Evaluation of liquefaction potential of soils using SDS data in Christchurch

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ABSTRACT: During severe earthquake shaking, soil liquefaction is a major concern for structures constructed on saturated loose sandy soils. A large number of civil engineering structures were damaged due to liquefaction during huge recent earthquakes in Christchurch. Several in-situ tests have been used for evaluating liquefaction resistance of soils. Cone penetration testing (CPT) is one of the most common in-situ tests, which is used worldwide for assessing the liquefaction potential of sandy soils. CPT is simple, fast, and it supplies continuous records with respect to depth. However, this test needs skilled operator and is relatively expensive. The Screw Driving Sounding (SDS) test is a relatively new operating system developed in Japan consisting of a machine that drills a rod into the ground at different steps of loading while being rotated. This machine can continuously measure the required torque, load, speed of penetration and rod friction during the test, so 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 graph is presented which relates the cyclic stress ratio to the SDS parameters. Using the available data points a boundary line is defined between liquefied and unliquefied soil layers. By means of the proposed graph, liquefaction potential of soil can be estimated directly using SDS data. As SDS is simpler, faster and more economical than CPT, it can be a good alternative in situ test for soil characterization.

1 INTRODUCTION

Soil liquefaction phenomenon has been recognized for many years and is a major concern in Christchurch for structures constructed on saturated sandy soils. The most popular simple in-situ method for estimating cyclic resistance ratio of 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 the continuous nature of soil profile that can be obtained (Roberson and Wride, 1998).

In this study, a new in-situ test called Screw Driving Sounding (SDS) method is introduced and a procedure to evaluate the liquefaction potential of soil using SDS data is discussed. A series of SDS tests were conducted in Christchurch in both liquefied and unliquefied areas. All the SDS tests were performed adjacent to locations of CPT tests which have been previously done in Christchurch. Liquefaction potential of each site was evaluated using the three different methods based on available CPT data. By measuring the liquefaction potential of the soil layers and using the results of SDS tests a graph is generated that shows the relationship between cyclic stress ratio and SDS parameter. A boundary line is also defined that separates the liquefiable layers data from unliquefiable layers.

As the cone penetration test CPT is a reliable and repeatable in situ index test that has found widespread use as a tool for assessing the liquefaction resistance of potentially liquefiable soils, it is selected as a basis for evaluation of liquefaction susceptibility of soil layers.

2 PRINCIPLE AND TEST PROCEDURE

2.1 Swedish Weight Sounding (SWS) Method

Swedish weight sounding (SWS) is another in-situ test that is popular in Japan and Nordic countries. SWS consists of weights (a 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 key advantages of this test are that it is highly portable, low cost and, similar to CPT, provides a continuous profile of the soil.

Although the SWS test is highly portable and simpler than other sounding tests, this test has some limitations, such as the results being fairly influenced by rod friction. In cases where the soil contains gravel, the required load to penetrate, the number of half-turns and, consequently, the soil resistance from the SWS tends to be over-estimated as the rod friction becomes large.

2.2 Screw Driving Sounding

2.2.1 Test procedure

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 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 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. In the SDS as well as the SWS, a set of loading is conducted at every 25cm of penetration and after each 25cm penetration, the rod is lifted up by one centimetre and then rotated to measure the rod friction. The procedure of measuring the rod friction is described by Tanaka et al. (2012). Figure 1 illustrates the SDS test machine during operation.

2.2.2 Definition of energy and specific energy

As it was discussed in the previous section in the SDS test load and torque are applied to the rod at the same time. Another parameter is defined here which is the combination of applied load and torque. An incremental work done δE by torque and vertical force is given by

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

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 δ_{st} is the incremental settlement caused by the load. Specific energy is defined as the amount of energy divided by volume of penetration.

