Evaluation of liquefaction susceptibility of soils using Screw Driving Sounding method

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ABSTRACT

During the recent devastating earthquakes in Christchurch, many residential houses were damaged due to widespread liquefaction of the ground. In-situ testing is widely used as a convenient method for evaluating liquefaction potential of soils. Cone penetration test (CPT) and standard penetration test (SPT) are the two popular in situ tests which are widely used in New Zealand for site characterization. The Screw Driving Sounding (SDS) method is a relatively new operating system developed in Japan consisting of a machine that drills a rod into the ground by applying torque at seven steps of axial loading. This machine can continuously measure the required torque, load, speed of penetration and rod friction during the test, and therefore can give a clear overview of the soil profile along the depth of penetration. In this paper, based on a number of SDS tests conducted in Christchurch, a correlation was developed between tip resistance of CPT test and SDS parameters for layers consisting of different fines contents. Moreover, using the obtained correlation, a chart was proposed which relates the cyclic resistance ratio to the appropriate SDS parameter. Using the proposed chart, liquefaction potential of soil can be estimated directly using SDS data. As SDS method is simpler, faster and more economical test than CPT and SPT, it can be a reliable alternative in-situ test for soil characterization, especially in residential house constructions.

Keywords: earthquake, liquefaction, field test, Screw Driving Sounding test, CPT test

1 INTRODUCTION

The occurrence of soil liquefaction following major earthquakes has been recognized for many years and is a major concern in Christchurch for structures constructed on saturated loose sandy soils. The most popular and simple in-situ method for estimating the cyclic resistance ratio (CRR) of the soil is to make use of penetration resistance from the standard penetration test (SPT), although recently, the cone penetration test (CPT) has become very popular because of its repeatability and its ability to obtain continuous soil profile. Currently CPT is widely used around the world for predicting liquefaction potential of the soil.

In this study, a new in-situ test called Screw Driving Sounding (SDS) method is introduced and a correlation is investigated between SDS-obtained parameters and CPT tip resistance ($q_c$) performed at similar sites. For this purpose, a series of SDS tests was conducted in Christchurch, adjacent to locations of CPT tests which have been previously conducted and stored in the Canterbury Geotechnical Database (CGD 2013). It is envisioned that correlating the SDS parameters to $q_c$ values would be a logical first step in investigating the applicability of the SDS test in evaluating field performance, especially in predicting the liquefaction potential of the ground. Note that because CPT is a reliable and repeatable in-situ test and is popularly used as a tool for assessing the liquefaction resistance of potentially liquefiable soils, it is selected as a basis for evaluating of liquefaction susceptibility of soil layers.

2 PRINCIPLE AND TEST PROCEDURE

Before introducing the SDS test, it is necessary to review the Swedish Weight Sounding (SWS) method, from where the SDS test has evolved. The SWS method, which is popular in Japan and in many Nordic countries, make use of weights (5 kg clamp, two 10 kg and three 25 kg weights), a screw-shaped point, 22mm extension rods and a handle (or a motor) for rotating the rods. The field test, which can be done either using a machine or manually, is comprised of two phases: (1) static penetration; and (2) rotational penetration. The testing procedure and the interpretation of test results are described by Tsukamoto et al. (2004) and Tsukamoto (2013). The key advantages of the SWS test are that it is highly portable, low cost and, similar to CPT, provides a continuous profile of the soil. Nevertheless, SWS results are fairly influenced by rod friction, especially when the layer contains gravel, resulting in over-estimation of soil resistance.
2.1 Screw Driving Sounding test

A new operating 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 test, monotonic loading system is used and the number of loading steps is increased to 7, while the rod is always rotated at a constant rate (25 rpm) during the test. The step loads are 0.25, 0.38, 0.50, 0.63, 0.75, 0.88, and 1kN and the load is increased at every complete rotation of the rod. 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. Similar to the SWS method, a set of loading is applied in SDS test at every 25cm of penetration and after each 25cm penetration, the rod is lifted up by 1cm and then rotated to measure the rod friction. The procedure to measure the rod friction is described by Tanaka et al. (2012). Figure 1 illustrates the SDS test machine during operation (on top of a crawler) while Figure 2 shows both the SDS machine and CPT rig side-by-side. It is obvious that SDS machine is much smaller in scale and requires less operating area than even the smallest CPT rig. Further details of the SDS application in Christchurch have been discussed by Orense et al. (2013) and Mirjafari et al. (2013).

2.2 Definition of energy and specific energy

As discussed above, both load and torque are applied to the rod at the same time during the SDS test. The combined effect of the applied load and torque can be expressed in terms of energy, i.e., the incremental work done, $\delta E$, by the torque and vertical force for a small rotation can be calculated as (Suemasa et al. 2005):

$$\delta E = \pi T \delta n_{\text{ht}} + W \delta s_i$$ (1)

where $T$ is the required torque to rotate the screw point, $W$ is the required vertical load, $\delta n_{\text{ht}}$ is the number of incremental half turns and $\delta s_i$ is the incremental settlement caused by the load. The specific energy, $E_s$, is defined as the amount of energy for complete rotation, $E$, divided by volume of penetration:

$$E_s = \frac{E}{L \cdot A}$$ (2)

where $L$ is the depth of penetration and $A$ is the maximum cross-sectional area of the screw point.

