NZGS SYMPOSIUM 2021
Good grounds for the future
24-26 March 2021 • Dunedin • New Zealand

Correlation between Screw Driving Sounding and popular in-situ tests for soil characterisation in New Zealand

S.Y. Mirjafari
Tonkin and Taylor Ltd, New Zealand.

R. P. Orense
University of Auckland, New Zealand.

N. Suemasa
Tokyo City University, Japan.

ABSTRACT

Standard penetration test (SPT), cone penetration test (CPT) and vane shear test (VST) are the most common in-situ tests around the world due to their high capabilities in soil characterisation and estimation of shear strength parameters of soil. Screw Driving Sounding (SDS) is a relatively new in-situ testing method in which a machine drills a rod with a screw point on its tip into the ground in several loading steps while the rod is continuously being rotated. Several parameters such as torque, load, speed of penetration and friction, are measured at every rotation of the rod; these provide a robust way of characterising soil stratigraphy. In this study, based on the results of many SDS tests in a variety of soil types in New Zealand and conducted adjacent to other in-situ tests which have been performed previously, different correlations are developed to estimate the equivalent SPT blow count, undrained shear strength and CPT tip resistance directly from the SDS results. Being a fast and economical test to perform, high capability in soil characterisation and good correlations with other popular in-situ test results make SDS testing a reliable alternative in-situ test for soil characterisation, especially in residential house construction.

1 INTRODUCTION

Identification of the ground condition is a very important step to take before starting to build any geotechnical structure. Several different field-testing techniques are available in New Zealand to be used for soil characterisation. These include the standard penetration test (SPT), the cone penetration test (CPT) and the vane shear test (VST).

SPT has been the most widely used in-situ test for site characterisation in many countries and is performed during the advancement of soil boring to obtain an approximate measure of the soil resistance. Samples can be taken from the borehole for additional laboratory tests if required (Clayton, 1995). Recently, the CPT has been the preferred choice because it gives a continuous record of soil profile and it is not operator dependent. Although sampling is not possible, soil type (or, more accurately, soil behaviour type) can be inferred from the information collected during the test. The VST is another popular in-situ test which is used to evaluate the undrained shear strength of soft to stiff clays and silts. The test is best performed when the vane is pushed at the bottom of a pre-drilled borehole into the soil.

The Screw Driving Sounding (SDS) test is a relatively new method for soil characterisation which has recently been developed in Japan. The SDS machine drills a rod, with a screw point at its tip, into the ground in several vertical loading steps while the rod is continuously rotated; at the same time, a number of parameters such as torque, load, rod friction, and speed of penetration are recorded at every rotation of the rod. Because this machine can continuously measure these parameters, it can give a clear indication of the soil profile throughout the depth of penetration. The SDS method has many advantages compared to other in-situ testing methods, such as faster implementation (time required for 10 m of penetration is approximately 30 min), simpler system for performing the test, and more compact machine compared to CPT and SPT; hence it is more economical compared to other in-situ tests.

To date, a total of 300 SDS tests have been performed at a variety of sites in New Zealand (NZ), mostly at sites where CPT/SPT data or borehole logs are available, so that correlations can be made with the SDS parameters. From the soil database obtained, a soil classification chart has been developed (Orense et al. (2018) and correlations with geotechnical parameters and SPT/CPT/VST data were established based on SDS-derived parameters.

2 SCREW DRIVING SOUNDING TEST

During the SDS test, a rod, with screw point at its tip, is drilled into the ground under seven steps of vertical loading. The rod is continuously rotated at a constant rate of 25 rpm. The load steps are 0.25, 0.38, 0.50, 0.63, 0.75, 0.88, 1kN, in this order, and the load is increased after each rotation of the rod. The parameters measured in the test are: maximum torque (T_{max}), average torque (T_{avg}), minimum torque on the rod (T_{min}), penetration length (L), penetration velocity (V) and number of rotations of rod (N). These data are measured on the completion of each rotation of the rod. after each 25 cm penetration, the rod is automatically moved up by 1 cm and then rotated to measure the rod friction. Figure 1 shows the SDS machine during operation.