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

where L is the amount of penetration and A is the maximum cross area of screw point. Figure 1 illustrates the changes of specific energy along the depth and the CPT profile of the site. The calculated specific energy is the average of specific energy in different steps of loading in each 25 cm of penetration. This data is from one of the locations located in Greenhaven Drive, Christchurch. As it is presented in Figure 2 specific energy changes in a similar way to the CPT parameters along the soil profile and it can be used in liquefaction potential analysis based on SDS data.

Figure 1. Screw driving sounding (SDS) equipment.

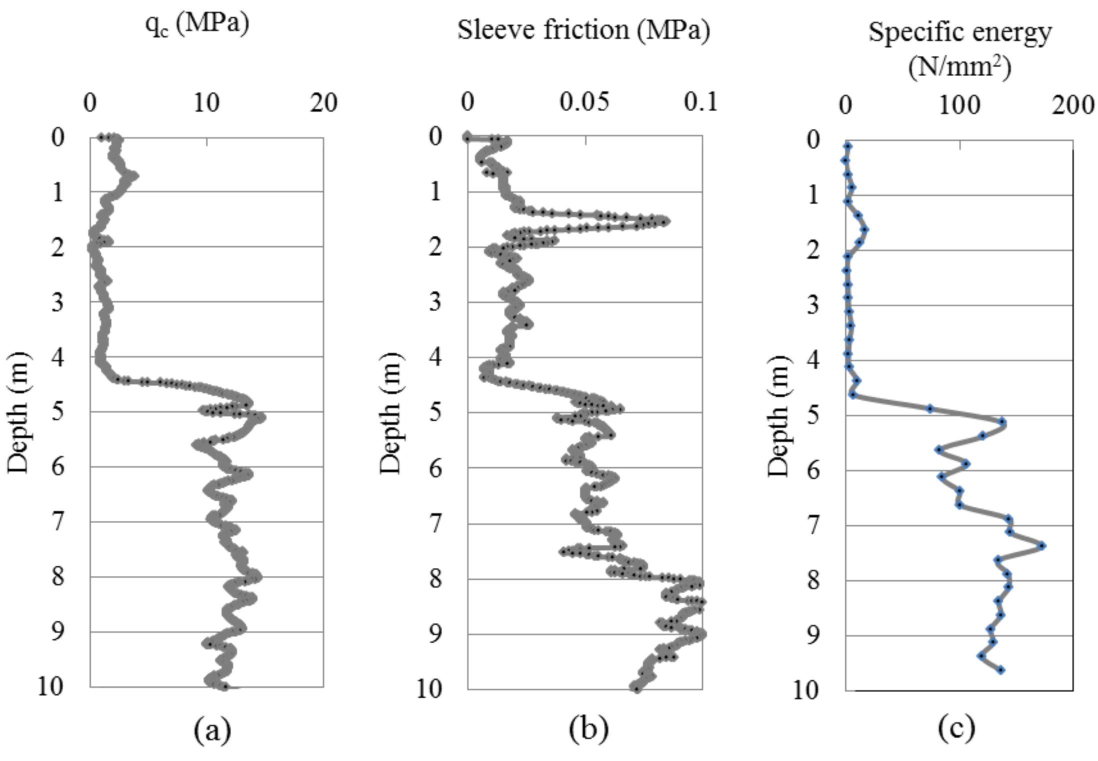

Figure 2. (a) cone resistanec (b) sleeve friction in CPT test and (c) changes in Specific energy of SDS test with depth, Site located in Greenhaven Drive, Christchurch

3 SDS TESTS IN CHRISTCHURCH

During the period 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 Feb 2011 earthquake. SDS tests were conducted within 1 – 3 m from CPT sites, as described in the CGD.

