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Soil classification and liquefaction evaluation using Screw Driving Sounding

S.Y. Mirjafari & R.P. Orense

University of Auckland, Auckland, New Zealand

N. Suemasa

Tokyo City University, Tokyo, Japan

ABSTRACT: A number of field testing techniques, such as standard penetration test (SPT), cone penetration test (CPT), and Swedish weight sounding (SWS), are popularly used for in-situ characterisation. The screw driving sounding (SDS) method, which has been recently developed in Japan, is an improved version of the SWS technique and measures more parameters, including the required torque, load, speed of penetration and rod friction; these provide more robust way of characterising soil stratigraphy. It is a cost-efficient technique which uses a machine-driven and portable device, making it ideal for testing in small-scale and confined areas. Moreover, with a testing depth of up to 10-15m, it is suitable for liquefaction assessment. Thus, the SDS method has great potential as an in-situ testing method for geotechnical site characterisation, especially for residential house construction. In this paper, the results of SDS tests performed at a variety of sites in New Zealand are presented. The soil database was employed to develop a soil classification chart based on SDS-derived parameters. Moreover, using the data obtained following the 2010-2011 Christchurch Earthquake Sequence, a methodology was established for liquefaction potential evaluation using SDS data.

1 INTRODUCTION

Soil stratigraphy in-situ is traditionally best determined through laboratory classification of samples retrieved from boreholes. However, if a continuous (or nearly continuous) subsurface profile is desired, various field investigation methods are commonly used to provide economical alternatives over the conventional methods of sampling and testing. Currently, a number of field testing techniques are being used to characterise sites, and these include standard penetration tests (SPT), cone penetration tests (CPT) and Swedish weight sounding (SWS) method. Although SPT is still popular worldwide due to its simplicity and applicability to many types of soils, it suffers from many limitations such as lack of repeatability, no continuous soil profile and the SPT blow-count is dependent on soil type, particle size, and the age and stress history of the deposit. CPT is quickly becoming popular because it is fast to perform and it provides continuous records with depth and is generally not operator-dependent; although sampling is not possible, soil type (or soil behaviour type) can be inferred from the information collected during the test. Finally, SWS is a highly portable and low-cost technique which provides a continuous profile of the soil. It is used very often in Japan to evaluate the allowable shear strength of soils for small-scale projects, and it is officially recommended as an investi-

gation tool by the Ministry of Land, Infrastructure and Transport (Japan).

The screw driving sounding (SDS) method, which has been recently developed in Japan, is an improved version of the SWS technique and can be used to characterise soft shallow sites, typically for residential house construction. While the SWS measures only two parameters during the test (weight during static penetration, W_{sw} and number of rotations during rotational penetration, N_{sw}), SDS measures four parameters: the required torque, load, speed of penetration and rod friction; these provide more robust way of characterising soil stratigraphy.

The SDS method was introduced in New Zealand in 2013 and a total of 164 SDS tests have been conducted at various sites to validate and/or adjust the methodologies originally developed based on Japanese soil database. Of these, a total of 74 SDS tests were conducted in Christchurch, mostly in areas which were affected by the 2010-2011 Canterbury Earthquake Sequence, with the aim of characterising various sites in the area for the on-going rebuild programme and estimating liquefaction potential considering future earthquakes. Most of the SDS tests were conducted at sites where CPT, SPT and borehole logs were available; the comparison of SDS results with existing information showed that the SDS method has great potential as an in-situ test-

ing method for classifying the soils. Moreover, based on Christchurch data, a methodology was developed to estimate the liquefaction potential of sites using SDS-derived parameters.

2 TEST PROCEDURE

2.1 Swedish Weight Sounding (SWS)

Before discussing the principle and test procedure for SDS test, it is worthwhile to review the Swedish weight sounding (SWS) method, from where the SDS test has evolved. In the SWS method, which is popular in Japan and in many Nordic countries, weights (5kg clamp, two 10kg and three 25kg weights) are used together with a screw-shaped point, 22mm extension rods and a handle (or a motor) for rotating the rods. The test, which can be performed using either a machine or manually, comprises of two stages: (1) static penetration; and (2) rotational penetration. 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 to a specified 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 load 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 weight, the rod is rotated by using a handle (or a motor). Further details of 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. On the other hand, SWS has several disadvantages, such as the results being fairly influenced by rod friction. In cases when the layer contains gravel, the soil resistance tends to be over-estimated as the rod friction becomes large.

