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Assessment of In-Situ Liquefaction Resistance of Soils Using Screw Driving Sounding

S.Y. Mirjafari. M[1]& R.P. Orense[2], N. Suemasa[3]

ABSTRACT

The city of Christchurch experienced many large earthquakes in 2010-2011 and a host of civil engineering structures was damaged due to soil liquefaction. In situ testing, such as cone penetration test (CPT), is a popular method to characterize the liquefaction resistance of soil. Screw driving sounding (SDS) test is a new in-situ testing method for site characterisation. This method involves penetrating a rod into the soil at different loading steps while being rotated, with continuous measurement of the required torque, load, penetration speed and rod friction. In this paper, the results of a number of SDS tests conducted in Christchurch adjacent to locations of CPT tests were discussed where it was noted that there was good agreement between the results of CPT and SDS tests. Moreover, plots of cyclic shear stress ratios (CSR) induced by the earthquakes and the corresponding energy of penetration during SDS tests were drawn. By identifying liquefied or unliquefied layers using three different CPT-based methods popularly used in conventional practice, boundary lines to determine the cyclic resistance ratio (CRR) as a function of SDS parameter were established for different fines contents; these can then be used for estimating the liquefaction potential of soil directly from the SDS data. As a simple, fast and economical test, the SDS method can be a reliable alternative in-situ test for site characterization, especially in residential house constructions.

Introduction

Huge earthquakes in Christchurch in 2010-2011 brought about extensive damage to various engineering structures such as buildings, bridges and lifeline facilities. Many of the buildings tilted considerably as a result of the liquefaction of loose saturated sands. Correlations based on in situ tests are widely used in engineering practice to estimate the liquefaction potential of soil. Currently, cone penetration test (CPT) is widely used around the world as a means for geotechnical design and liquefaction potential evaluation of soil.

In this study, a new in-situ test called Screw Driving Sounding (SDS) method is introduced and the development of an empirical chart to evaluate the liquefaction potential of soil using SDS data is discussed. For this purpose, a series of SDS tests was conducted in Christchurch at both liquefied and unliquefied areas. All the SDS tests were performed adjacent to locations of CPT tests which have been previously done in Christchurch as part of the Canterbury Geotechnical Database (CGD 2013). Firstly, using the results of SDS tests, plots were generated showing the relationship between the cyclic shear stress ratio (CSR) induced during the earthquake and

[1] PhD Student, Dept of Civil & Env. Engineering, University of Auckland, Auckland, New Zealand, smir332@aucklanduni.ac.nz
[2] Associate Professor, Dept of Civil & Env. Engineering, University of Auckland, Auckland, New Zealand r.orense@auckland.ac.nz
[3] Professor, Department of Urban & Civil Engineering, Tokyo City University, Tokyo, Japan, nsuemasa@tcu.ac.jp

energy of penetration in SDS method. Next, the liquefaction potential of each data point was evaluated using three different methods based on the available CPT data. Note that because CPT is widely used as a tool for assessing the liquefaction resistance of potentially liquefiable soils, it is selected as a basis for evaluating the liquefaction susceptibility of the soil layers. Finally, by delineating points which were deemed to have liquefied, three boundary lines corresponding to different fines content (*FC*) were drawn to define the cyclic resistance ratio (CRR). Such empirical chart can then be used to assess the liquefaction potential based directly on SDS data.

Principle and test procedures

Screw Driving Sounding test

Screw Driving Sounding (SDS) test consists of a machine drilling a rod into the ground in 7 steps of monotonic loading. In this test the load increases at every complete rotation of the rod and the load steps are 0.25, 0.38, 0.50, 0.63, 0.75, 0.88, and 1kN. The speed of rotation is constant and equal to 25 rpm. Measured parameters in the test are: the applied torque on the rod (*T*), amount of penetration (*L*), penetration velocity (*V*) and number of rotations (*N*) of the rod. The parameters are measured at every complete rotation of the rod. In this test a set of loading is applied 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) shows both the SDS machine on top of a crawler and CPT rig side-by-side. It is obvious that SDS machine is much smaller in scale (especially without the crawler) and requires less operating space than even the smallest CPT rig.

