CPTU AND SPT FIELD TESTS FOR SOIL LIQUEFACTION AND SETTLEMENT ASSESSMENT IN THE PORT OF SAN ANTONIO, CHILE

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ABSTRACT: Cone Penetrometer Tests (CPTU) and Standard Penetration Tests (SPT) results are compared in terms of their capabilities to characterize soil stratigraphy, to assess the potential for liquefaction, and to estimate settlement due to liquefaction. Deduced settlements are contrasted with measured settlement after the 1985 Chilean earthquake in a nearby site. Results show the good repeatability of CPTU tests to characterize the soil and very adequate performance to deduce seismic settlement after an earthquake. SPT tests are inconsistent between the different locations despite they were carried out at the same or similar location as the CPT tests.

1. Introduction

The state of the practice on liquefaction evaluation is mainly based on empirical correlations of earthquake case histories. The main in-situ tests used to characterize liquefaction susceptibility are the Standard Penetration Test (SPT), the Cone Penetration Test (CPT), and measurements of shear wave velocity (V_s). Liquefaction charts allow the assessment of whether a soil would potentially suffer liquefaction or not. The validity of these liquefaction charts and their link with the state of the art research in the topic has been summarized recently by Dobry and Abdoun (2014). The ability of the main liquefaction evaluation methods has been examined, for the New Zealand earthquake, by Chen and Yuan (2014). These methods have proved to be successful in identifying liquefaction potential, but they could be over-conservative in some cases.

New case histories allow us to frequently re-evaluate these in-situ-tests charts as it is shown recently by Boulanger and Idriss (2014), who revised the CPT- and SPT-based liquefaction triggering procedures.

Liquefaction-induced settlement estimation is a very important variable that has to be estimated in geotechnical projects. Obtaining good quality soil samples of loose sandy soils is a very expensive and difficult task. Therefore, it is common practice to evaluate post-seismic settlement using in-situ measurements of CPT, SPT or Vs. Methods to estimate liquefaction settlement based on SPT have been developed for more than 25 years (Tokimatsu and Seed, 1987). The CPT-based approach is more recent

(Zhang et al. 2002), but it has gain better acceptance due to its greater repeatability and continuous nature of its profile.

The Port of San Antonio is located about 2 km north from the delta of the Maipo River. The geology of site consists of recent alluvial deposits (south part) and of Paleozoic metamorphic basement (north part). The portion of the land located to the south of the port corresponds to a recently reclaimed platform formed by the sediments of the Maipo river.

This paper presents an analysis of liquefaction assessment and post liquefaction settlement expected on the studied site. Results from CPT soundings are compared with observed settlements measured after the 1985 Chilean Earthquake.

2. Liquefaction assessment at San Antonio, Chile

Figure 1 shows the location of SPT tests (BSA and SC) and CPT tests (CPT) on the site. This soil exploration extends about 150 m in the N-S direction and 50 m in the E-W direction. The exploration site is 120m west of a site that experienced soil liquefaction during the 1985 Chilean earthquake (see Figure 2).