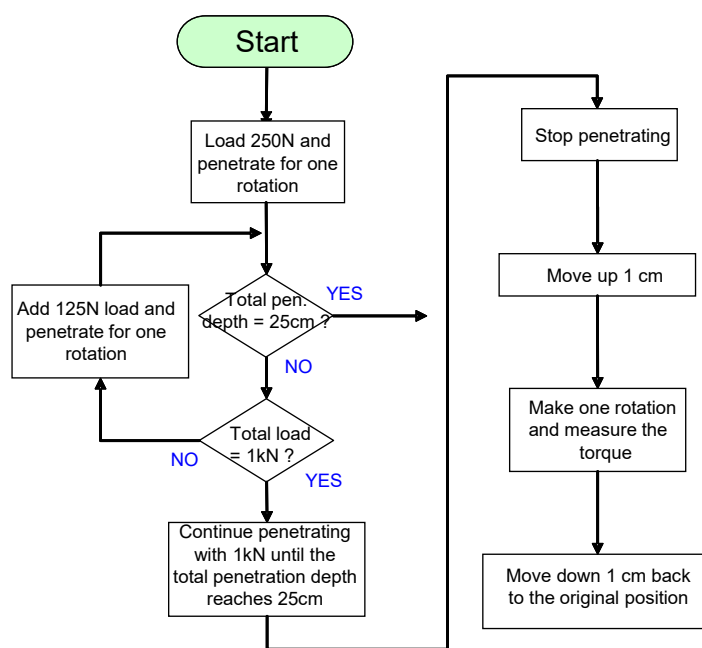
Suemasa et al. (2005) investigated the interaction between the torque and the vertical load during SWS implementation and proposed an analogy model based on plasticity theory and the results of SWS miniature test results. From the results, they noted that the coefficient of yield locus, c_y (which relates the normalised torque and normalised weight applied) and the coefficient of plastic potential, c_p (which relates the normalised half-turns and the torque on the rod), vary depending on the soil type; i.e. clay, loam, medium sand or dense sand. Consequently, they proposed that soil can be classified based on the data obtained from SWS tests if the torque can be measured. This resulted in further refinement of the SWS method in terms of operating system, which led to the development of the SDS method.

2.2 Screw driving sounding (SDS)

To minimize the disadvantages of the SWS as well as to incorporate a procedure to measure the rod friction, a new operating system for conducting the SWS was developed in Japan. The new system, now referred to as screw driving sounding (SDS), makes use of an improved version of the machine originally used for the SWS test. In the SDS 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



(a)



(b)

Figure 1. (a) SDS equipment; and (b) SDS test procedure.

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_{max}), average torque (T_{avg}), minimum torque (T_{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(a) illustrates the SDS test machine during operation while Figure 1(b) summarises the test procedure adopted. Further details of the SDS method are reported by Tanaka et al. (2012; 2014) and Maeda et al. (2015), while preliminary SDS results of application in New Zealand have been reported by Mirjafari et al. (2013; 2015a; 2015b) and Orense et al. (2013).

2.3 Definition of some SDS parameters

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, δE , by the torque and vertical force for a small rotation can be calculated as (Suemasa et al. 2005):

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

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 specific energy, E_s , is defined as the amount of energy for complete rotation, E , divided by the volume of penetration:

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

where L is the amount of penetration per load step and A is the maximum cross-sectional area of the screw point.

Figure 2 illustrates a typical SDS result showing 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). 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 SOIL CLASSIFICATION CHART

Overall, SDS tests were performed at 164 sites in New Zealand (74 in Christchurch, 56 in Auckland and 34 in Wellington). These tests were conducted