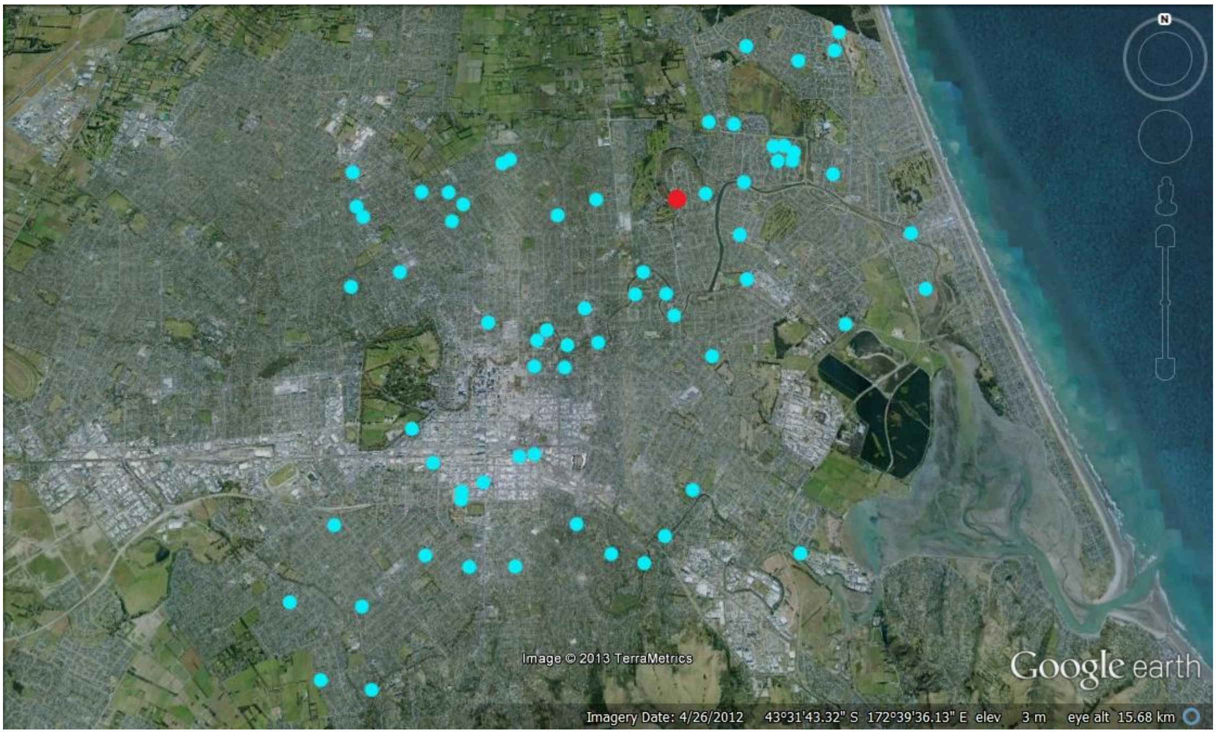

Figure 3. Location of SDS test sites in Christchurch.

As in this study evaluating the liquefaction potential of clean sand is considered, 25 sites where mostly have clean sand along the soil profile were selected for liquefaction potential analysis.

There are several methods for identifying liquefaction potential of soils. Different methods use certain correction factors such as r_d or *MSF* for calculating cyclic stress ratio and their defined threshold of liquefaction triggering are slightly different from each other. Hence to minimize the uncertainty about liquefaction potential of soil layers three different methods are used for liquefaction analysis including methods developed by Moss (2006), Idriss and Boulanger (2008) and Robertson and Wride (1998). Figure 4 and 5 show a sample of liquefaction analysis plots for a site that is at the location of the red circlein Figure 3. Plots generated using Cliq software (GeoLogismiki, 2006).

Data collected and compiled for this study are shown in Fig. 6 as a plot of the liquefied and unliquefied case histories based on SDS parameter. After doing liquefaction potential analysis it was found that some soil layers were identified as liquefiable soil as the factor of safety against liquefaction (F_L) was less than one based on all three methods which are shown by red points in Figure 6 and some are unliquefiable (F_L more than 1) which are shown in green. There were some soil layers where the results of three methods were not the same. For instance in analysis based on Robertson and Wride (1998) method, F_L was less than 1 however the other two methods showed F_L more than 1. Due to this uncertainty about the liquefaction potential of these layers, these are illustrated as yellow points.