Figure 1: Screw driving Sounding (SDS) machine during operation

Additional useful information can be obtained by processing the measured data from SDS tests (Mirjafari 2016). For example, $N_{SD}D$ is the normalised half-turns obtained by multiplying the number of half-turns for every 25 cm of penetration (N_{SD}) by the outer diameter of the screw point (D). This number gives an indication of the level of torque required to twist the rod. Another parameter, $\pi T/WD$, represents the normalised torque and is defined using the torque (T), the weight applied (W) and the outer diameter of the screw point (D). Other SDS-derived parameters include the following:

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

$$c_p" = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{N_{SD}D}{\pi T/WD}\right)_i \tag{2}$$

$$T_{ave} = \frac{1}{n}\sum_{n=1}^{7} T_n \tag{3}$$

where $Ave\delta T$ is the average change in torque, T, at each step of loading, i; n (= 7) is the number of loading; and c_p" is the modified coefficient of plastic potential. $Ave\delta T$ relates to the grain size of the soil and c_p" related to difficulty of penetration (Mirjafari, 2016). T_{ave} is the average of the measured torque at different steps of loading.

During the SDS test, both load and torque are applied to the rod at the same time 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):

$$\delta E = \pi T \delta n_{ht} + W \delta s_t \tag{4}$$

where 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 volume of penetration:

$$E_s = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{E}{L\times A}\right)_i \tag{5}$$

where L is the depth of penetration and A is the maximum cross-sectional area of the screw point. E_s is taken as the average of the specific energies calculated at different steps of loading at each 25 cm of penetration. Several correlations between SDS data and geotechnical parameters of the soil, such as undrained shear strength, friction angle and liquefaction resistance have been developed by the authors (e.g. Mirjafari, 2016; Orense et al. 2018). In the following section, a methodology is described for identifying fines content directly from SDS data.

3 FINES CONTENT ESTIMATION

Fines content (FC) in sandy soil plays an important role in the engineering design of geotechnical structures, particularly when the area is prone to earthquakes. The value of FC significantly influences the liquefaction potential of soil. In engineering practice, it is very common to estimate FC using the CPT data, as this test has become the most common field test for the design of structures. However, experience in Christchurch showed that CPT could overestimate the fines content within soil (Van T Veen, 2015). Hence, an attempt was made to formulate a relationship between the fines content and the SDS parameter(s) as an alternative to the CPT-based estimation.

For this purpose, sieve analyses were performed on 120 samples obtained from different sites in New Zealand. The particle size distribution for each sample was obtained by the method of wet sieving described in NZS 4402.2.8 (Standards NZ, 1986), with FC defined as the percentage by weight passing through a 63 mm sieve. As mentioned in Section **Error! Reference source not found.**, $Ave\delta T$ relates to the grain size of the soil and c_p" related to difficulty of penetration, which is also indirectly related to the amount of fines in the soil. By combining these two parameters, a new parameter is defined which is used to correlate with *FC*. This parameter is defined as follows:

$$S = 9.44 - 2.44 \times log(\frac{c_p"}{0.026e^{-0.75Ave\delta T}}) \quad (6)$$

And the correlation with *FC* is defined in Equation (7).

$$FC = 2.1S^2 + 4.2S \quad (7)$$

For *AveδT* < 1 N·m, *FC* can be considered to be 100%, while for negative values of *S*, *FC* is 0%. Figure 2 shows how *S* correlates with *FC*.