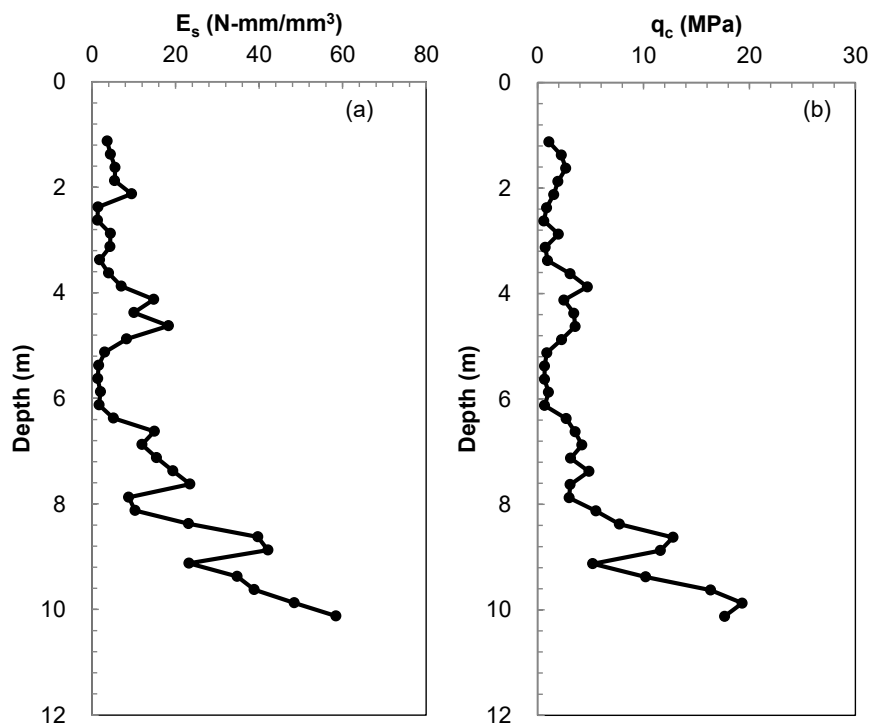


Figure 2. Variation with depth of: (a) specific energy from SDS test; and (b) cone tip resistance from CPT test conducted at a site located in Wordsworth Street, Christchurch.

adjacent to CPT sites and boreholes and therefore the soil types within a given layer are known. Various SDS parameters (expressed in terms of measured torque, load, energy, etc.) were investigated to examine which of these best correlate with the appropriate soil types. Based on the NZ soil database, the following parameters were considered:

$$\text{Ave}(\delta T) = \frac{1}{n-1} \sum_{i=1}^{n-1} (T_{i+1} - T_i) \quad (3)$$

$$c_p'' = \frac{1}{n} \sum_{i=1}^n \left(\frac{N_{SD} D}{\pi T / WD} \right)_i \quad (4)$$

where δT is the change in torque, T , at each step of loading, i ; n ($=7$) is the number of loading; c_p'' is the modified coefficient of plastic potential; N_{SD} is the number of normalised half-turns; W is the applied load; and D is the cross-sectional diameter of the screw point. The soil classification chart obtained based on the NZ soil database is shown in Figure 3.

Note that the boundary lines were drawn visually to separate data such that points representing similar soil types are grouped together. Data points in region A are sandy soils which, because of their frictional nature, are expected to have higher $\text{Ave}(\delta T)$ and c_p'' values compared to the other soil types. Based on borehole data analysis, sands on the left part of the region are finer than those on the right part. In addition, as c_p'' is an indication of the difficulty in penetration, the upper part of region A would be denser than those on the lower part. Region B is for stiff peat, which can be found in South Auckland; peat is considered as $c-\phi$ soil and it is reasonable that it is

positioned to the right side of Regions D and E, both of which represent cohesive soils. Region C represents silty sand and silty sands. Soils at the bottom left of region B contain more silt than sand; therefore, this region can be considered as a transition zone from frictional behaviour to frictionless (cohesive) one. Soils in region D are highly-plastic stiff clays which have $\text{Ave}(\delta T)$ values < 1 and $1 < c_p'' < 2$. Finally, region E belongs to clayey silt, silty-clay, silt and clay. Note that the available borehole data for clayey soils were scarce and more analysis are planned to separate clay and silt. However, it is expected that the upper part of this region would represent stiff clay or silt while the lower part would be for soft clay.