Previous investigations show that Liquefaction resistance of sand is not affected by fines unless the fines comprise more than 5% of soil (Kramer, 1996). In the presented graph cyclic stress ratio and fine content were calculated based on Robertson and Wride (1998) method and only the soil layers with fine content less than 5% were selected to use in this graph.

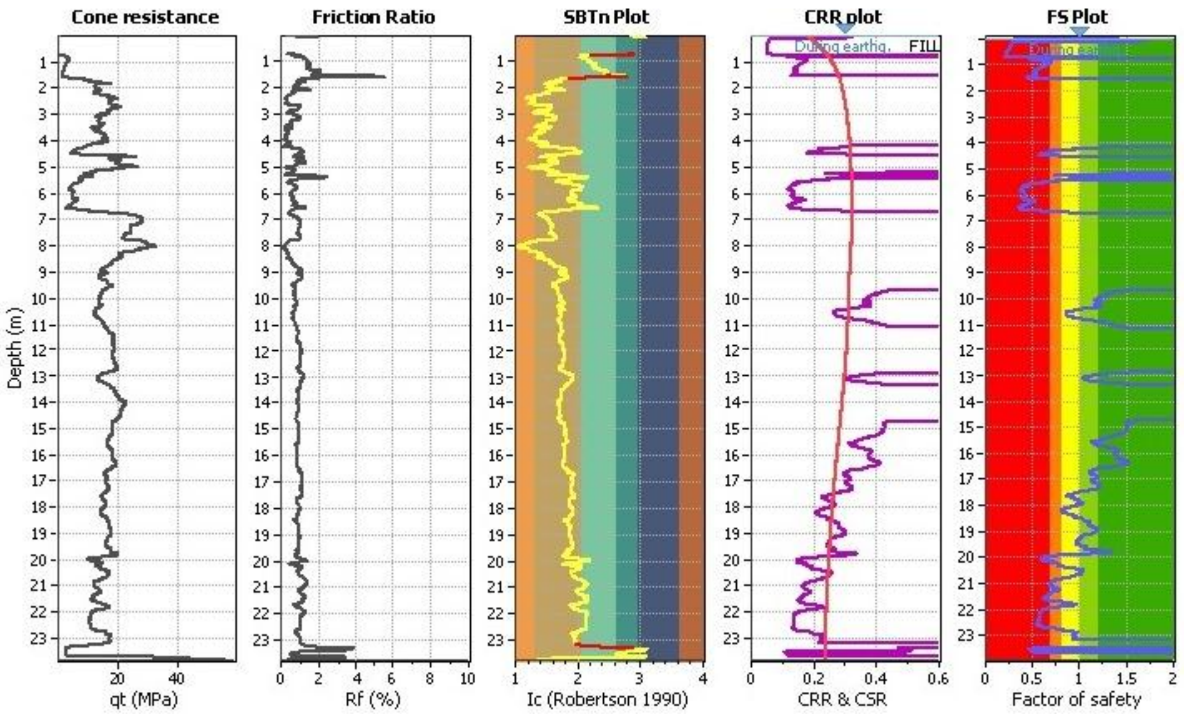

Figure 4. Liquefaction potential analysis based on Roberston and Wride (1998) for the site located in Broomfield Terrace, Christchurch, (GeoLogismiki, 2006).

