Soil characterization using SDS data in Christchurch

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ABSTRACT

During past major earthquakes in Christchurch, enormous damage to engineered structures and lifelines has been caused by liquefaction-induced ground failures. Standard penetration test is the most commonly used in situ test for soil characterization of liquefaction resistance. However this test has some limitations. A major disadvantage of SPT is the lack of repeatability and variation of energy delivered to the drilled rod. Moreover, this test cannot provide continuous profile of the soil. Screw Driving Sounding test (SDS) is a new testing method developed in Japan which consists of a machine drilling a rod into the ground surface at different steps of loading while rotating. This machine can continuously measure the required torque, load, speed of penetration and rod friction during the test, so can give a brief overview of soil profile along the depth of penetration. Based on many SDS tests conducted in Japan, it was shown that by measuring penetration velocity, rod friction and applied torque and load, soil properties can be identified with acceptable accuracy. Based on a number of SDS tests conducted in Christchurch, a correlation is made in this study between the normalized SPT N value and SDS results and using the obtained correlation factor, it is shown that liquefaction potential of soil can be measured by using SDS data which is simpler and faster test compared to SPT.

1 INTRODUCTION

The devastating earthquakes which recently hit Christchurch caused a large number of structural damage requiring extensive repair and rebuild. 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 as most of damages in Christchurch were caused by ground failures induced by liquefaction. In preventing similar damages in the future, the designer of a building foundation must perform a detailed surface and subsurface (soil) exploration of the potential site prior to deciding on the nature and type of the foundation. Two basic approaches have been used to predict the liquefaction resistance of soil strata. First method is evaluation based on cyclic laboratory tests on soil samples and second is empirical methods based on observations of field performance in previous earthquakes. Unfortunately, liquefaction evaluation based on laboratory tests has some limitations such as obtaining high quality undisturbed sample in loose sands and difficulties in transporting the samples due to their sensitivity. Hence in-situ test has become popular for many geotechnical applications. Several in-situ tests have been used for evaluating liquefaction resistance of soils. The two most common field tests, which are used worldwide for assessing the liquefaction potential of soils, are the Standard Penetration Test (SPT) and the Cone Penetration Test (CPT). In this study after a review of SPT and Swedish Weight Sounding (SWS) test which is a popular in-situ test in
Nordic countries and in Japan for soil characterization, a new in-situ test called Screw Driving Sounding (SDS) method is introduced and the results of the tests in Christchurch are compared to SPT data.

2 POPULAR IN SITU TESTS FOR SOIL CHARACTERIZATION

In many countries, the standard penetration test (SPT) has been the most commonly used in situ test for characterization of liquefaction resistance and is performed during the advancement of a soil boring to obtain an approximate measure of the soil resistance. The test was introduced by Raymond Pile Company in 1902 and remains today as the most common in-situ test worldwide. The procedures for the SPT are detailed in ASTM D 1586 and AASHTO T-206 (AASHTO, 1988). Factors that tend to increase the liquefaction resistance (density, prior seismic straining, over consolidation ratio, lateral earth pressure) also tend to increase the SPT resistance. Although SPT is a popular test and is widely used in the world, there are some limitations in this test such as lack of repeatability and variation of delivered energy to the drilled rod.

An alternative test, which is much cheaper than SPT to perform, is the Swedish Weight Sounding test (SWS). There are several correlations established between SWS and SPT results, which are mostly presented by Japanese and Nordic engineers. The SWS was originally developed in 1915 and standardised shortly thereafter by the Swedish Railway Association. It has been used ever since in predominantly Nordic countries either manually or by hydraulic machinery with the number of half-turns and resistances measured by electronic sensors (Smoltczyk & Bauduin, 2002). It has also been adopted by the Japanese as a standard test required for small scale housing development investigations. Consequently extensive field experience has been obtained using this technique (Ishihara, 1993). The key advantages of this test are that it is highly portable, low cost and 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).](image)

The penetration resistance of soil can be estimated either by measuring the required load or the number of half-turns that the screw point is rotated to penetrate up 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 the handle. Although the SWS test is highly portable and simpler than other in-situ tests, this test has some disadvantages. For instance the result is fairly influenced by rod friction, which may affect the measured results.
3 SCREW DRIVING SOUNDING TEST