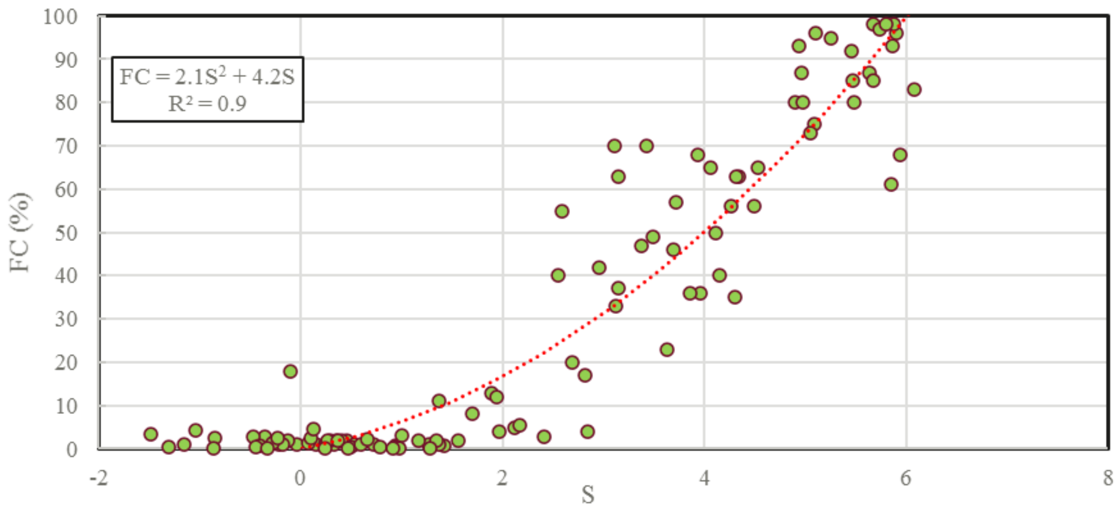

Figure 2: Relationship between the SDS parameter S and FC

4 CORRELATION WITH OTHER IN-SITU TESTS

4.1 Correlation with CPT tip resistance

Using the results of all the SDS tests conducted adjacent to CPT sites (less than 2 m away), a correlation was made between specific energy of penetration (E_s) and the cone tip resistance. For this purpose, the SDS parameters and the CPT cone tip resistance, q_c, at similar depths were compared. Among the SDS parameters, the specific energy, E_s, best correlated with q_c.

Separate correlations were developed for different *FC* of soil which were estimated from the SDS data using Equation (7). Figure 3 illustrates the relationship between E_s and q_c for soils with different fines content (*FC*). As can be seen in the plots, the slope of the line increases with increasing FC.

Data scatter is clearly seen in the plots, and this may be due to the difference in the penetration mechanism (static penetration for CPT and static + rotational penetration in SDS) and the uncertainty associated with depth measurements (CPT was measured every 20 cm, while SDS was recorded every 25 cm). While care was taken when selecting data for analyses, zones in the transition between layers were problematic. Also, many of the CPT and SDS tests were performed with a time gap between them, and it is possible that soil conditions, such as the water table, may have changed during this time gap, which could have affected the penetration resistance of the soil.