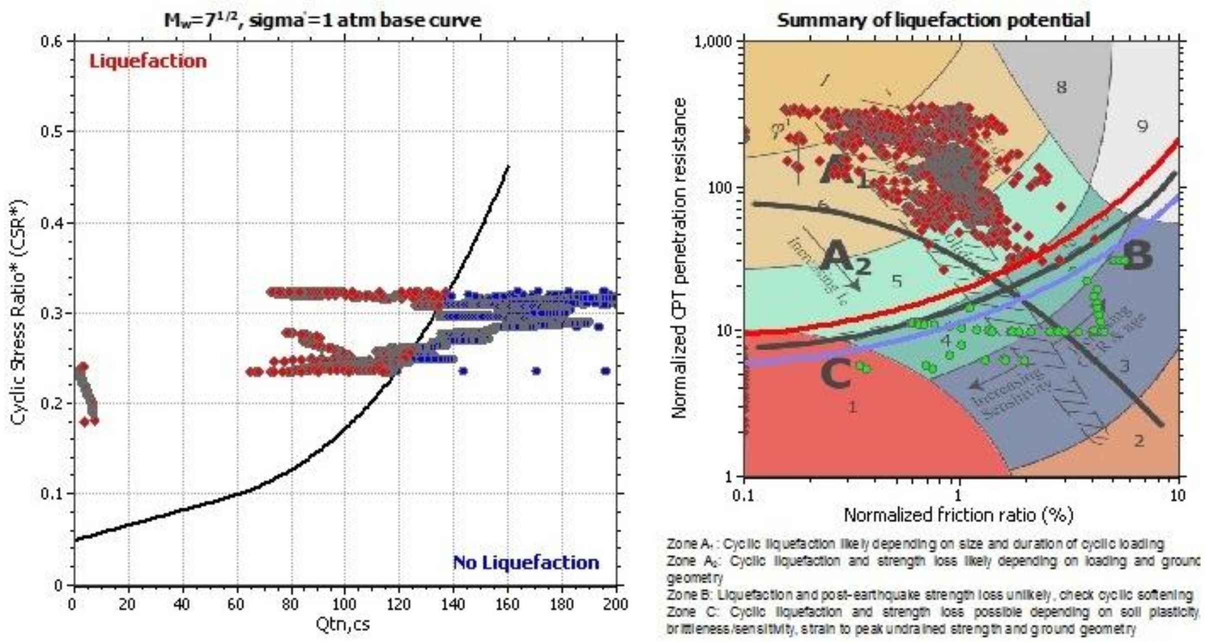

Figure 5. Summary of liquefaction potential analysis based on Roberston (1998) for the site located in Broomfield Terrace, Christchurch, (GeoLogismiki, 2006).

The boundary line for liquefaction potential has been located deterministically by engineering judgment. Based on the position and spread of the liquefaction and nonliquefaction data points, a curve is drawn to estimate the threshold of liquefaction triggering (Figure 6). As it is shown in Figure 6 the data points on the right side of the graph shows more penetration energy and are considered as dense sand layers within the soil profile and hence not liquefiable. The boundary is defined conservatively such that most of the cases in which liquefaction has been observed lie above it. However a few liquefied soils are located on the right side of the boundary line and some unliquefied data points on the left side of it. This can be explained by the fact that specific energy which was used in the graph is the average of specific energy in incremental steps of loading in each 25 centimetre of penetration while for CPT test the liquefaction potential calculations of layers is based on obtained data in every 1 centimetre of penetration. The other reason can be due to the small difference in the starting point of the two tests especially in some depths which soil layers suddenly changes effects of the difference of starting points would be more significant and makes some discrepancy.