Definition of energy and specific energy

In SDS test, both load and torque are applied to the rod at the same time. The energy which is required for penetration is a parameter that represents the combined effect of both vertical load and torque. The incremental work done, δE, by the torque and vertical load for a small rotation can be calculated as (Suemasa et al. 2005):

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

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 and torque. The average specific energy, E_s, is defined as the average of the penetration energy for different steps of loadings, E, divided by the volume of penetration of the screw point:

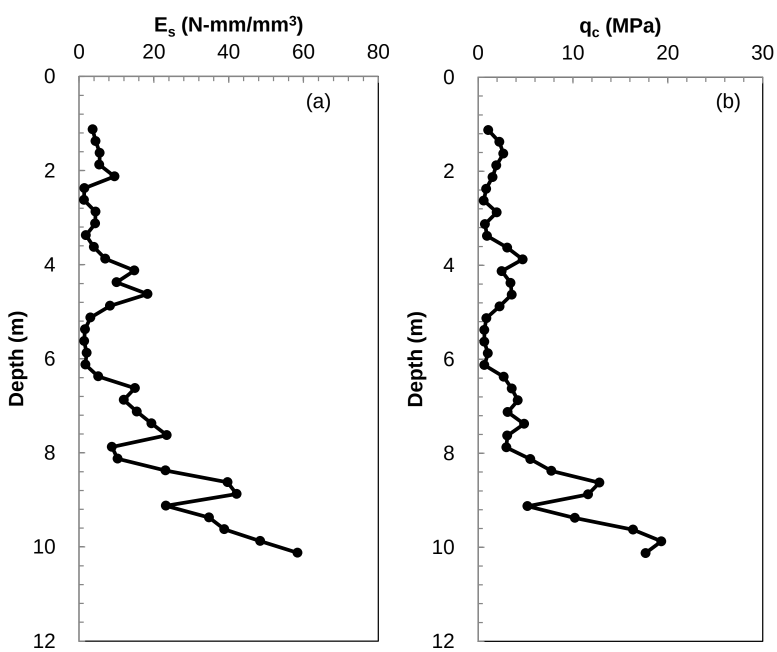
$$E_s = \frac{E}{L \times A} \tag{2}$$

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

(a) (b)

Figure 1. (a) Screw driving sounding (SDS) equipment; (b) The SDS equipment on the fore-ground (on top of a crawler) and small-scale CPT rig on the background.

Figure 2 illustrates the variation with depth of average specific energy, E_s, for all steps of loading as well as the CPT tip resistance obtained at essentially the same location (i.e. at Wordsworth Street, Christchurch – highlighted in Figure 3). As seen in the figure, the variation of E_s with depth is similar to the variation of the CPT tip resistance (q_c) along the soil profile.



(a) (b)

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

SDS Tests in Christchurch

Between June-August 2013, 69 SDS tests were conducted in Christchurch. The locations of these sites are presented in Figure 3. These sites are located at both liquefied and non-liquefied areas following the Canterbury earthquake sequence (CES). SDS tests were conducted within 1–3 m from CPT sites, whose locations are described in the CGD (2013). Further details of the SDS application in Christchurch are discussed by Orense et al. (2013) and Mirjafari et al. (2013).

Figure 3. Location of SDS test sites in Christchurch (modified from Google Earth).

The simplified procedure by Seed and Idriss (1971) for estimating earthquake-induced cyclic shear stresses continues to be the basis of analysis, although there have been a number of refinements to the various components of this framework. Cyclic shear stress ratios (CSR) induced by earthquake ground motions with magnitude M=7.5, at a depth z, is estimated as:

$$(CSR)_{M=7.5} = 0.65 \frac{a_{\max}}{g} \frac{\sigma_{v0}}{\sigma'_{v0}} \frac{r_d}{MSF} \quad (3)$$

where σ_{v0} and σ'_{v0} are the total and effective overburden stresses, respectively, at the depth in question, $a_{\max}$ is the peak horizontal ground acceleration generated by the earthquake, g is the acceleration due to gravity, r_d is the stress reduction factor and MSF is the magnitude scaling factor. Different methods use certain expressions for r_d or MSF in calculating the CSR and the defined thresholds for liquefaction triggering are slightly different for each method. Hence to minimize the uncertainty in terms of liquefaction potential of soil layers in Christchurch, three different methods are used for liquefaction analysis: (1) Moss et al. (2006); (2) Idriss and Boulanger (2008); and (3) Robertson and Wride (1998). Figure 4 shows a sample of liquefaction analysis plots for the site whose location is shown by the yellow circle in Figure 3 and generated using the CLiq software (GeoLogismiki, 2006).