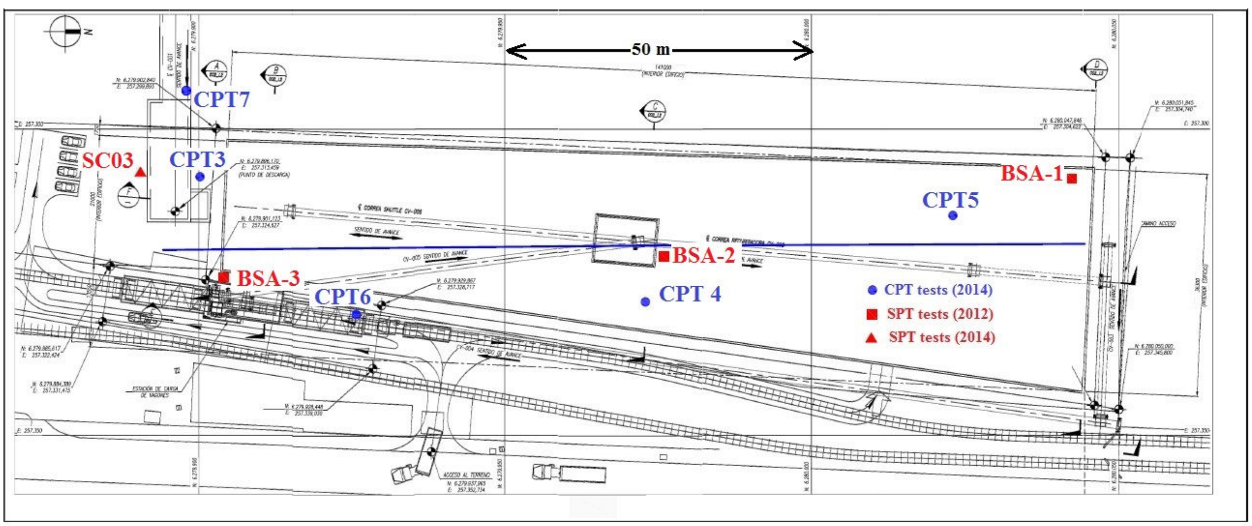
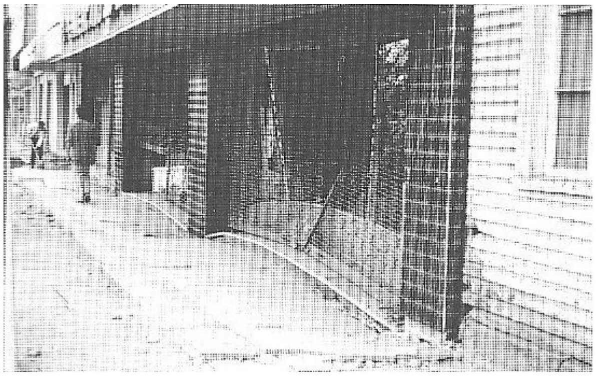


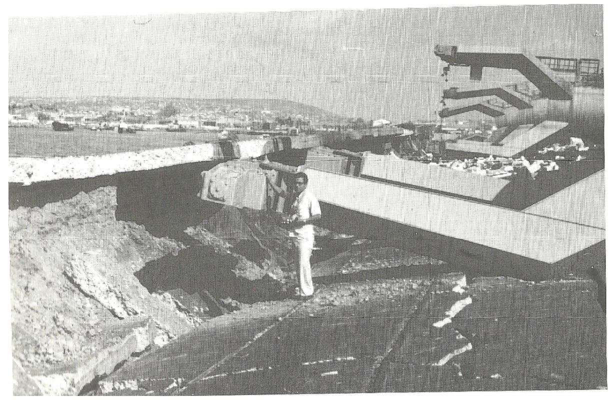
Figure 1. – SPT and CPT tests location.

At least three different places were reported to show liquefaction during the 1985 earthquake as it can be seen in Figures 2 and 3. The new soil exploration is located between sites B and C at less than 120m away from these two locations. This information together with the homogeneous CPT soundings, allow us to consider that the explored site would be very similar to the site B, where observed settlements were in the order of 30 to 40 cm (Ortigosa, 1986). Similar settlements were observed in other structures built on in similar subsoil around the city.

Figure 2. Different places where soil liquefaction was observed during 1985 Chilean earthquake.



a)



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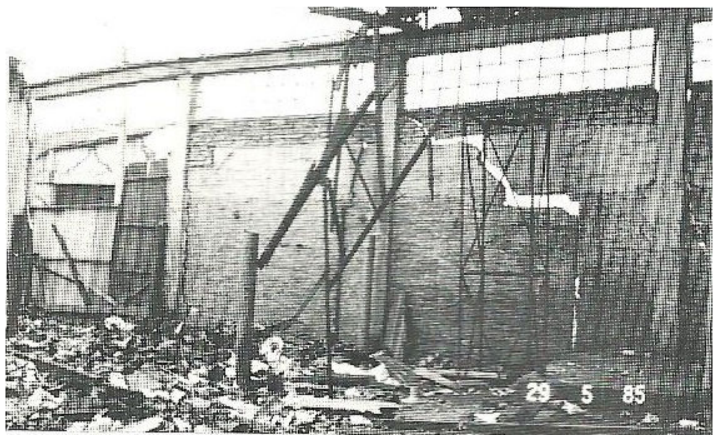

c)

Figure 3. Earthquake damage at Zones; a) Site A, b) Site C, and c) Site B. (from Ortigosa 1986)

2.1. SPT liquefaction evaluation

SPT tests were carried out in the area (see BSA and SC locations in Fig. 1). The summary of the measured number of blow counts, N values, are shown in Figure 4. It is possible to observe from this figure that in all SPTs consistently there are low blow counts below 4m depth. Between 4m and 15m depth, there is a large difference of blow counts that may imply that the liquefaction potential could be different from one location to another. Below 15m depth the blow count numbers experiment a considerable increase.