4 LIQUEFACTION POTENTIAL EVALUATION

Following the 2010-2011 Canterbury Earthquake Sequence, 74 SDS tests were conducted in Christchurch at both liquefied and non-liquefied areas. The SDS tests were conducted within 1–3 m from CPT sites, as described in the CGD (2013). For liquefaction potential evaluation, another SDS parameter, called normalised energy, $E_{s,1}$, was used:

$$E_{s,1} = E_s \left(\frac{P_a}{\sigma'_{v0}} \right)^m \quad (5)$$

where E_s represents the combined effect of the applied load and torque, as expressed by Eqtn (2), σ'_{v0} is the effective overburden pressure and P_a is the reference pressure ($=100$ kPa). After several anal-

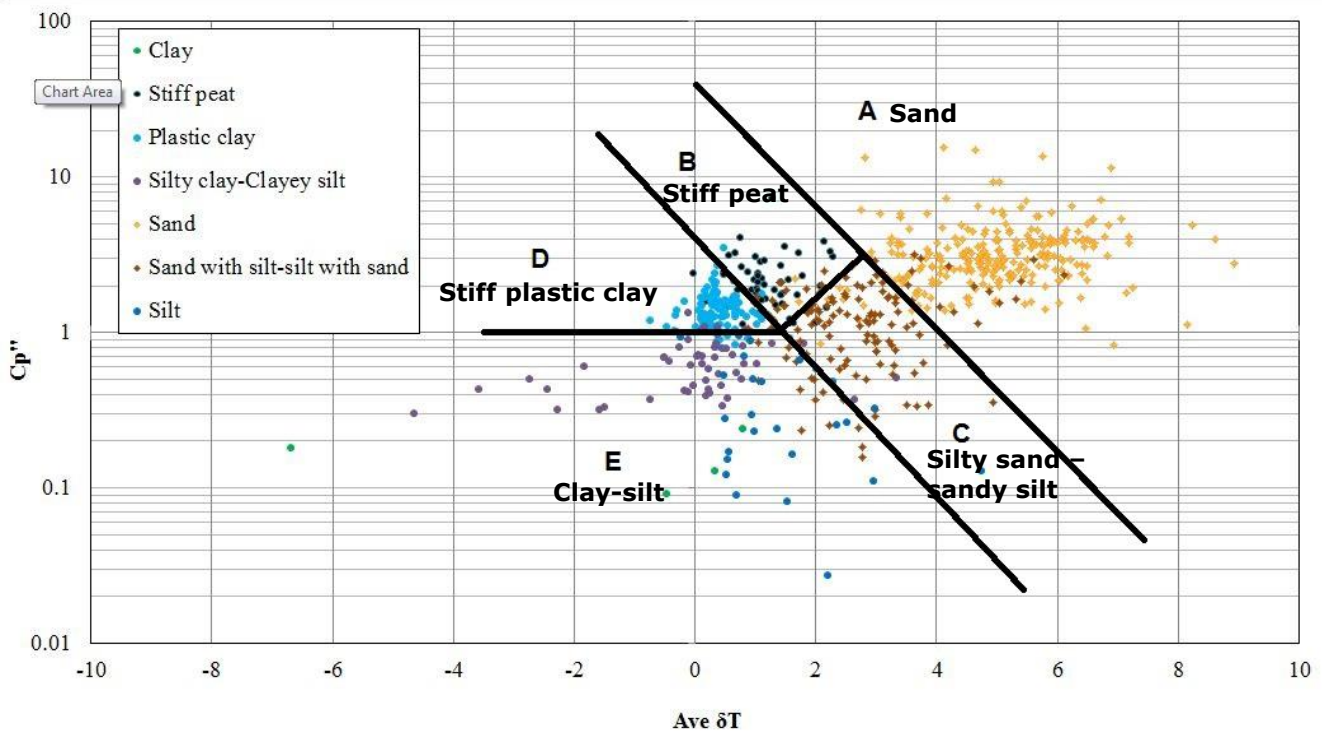


Figure 3. Soil classification chart based on SDS data.