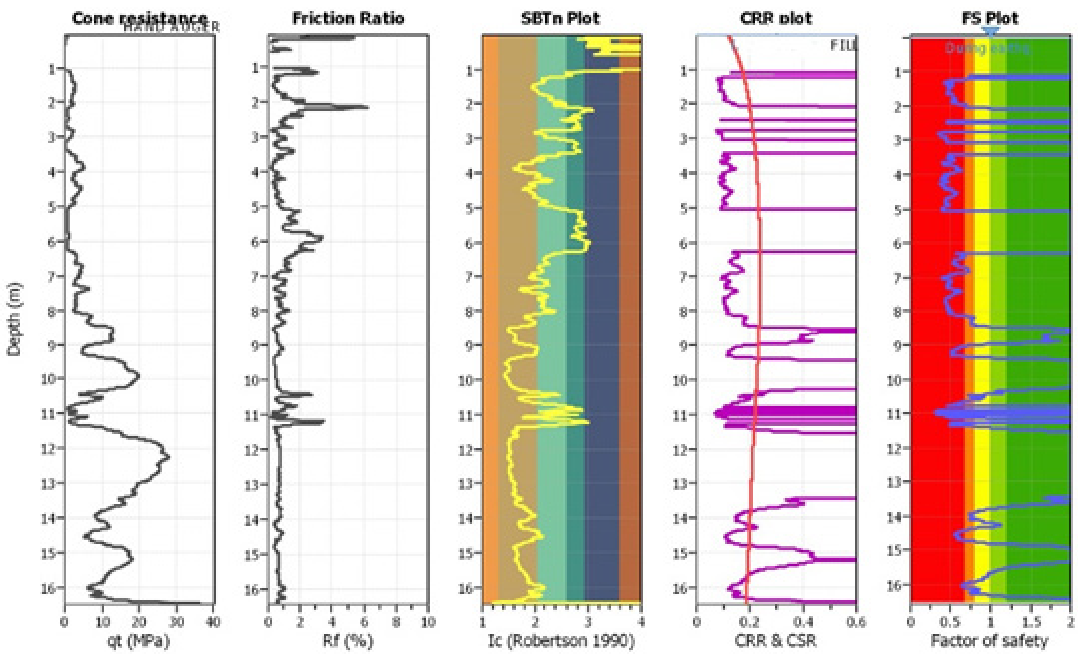


Figure 4. Liquefaction potential analysis based on Roberston and Wride (1998) method for the site located in Wordsworth Street, Christchurch (GeoLogismiki, 2006).

The SDS data points obtained in Christrchurch are summerised in Figure 5 in terms of the relation between CSR (calculated using Robertson & Wride (1998) method) for M=7.5 earthquake and the SDS parameter, $E_{s,1,\ \mathrm{which}}$ is the average specific energy during penetration normalized by the reference overburden pressure of P_a=100 kPa (or 1 atm):

$$E_{s,1} = E_s \left(\frac{P_a}{\sigma_{v0}^{'}} \right)^m \tag{4}$$

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

Each plot in the figure corresponds to a specific range of fines content, *FC*. For this purpose, the value of *FC* used for each layer was estimated from the CPT data based on Robertson and Wride (1998) method, with soil layers having *FC* > 50% not included in the analysis. Each data point was judged to have liquefied if the factor of safety against liquefaction, F_L < 1.0 based on all three methods; these are shown as black points in the figure. Soils deemed to have not liquefied by all three adopted methods are shown by yellow points.