Figure 3 illustrates the variation of specific energy with depth and the tip resistance obtained by CPT test conducted at essentially the same location, (i.e. at Wordsworth Street, Christchurch – highlighted in Figure 4). The specific energy shown is the average of the specific energies calculated at different steps of loading at each 25cm of penetration. As can be seen in the figure, the variation of the specific energy with depth is similar to the variation of the CPT tip resistance along the soil profile.

3 SDS TESTS IN CHRISTCHURCH

Between June-August 2013, 69 SDS tests were conducted in Christchurch. The locations of these sites are presented in Figure 4. These sites are located at both liquefied and non-liquefied areas following the recent earthquakes. SDS tests were conducted within 1–3 m from CPT sites, as described in the CGD (2013).
Using the results of the SDS tests conducted, a correlation was made between the specific energy and the cone tip resistance. For this purpose, the cone tip resistance is normalised by the effective overburden pressure and expressed as (Roberston and Wride, 1998):

$$E_{s,1} = E_s \left( \frac{P_a}{\sigma_v^e} \right)^m$$

(4)

After several analyses, it was found that $m=0.5$ is the best value for normalizing the energy with respect to overburden pressure.

Figure 5 illustrates the relationship between $E_{s,1}$ and $q_{c1N}$ for sands with different fines content (FC). The values of FC were estimated from the CPT data based on Robertson and Wride (1998) method.

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$$q_{c1N} = C_Q \left( \frac{q_c}{P_a} \right)$$

(3)

where $q_{c1N}$ is the normalized dimensioness cone tip resistance; $q_c$ is the measured cone tip penetration resistance; $C_Q = (P_a / \sigma_v^e)^n$ is the normalising factor for effective overburden pressure $\sigma_v^e$; the exponent $n$ is typically equal to 0.5; $P_a = 1$ atm of pressure in the same units used for $\sigma_v^e$. A maximum value of $C_Q = 2$ is generally applied to CPT data at shallow depths.

In similar manner, the specific energy during penetration is normalized to the reference overburden pressure of $P_a=100$ kPa (or 1 atm) by

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Figure 5 illustrates the relationship between $E_{s,1}$ and $q_{c1N}$ for sands with different fines content (FC). The values of FC were estimated from the CPT data based on Robertson and Wride (1998) method.

It can be seen from the figure that with the high values of the coefficient of determination, $R^2$, there is good correlation between specific energy during penetration in SDS test and the normalized tip resistance of CPT test. Note that there are some scatter in the plot, especially for the case of FC > 35%. One possible reason for this is the uncertainty regarding the accuracy of CPT-based method in predicting the high fines content. To deal with this issue, some
supplementary laboratory testing is currently underway to directly measure the fines content from soil samples obtained at CPT sites for the purpose of checking the applicability of the empirical method to Christchurch soils.

Next, by using the proposed correlation, $E_{s,1}$ is converted to an equivalent $q_{c,1}$ and a graph is generated based on the empirical chart proposed by Robertson and Wride (1998) for evaluating the liquefaction potential of soil. Three different boundary lines were defined for different fines content (which, as mentioned earlier, were calculated based on the CPT data). Figure 6 shows the relationship between the cyclic resistance ratio (CRR) for earthquakes with magnitude $M=7.5$ and SDS normalized specific energy.

To evaluate the applicability of the proposed graph, detailed analysis of several sites in Christchurch were conducted and their cyclic shear stress ratio (CSR) computed for 2010 Darfield earthquake (M7.1); in addition, the normalized specific energy derived from SDS tests were calculated along the soil profiles. In sites known to have clean sand (FC<5%), two of these sites (Avonside Drive, Bexley) liquefied during the 2010 earthquake while the other 3 sites (Broomfield Tce, Pavitt Street and Greenhaven Drive) were known not to have liquefied. In addition, 3 locations with 5%<FC<35% were also analysed – one site located in River Road and the other two along Avonside Drive. The plots of CSR vs normalized specific energy are shown in Figures 7(a) and 7(b) for the case of FC<5% and 5%<FC<35%, respectively. It can be seen that the data points corresponding to liquefied sites plot to the right side of the proposed boundary line, while the data points for the liquefied sites are located on the left.

Thus, by making a correlation between normalized cone tip resistance and normalized SDS penetration energy, soil characterization for liquefaction resistance...
can be done using the SDS test. Currently, additional laboratory tests are being conducted to find a direct relationship between FC and SDS parameters for the purpose of upgrading the proposed empirical chart.

4 CONCLUSIONS

In this study, after a review of Swedish Weight sounding (SWS) as a popular method for soil characterization, a new in-situ test called Screw Driving Sounding (SDS) method was introduced. Based on a number of tests conducted in Christchurch, it was shown that the SDS parameters, especially specific energy during penetration, correlated well with the CPT tip resistance. By using the obtained correlation in conjunction with the Robertson and Wride (1998) method, a boundary was defined to determine the cyclic resistance ratio of the soil for different fines content (FC). Analyses of liquefied and non-liquefied sites in Christchurch proved the validity of the proposed correlations. As SDS is simpler, faster and more economical test when compared to CPT, it can be a good alternative as an in-situ test for soil characterization.

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