3.1 Background and test procedure

A new system for conducting the SWS, the Screw Driving Sounding test, hereafter called SDS test, 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 SDS test, monotonic loading system is used and the load is increased in 7 steps until reaching 25 cm penetration, while the rod is always rotated at a constant rate (25rpm) during the test. The step loads are 0.25, 0.38, 0.50, 0.63, 0.75, 0.88, and 1 kN. In this order the load is increased at every complete rotation of the rod. This process is repeated at every 25 cm of penetration. Measured parameters in the test are maximum torque ($T_{\text{max}}$), average torque ($T_{\text{avg}}$), minimum torque ($T_{\text{min}}$) on the rod, penetration length ($L$), penetration velocity ($V$) and number of rotations ($N$) of the rod. The parameters 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 25 cm of penetration and after each 25 cm penetration, the rod is lifted up by one centimetre and then rotated to measure the rod friction.

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 was proposed by Suemasa et al. (2005) by using the results of a SWS miniature test. A 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 $\Delta E$ by torque and vertical force is given by

$$
\Delta E = \pi T \Delta n_{ht} + W \Delta \delta_l
$$

(1)

where $T$ is the required torque to rotate the screw point, $W$ is the required vertical load, $\Delta n_{ht}$ is the number of incremental half turns and $\Delta \delta_l$ 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 Eq. (2).

$$
\frac{\Delta E}{W_pD} = \pi T \frac{\Delta n_{ht}}{D} + W \frac{\Delta \delta_l}{W_pD} = T_n \Delta n_{ht} + W_n \frac{\Delta \delta_l}{D}
$$

(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 centred on the origin is assumed in this model, i.e.

$$
c_y T_n^2 + W_n^2 = 1
$$

(3)

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

$$
c_p T_n^2 + W_n^2 = 1
$$

(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

$$
N_{sw}D = \frac{\Delta n_{ht}}{D} = c_p \frac{\pi T}{WD}
$$

(5)

where $N_{sw}D$ is the number of normalized half-turns. From these results, it is found that each soil type 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 values 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

\[
\tau_{\text{max}} = \frac{T_m}{2\pi^2 \cdot L} \tag{8}
\]

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 penetration depth. Assuming that the directions of rotational velocity \( (V_\theta) \) and of settlement velocity \( (V_z) \) are equal to those for horizontal shear stress \( (\tau_\theta) \) and vertical shear stress \( (\tau_z) \) on rod surface, respectively, the formulas can be given as follows:

\[
\tau_\theta = \tau_{\text{max}} \cdot \sin \theta \tag{9}
\]

\[
\tau_z = \tau_{\text{max}} \cdot \cos \theta \tag{10}
\]

Figure 2 shows the concept of measuring rod friction in SDS test.

![Figure 2: Concept of measuring rod friction in SDS test (Tanaka, 2012).](image)

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

\[
T_f = 2\pi^2 L \frac{V_\theta}{\sqrt{V_z^2 + V_\theta^2}} \cdot \frac{T_m}{2\pi^2 L} \tag{11}
\]

\[
W_f = 2\pi r L \frac{V_z}{\sqrt{V_z^2 + V_\theta^2}} \cdot \frac{T_m}{2\pi^2 L} \tag{12}
\]

3.4 Estimation of SPT value using Japanese data

\( \Sigma E \) is defined as the sum total of penetration energy in every incremental load steps as follows,

\[
\Sigma E = \delta E_{0.25} + \delta E_{0.38} + \ldots + \delta E_{1.0} \tag{13}
\]
ΣE represents the energy to penetrate a screw point by 25 cm. Normalized settlement is defined for every 25 cm of penetration

\[ \Sigma_{st} = \left( \frac{\delta_i}{0.25m} \right)^{2/3} \]  

(14)

Figure 3 shows a typical relationship between penetration energy (ΣE) and normalized settlement (Σst/0.25)2/3 at each 0.25 m section. In order to express relationship between ΣE and Σst with approximate slope, Σst is raised to the power of 2/3. The normalized energy (E0.25) is calculated as the linear slope of ΣE and Σst/0.25 relation.