Based on the position of the liquefied and non-liquefied data points in each plot, a curve is drawn to estimate the threshold for liquefaction triggering. As shown in the figure, data points on the right side of the boundary curve show more penetration energy and are considered as dense and hence not liquefiable. Note that the boundary line for liquefaction triggering for each group of soils was drawn visually by engineering judgment and were defined conservatively such that most of the liquefied cases lie to the left of the curve. However, a few liquefied data are located to the right side of the boundary line while some unliquefied data points plot to the left.

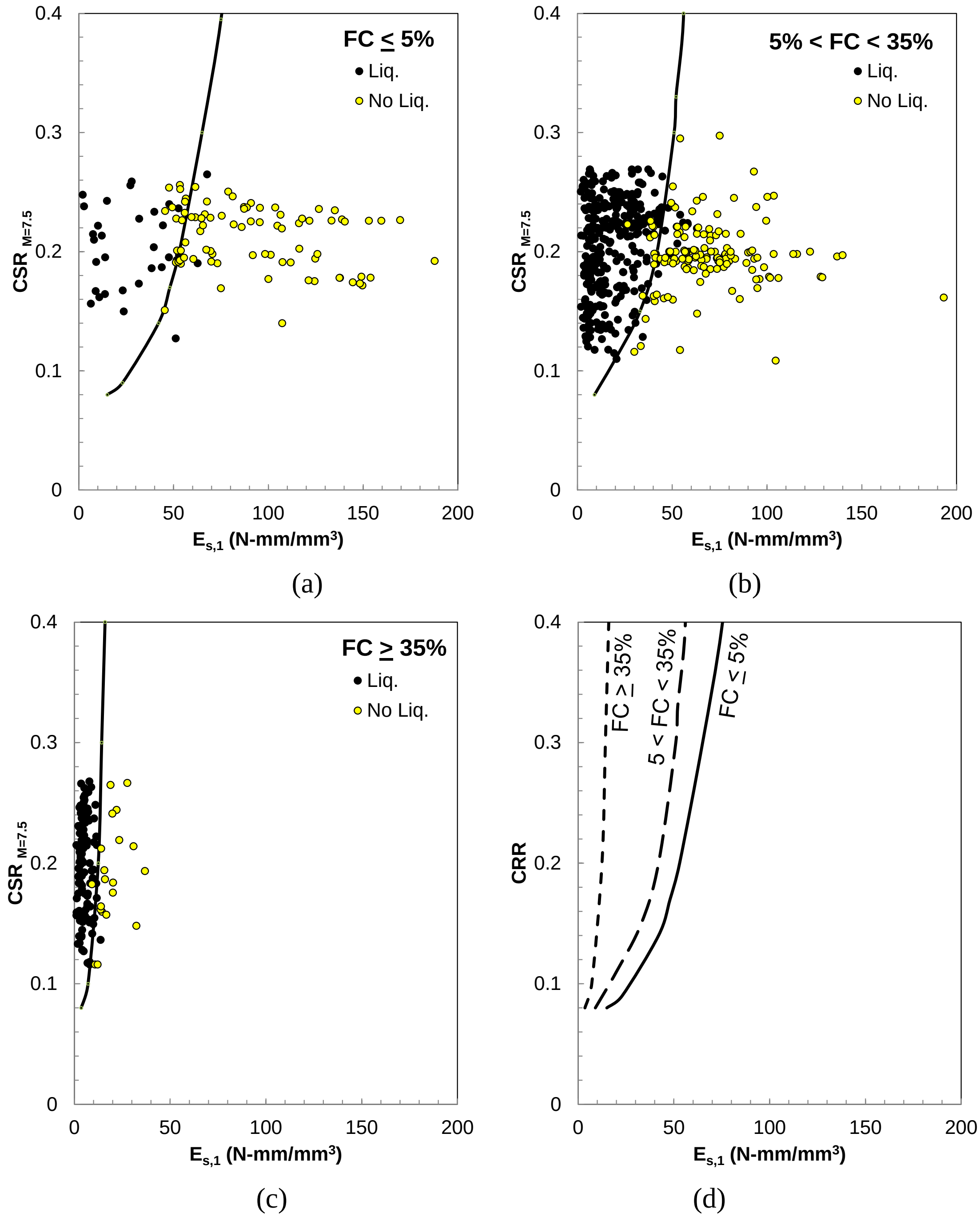


Figure 5. Relationship between CSR (or CRR) and normalized specific energy of penetration based on the SDS tests conducted in Christchurch: (a) *FC* ≤ 5%; (b) 5% < *FC* < 35%; (c) *FC* ≥ 35%; and (d) proposed chart for evaluating liquefaction potential of soil.

