7	Dense sand to gravelly sand
8	Stiff sand to clayey sand
9	Stiff fine-grained

Table 2 shows the comparison of the results of soil classification using SDS, CPT and borehole. As seen from the table, the results obtained from SDS are very close to those indicated in the borehole description. Thus, even without sampling, SDS can classify soils with acceptable degree of accuracy.

It should be mentioned though that the SDS-based classification was formulated from a database of Japanese soils. Thus, more tests are currently being planned in New Zealand to increase the range of soil types in the database and to further refine/improve the proposed classification scheme. Moreover, it is planned to make use of the SDS parameters to identify regions of high liquefaction potential using the Christchurch experience as benchmark. Indeed, the

Table 2 Results of soil classification using SDS, CPT and borehole data

CPT Soil description	SDS Soil description	Borehole Strength/ Density	Borehole Soil description	Depth (cm)
-	-	Loose	FILL: Fine sand, dry, poorly graded	0-80
Silty sand- Sandy silt	Sandy Silt	Soft	Sandy silt, Moist, low plasticity, sand is fine	80-275
Sand and Silty sand	Silty Sand	Loose	Fine sand with trace silt, wet, poorly graded	275-300
Silty sand-Sandy silt	Silty Sand	Soft	Sandy silt, moist, low plasticity, sand is fine	300-350
Silty sand-Sandy silt	Sand	Loose	Fine sand with trace silt, Wet, poorly graded	350-375
Sand and Silty sand	Sand			375-470
Sand and Silty sand	Sand	Loose	Fine to medium sand with trace silt, wet, well graded	470-525
Silty sand	Silty sand			525-600
Silty sand- Sand	Sand			600-750

SDS method has a very good potential in geotechnical in-situ investigation.

6. CONCLUSIONS

In this study, a comparison between the most common field tests was made and a new in-situ test, called Screw Driver Sounding (SDS) was introduced. Based on a large number of tests conducted in Japan, it was shown that soils can be classified using SDS parameters, such as c_p, average corrected torque and dT/dW. For a site located in Christchurch, SDS was performed and the results of soil classification using SDS parameters were compared with those obtained from a borehole and a CPT site located less than 2m. It was shown that both methods, i.e. SDS and CPT, give almost similar results, indicating that SDS provides accurate soil classification.

More tests are currently planned in New Zealand to refine the current method of soil classification. As a future research, it is planned to evaluate the liquefaction potential of sites based on SDS parameters.

Acknowledgments

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