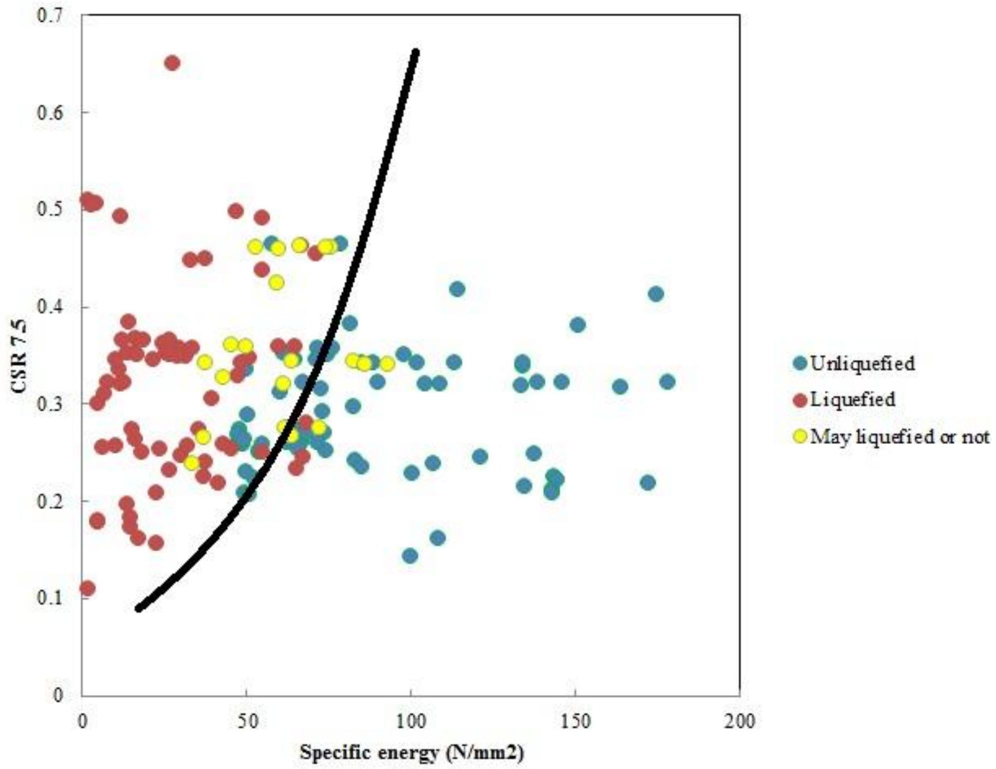

Figure 6 Relationship between CSR and Specific energy of penetration based on the SDS tests conducted in Christchurch.

Using the obtained correlation and boundary line liquefaction potential of soil can be measured by means of SDS testing which is a simple, economical and fast test. However, the effect of fine content has not been considered in this graph. Recently some relationships have been developed for soil classification based on SDS data in Japan and accuracy of the relationships was evaluated in Christchurch (Tanaka et al., 2012; Mirjafari et al., 2013). Along with the available correlations for soil classification it is planned to find a relationship between fines content and SDS parameters and subsequently applying the obtained correlation to the presented boundary line. In addition in the proposed graph there is little data available in high (more than 0.5) and low (less than 0.2) CSR range and the defined boundary line can be refined by adding some extra test data which include these ranges of CSR. Moreover, adding some data points in the critical region (close to boundary) where some uncertainty exist about the liquefaction potential of soil can also help to refine the proposed boundary line. Finally, to validate and evaluate the accuracy of the proposed graph it is planned to make a correlation between CPT and SDS parameters. As the current CPT methods are based on a large amount of experience from observed case of liquefaction and the SDS and CPT are both similarly influenced by most soil variables, conversion of CPT data to SDS can be helpful to validate the proposed graph.

4 CONCLUSIONS

In this study a new in-situ testing method referred to as the Screw driving sounding (SDS) was introduced. This method has been recently developed in Japan to account for the limitations of Swedish weight sounding test. Compared to SWS, more parameters can be measured using SDS machine and hence it can gives a better image of soil profile and the same as CPT test it can provide a continues record of the soil strata.

For evaluating the capability of SDS method for soil characterization and identifying liquefiable soil layers 69 test have been conducted in Christchurch at both liquefied and unliquefied area. Based on the results of 25 tests which were conducted in the area containing mostly clean sand it was shown that using SDS parameters liquefaction potential of soils can be identified and a boundary line was defined to separate liquefiable soils from unliquefiable soils. The obtained correlation is only applicable for clean sands and it is planned to find a relationship between fine content and SDS parameters and make use of it in the proposed graph.

As SDS test is simpler, faster and more economical test than CPT, it can be good alternative for characterizing soils.

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