It is worthy to mention that in SDS test, the amount of penetration at each step of loading is not necessarily constant for all layers; thus, the average specific energy which was used in the graph is the average specific energy in incremental steps of loading at each 25 cm of penetration. This has to be adjusted to the elevation of each CPT test, which was conducted every 1 cm of penetration. Therefore, this may give rise to small difference in the starting points of the two tests especially at some depths where different soil layers occur abruptly.

Another point worth mentioning is the possible inaccuracy of CPT method in predicting the fines content of the soil. As mentioned earlier, the values of *FC* were estimated from the CPT data based on Robertson and Wride (1998) method. To investigate the applicability of this method to Christchurch soils, a series of laboratory tests were conducted on soil samples taken from a site located in Vainoni, Christchurch. *FC* was obtained from sieve analysis and then compared to the *FC* predicted by CPT-based method. Figure 6 illustrates the comparison between laboratory-obtained and CPT-predicted fines content where it is obvious that CPT-based method cannot predict the *FC* values accurately; thus, the use of CPT-based *FC* values has a direct impact on the proposed graph for different *FC*. To minimize the uncertainity regarding *FC* estimates, laboratory tests are currently being conducted on samples taken from the sites where SDS were conducted for possible direct correlation with SDS-derived parameters.

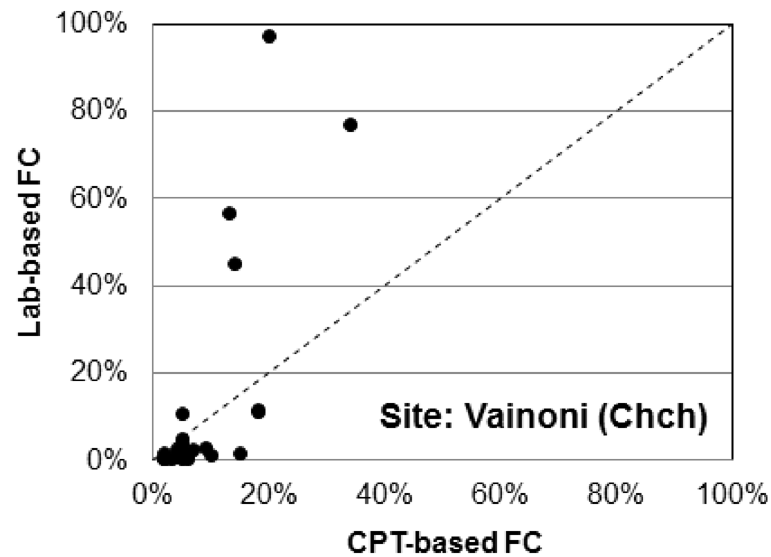


Figure 6. Comparison between *FC* obtained from laboratory testing and predicted based on CPT data for Vainoni site, Christchurch.

Finally, the current data set is limited by the CSR induced during the CES and data exist only in the range of $0.1 < CSR < 0.3$. More data (especially with $CSR > 0.3$) are required to further define the location of the proposed boundary lines. In addition, more data points in the critical region (close to boundary lines) where uncertainty exists regarding their liquefaction potential can also assist in refining the location of the proposed triggering curves. Once further refined, the liquefaction potential of soil can be estimated directly by means of SDS testing.

Conclusions

In this study a new in-situ testing method referred to as the Screw driving sounding (SDS) was introduced. Continuous recording of soil profile and the variety of parameters that can be recorded by SDS machine make a it a powerful machine for soil characterization.

In evaluating the capability of SDS method for soil characterization and identifying liquefiable soil layers 69 tests were conducted in Christchurch at both liquefied and unliquefied areas. Based on the results of the tests, it was shown that the liquefaction potential of soils can be assessed using SDS parameters through the boundary line defining liquefaction triggering. Because SDS test is simpler, faster and more economical test than CPT, it can be good alternative for characterizing soils.

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