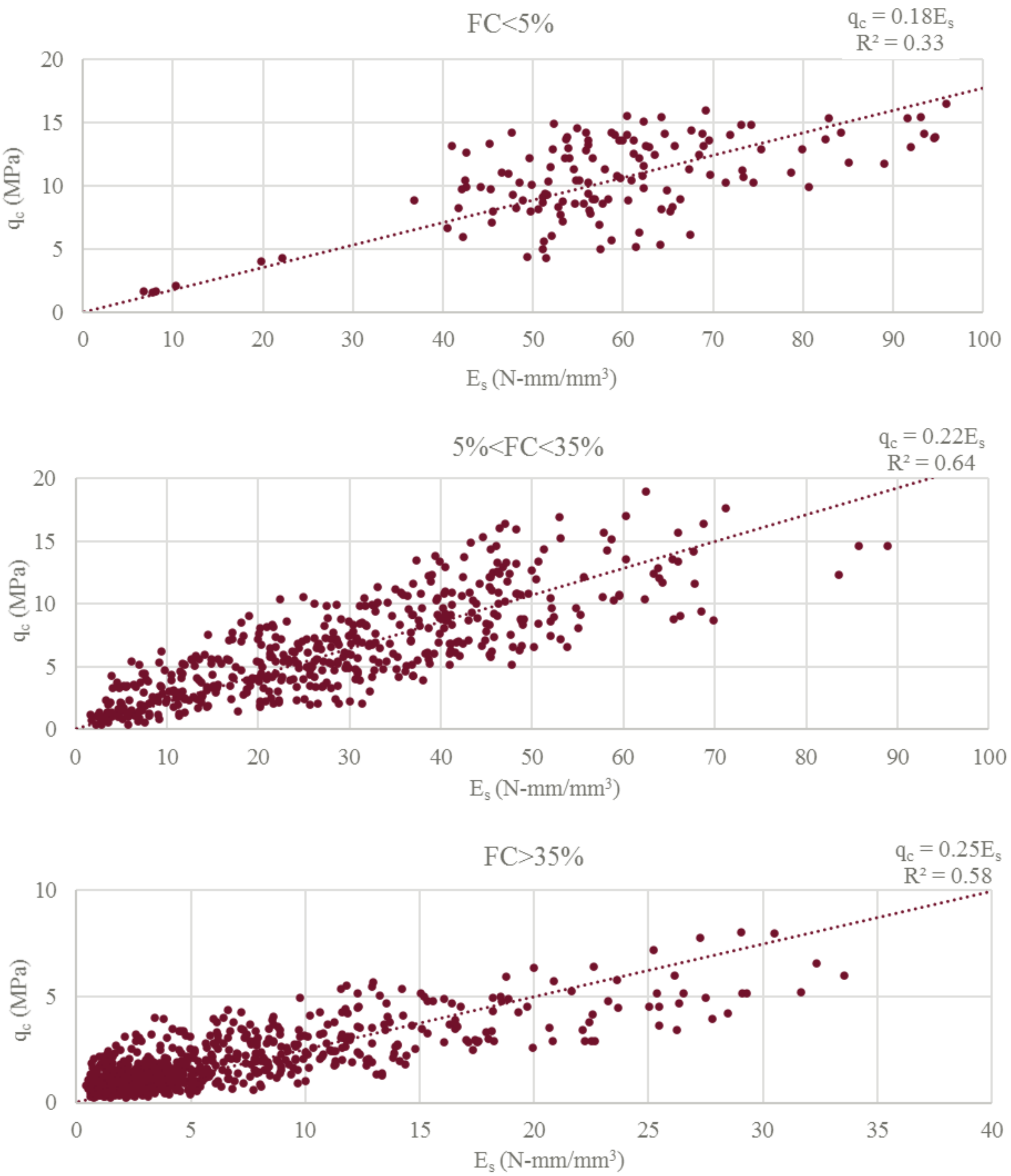

Figure 3: Plots showing the relation between E_s of SDS and CPT q_c

4.2 Correlation with SPT N value

One of the research purposes for performing the SDS tests near boreholes with SPT was to compare between the SDS parameters and the measured SPT *N* value. In this regard, SDS tests were conducted within a 2 m distance from the boreholes. The borehole and SPT data were obtained from the New Zealand Geotechnical Database. For developing this correlation, only sites with clean sand (*FC*<5%) were selected as the data for other types of soil were very limited. For this purpose, the soil type was identified through the borehole data as well as from the soil classification chart developed before the comparisons were made.

By comparing the SDS and SPT results, it was found that both the SDS-derived torque, *T*, and the SPT *N* profile show a similar trend indicating good correlation between these two tests. Nevertheless, the characteristics of the two tests are not similar. The SPT is based on counting the number of blows; however, the SDS is a test which drills a rod into the ground at a constant rotational speed providing an almost continuous record. To develop a correlation between the results of the two tests, data from 18 sites in Christchurch were compiled and the result is presented in Figure 4.