![Figure 3: Typical relationship between penetration energy (ΣE) at each 25cm section and normalized settlement (Σst/0.25)2/3 for Christchurch soil](image)

Based on a large number of SDS tests conducted in Japan, it was shown that there is a relationship between penetration energy and SPT blow counts. It was shown that as the SPT blow counts increase, the penetration energy increase and by drawing an approximate line, a correlation can be made between these two parameters (Tanaka, 2012).

### 4 SDS TESTS IN CHRISTCHURCH

Four SDS tests were conducted in Christchurch near boreholes with SPT data in order to make a comparison between the SDS output and measured SPT N value. All these areas showed evidence of liquefaction during 2011 Christchurch earthquake. Figure 4 shows the location of selected sites where the red points show the SDS test sites and yellow ones are the borehole sites. The measured PGAs for 2011 earthquake at each site is also indicated (Bradly & Hughes, 2012). The borehole and SPT data were obtained from the Canterbury Geotechnical Database.

![Figure 4: Location of test sites in Christchurch: (a) Avonside Drive; (b) 55 Brooker Ave; (c) Avonside Drive; and (d) Ferry Road](image)

Figure 5 shows a sample of SDS data which was be obtained by SDS. Using the results of tests, a correlation was made between E0.25 and (N1)_60. (N1)_60 is the normalized penetration resistance in sand to an equivalent 0.10 of Pa=1 atm (100kPa). This normalization takes the form:

\[ (N_1)_{60} = C_N (N)_{60} \]  

(16)

in which the (N)60 value corresponds to the SPT N value after correction to an equivalent 60% hammer efficiency, while C_N is defined by (Idriss & Boulanger, 2004):
From the above equation, solving for $C_N$ requires iteration. Figure 6 illustrates the relationship between $E_{0.25}$ and $(N_1)_{60}$. It should be noted that this relationship was obtained based on the results of only 4 tests and more tests are needed to improve the correlation.

By using the proposed correlation factor, $E_{0.25}$ can be used for predicting the liquefaction potential of soil. Figure 7 shows the relationship between the cyclic shear stress ratio (CSR) for earthquake with magnitude of 7.5 and normalized energy for the 4 selected sites in Christchurch. The curve indicates the boundary between liquefiable and unliquefiable soil for clean sand based on correlation with normalized SPT value in Idriss and Boulanger (2004) method.
Figure 7: Relationship between CSR and \( E_{0.25} \) based on the 4 tests conducted in Christchurch.

From Figure 7, it can be seen that in all liquefied sites, most of the \( E_{0.25} \) are located to the left site of the boundary line. Similar to the proposed graph by Idriss and Boulanger (2004), data points on the left of boundary line are susceptible to liquefaction. Based on the results of SPT test conducted at the site and borehole data, the points on the right side of boundary were dense sand layers within the soil profile and hence not liquefiable, so being on right side of the boundary is reasonable. However, the effect of fine content has not been considered in this graph. Note that although there was significant scatter in the results shown in Figure 6, the affected points are within the bounds of the boundary curve.

Thus, by making a correlation between normalized SPT blow counts and normalized SDS penetration energy, soil characterization for liquefaction resistance can be done using SDS testing which is a simple, economical and fast test. The preliminary results of four tests conducted in Christchurch confirmed this although and more tests are needed to obtain better relationship between normalized penetration energy of SDS and \((N_1)_{60}\) value for different soil types. 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 SDS method has a very good potential in geotechnical in-situ investigation.

5 CONCLUSIONS

In this study, after a review of SPT and SWS as two popular methods for soil characterization, a new in-situ test called Screw Driving Sounding (SDS) was introduced. Based on a large number of tests conducted in Japan, it was shown that correlation can be made between SPT N value and SDS parameters. Moreover using the data obtained from SDS test in Christchurch it was shown that \( E_{0.25} \) in SDS is proportional to \((N_1)_{60}\) and a correlation can be made between these two parameters. By using the correlation factor in conjunction with Idriss and Boulanger (2004) method, a boundary was defined to determine the liquefaction potential of soil. As SDS is simpler, faster and more economical test when compared to SPT, it can be a good alternative as an in-situ test for soil characterization. More tests are currently planned in New Zealand to obtain an accurate relationship between these two tests as well as possible correlation with CPT data. Also it is planned to develop a method for real-time assessment of liquefaction potential using SDS data.

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