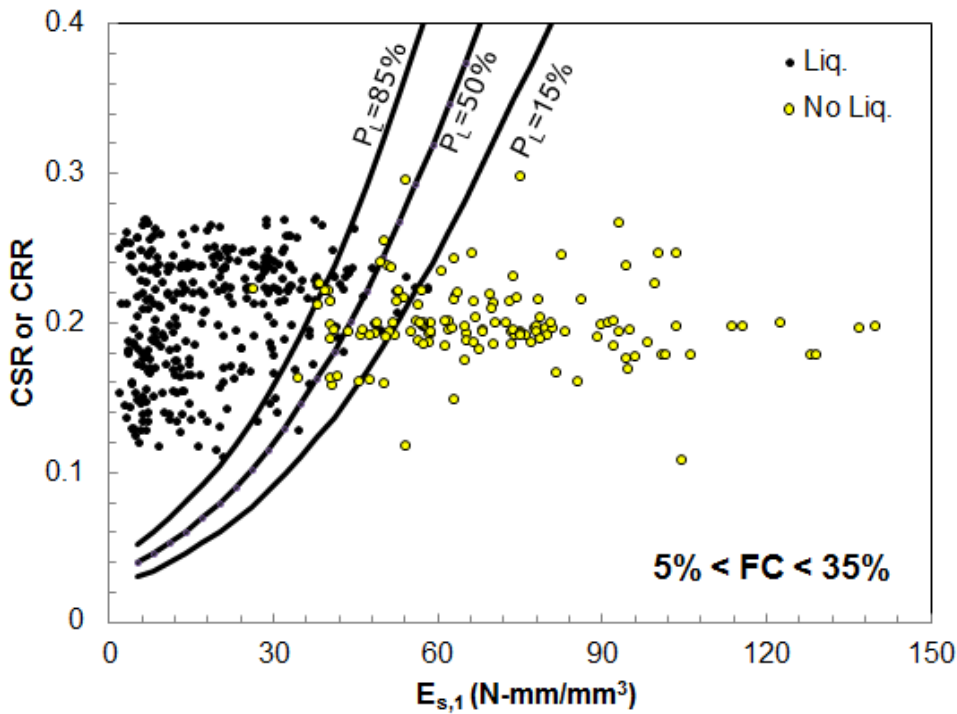


Figure 4: Proposed empirical chart for estimating CRR based on $E_{s,1}$ from SDS test ($5\% < F_C < 35\%$).

yses, it was found that $m=0.5$ is the best value to correlate the energy with the overburden pressure. For each data point, the cyclic shear stress ratio (CSR) and the factor of safety against liquefaction (F_L) during the 2011 Christchurch Earthquake were evaluated at adjacent CPT sites using three methods: (a) Robertson & Wride (1998); (b) Moss et al. (2006); and (c) Idriss & Boulanger (2008). If at least two of the methods indicate $F_L < 1$, the point is considered to have “liquefied”. Finally, logistic regression analysis was used to define boundary curves, delineating different probabilities of liquefaction, P_L . A typical chart showing the cyclic resistance ratio (CRR) as a function of $E_{s,1}$, for soils with fines content, F_C , between 5% - 35% is presented in Figure 4.

Note that the F_C values employed in the analyses were estimated from the adjacent CPT data (excluding soil layers with $F_C > 50\%$) using Robertson and Wride (1998) method. It is acknowledged that the applicability of this CPT-based F_C estimation for Christchurch soils is questionable (in the light of several evidence showing that the method does not work for Christchurch soils); further study is currently underway to correlate field-obtained SDS data with laboratory-derived F_C values of samples retrieved from the SDS sites.

To validate the proposed charts, liquefaction potential evaluation was conducted at several sites in Christchurch considering the 2010 Darfield earthquake ($M7.1$). Results indicated good correlation between estimated liquefied sites and actual/observed liquefaction. Finally, the recent $M5.7$ earthquake which hit Christchurch on 14 February 2016 also validated the proposed chart, with no liquefaction

occurring at SDS sites near the CBD, but liquefaction observed at SDS sites in Parklands, located east of the city.

5 CONCLUDING REMARKS

The screw driving sounding method, which has been recently developed in Japan as an improved version of Swedish weight sounding test, measures more in-situ parameters and therefore provides more robust way of characterising soil profiles. It is a cost-efficient technique which uses a machine-driven screw point, making it ideal for testing in confined areas. The results of SDS testing performed at a variety of sites in New Zealand showed the method's ability to classify soils based on the measured parameters. Moreover, using the data obtained following the Christchurch Earthquake Sequence, empirical charts were developed for liquefaction potential assessment using SDS data.

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