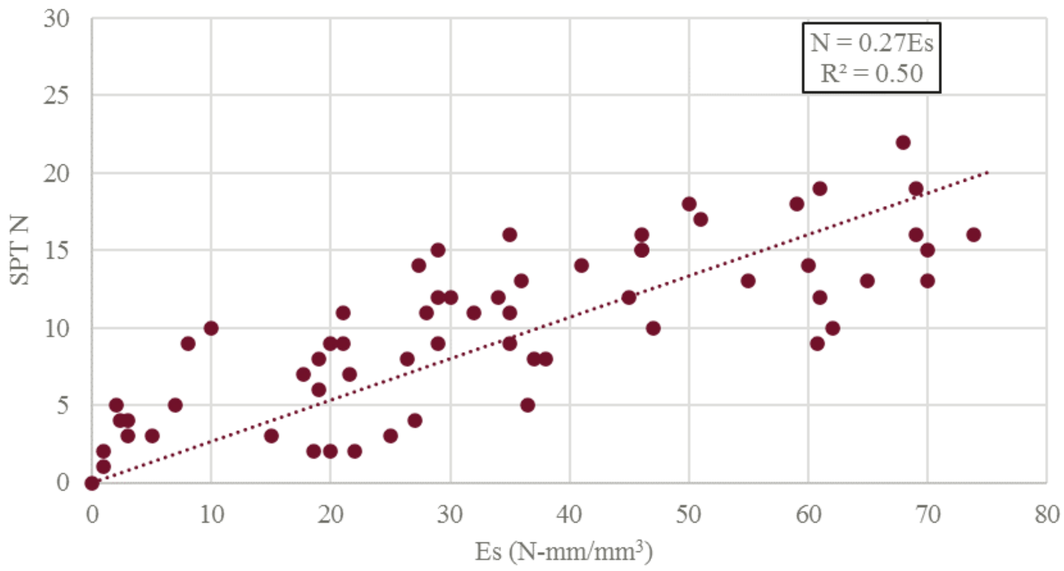

Figure 4: Plot showing the relation between SPT N value and E_s of SDS (FC<5%)

Some of the scatter shown in the figure can be explained as follows. Firstly, the number of readings between these two tests is different; the SDS records the parameters continuously along the depth every 25 cm, while the SPT N value is measured every 1 or 1.5 m. In dense sand, E_s may represent the properties of the soil for a layer with a length of even less than 25cm, which may not be captured in SPT. Secondly, from a statistical point of view, the reading patterns are not similar and, in some depths, an average of two subsequent 25 cm of SDS was used to compare with the SPT N value and some of the outliers which belong to the transition layers have been removed from the analysis. Finally, the loading patterns in the two tests are different: in the SDS, a rod is drilled into the ground by combination of load and torque, while in the SPT the penetration is caused by dropping a hammer.

Considering the above-mentioned limitations, there is still a good correlation between these two tests with an acceptable correlation coefficient of 0.5, as indicated in Figure 4. However, this correlation is only applicable to clean sand and more data are required to extend the correlation obtained to other types of soils.

4.3 Correlation with Vane Shear Test

The vane shear test (VST) is one of the most popular methods for estimating the undrained shear strength, S_u, of clay or silt in NZ and usually is undertaken during the advancement of boreholes or hand augers at selected depths. An attempt was made to correlate a SDS parameter to the undrained shear strength obtained from VST. As S_u is deemed to directly correlate with the measured torque of VST, a correlation was attempted between S_u and average applied torque, T_{ave}, of SDS; this relationship is shown in **Error! Reference source not found.**.

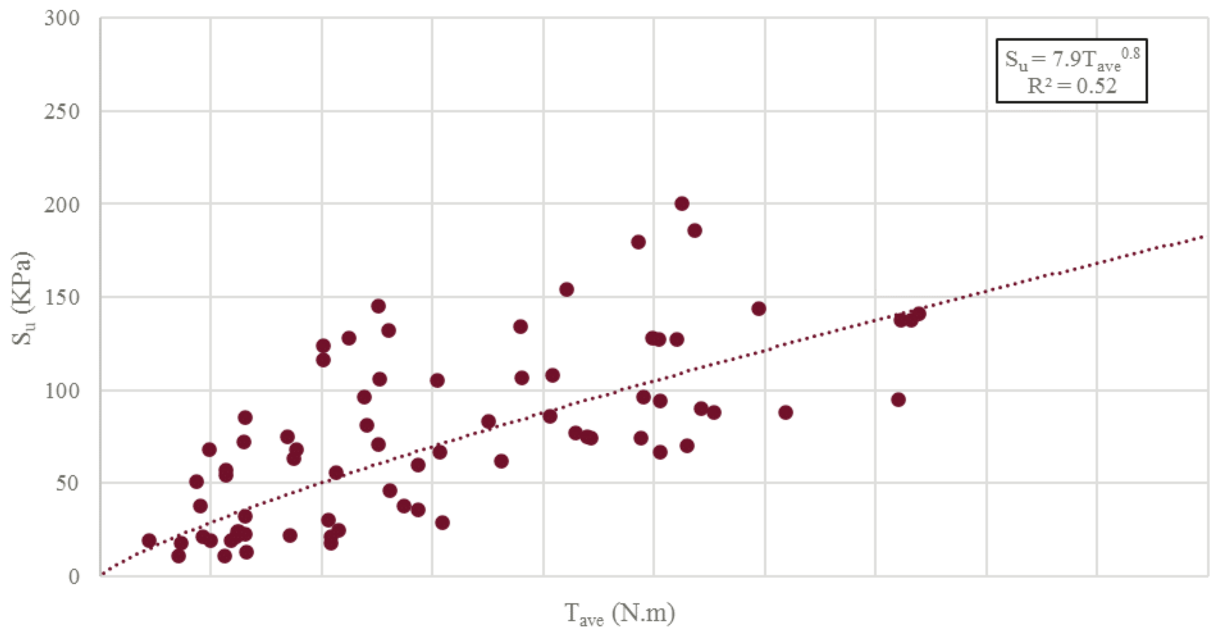

Figure 5 Plot showing the relation between S_u and T_{ave} of SDS

VST is a manual test and its accuracy highly depends on the skill of the operator. This can be a source of the scatter in the plot, as a small change in rotational speed of VST can influence the results significantly. Also, T_{ave} represents the average torque in 25 cm of penetration versus S_u from VST is estimated for a particular depth. Other factors such as seasonal changes in the water level may affect the S_u of the soil and be the source of scatter in the plot as SDS and VST were performed at different times of the year.

5 CONCLUSIONS

In this paper, a new in-situ testing method called the Screw Driving Sounding (SDS) test was introduced. This machine can continuously measure various parameters, including torque, load and speed of penetration, so it is able to give a clear overview of the soil profile throughout the depth of penetration. In comparison with other methods and considering the number of geotechnical parameters that can be obtained from the tests, SDS testing is simpler, faster and it does not need a large space to conduct the test.

By performing sieve analysis on samples obtained from SDS sites, a relationship was developed to estimate the *FC* directly from the SDS data. A good correlation was observed between the SPT *N* value of clean sand and the specific energy E_s of SDS. Similarly, different correlations were developed between the SDS parameter(s) and the CPT cone resistance and the undrained shear strength from VST.

As SDS is simpler, faster and more economical, the results suggest that SDS can be a supplement, or even an alternative to, CPT, SPT and VST for a more cost-effective geotechnical investigation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Nitto Seiko Company for providing the SDS machine and the Japan Home Shield Corporation for providing assistance for this research. They would also like to acknowledge the New Zealand Geotechnical Database for providing the borehole data and SPT/CPT records in the target sites and the city councils for providing access to the test sites.

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