Soil liquefaction is evaluated using the following parameters that are believed to be conservative but also representative for the site and the 1985 earthquake:

Water table = 1.90m (below ground level)

Earthquake magnitude, Mw = 7.8

Peak ground acceleration = 0.3 g

As a reference, there is an acceleration record measured 2.5 km away from San Antonio, in the Llolleo monitoring station, where the maximum accelerations were S80E = 0.41g, N10E = 0.65g, Vert. = 0.82g (Saragoni et al. 1993).

The semi-empirical procedure used to evaluate soil liquefaction potential using SPT measurements corresponds to the one explained by Idriss and Boulanger (2006). It is assumed that the hammer energy is 80% of the theoretical value and that a standard sampler was used.

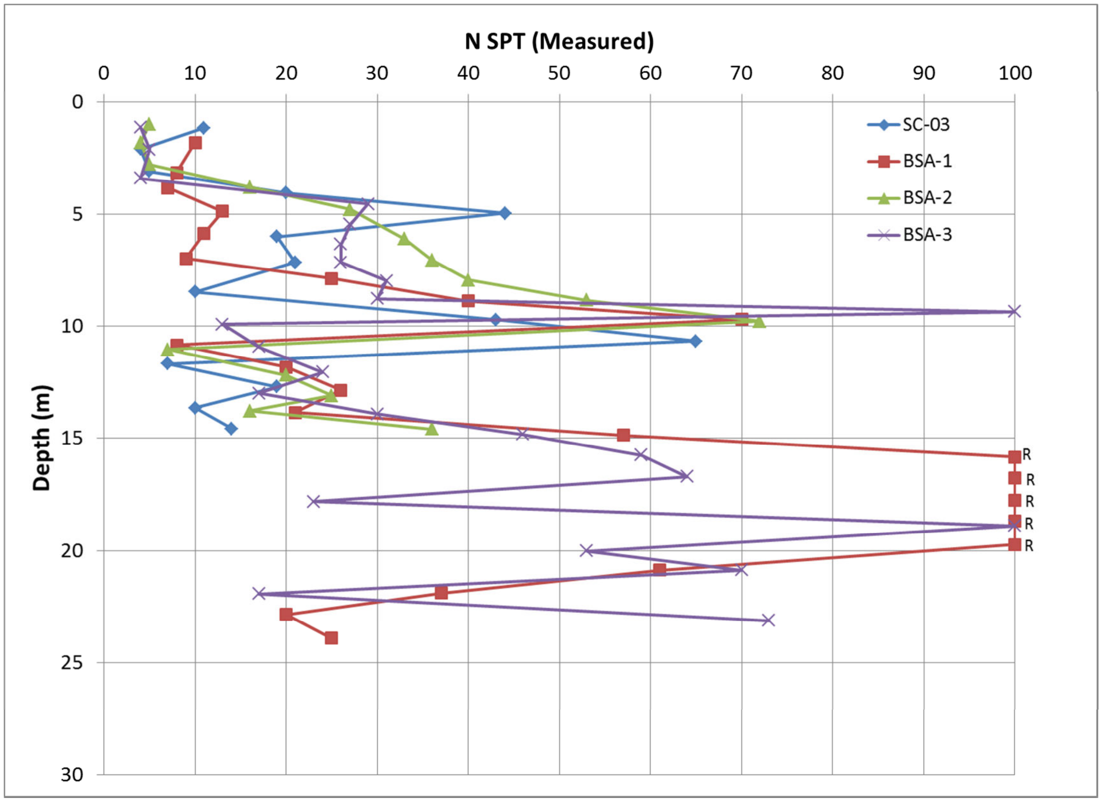

Fig. 4. N uncorrected blow count values

The results of the liquefaction analysis for the SC03 and BSA3 locations are shown in Fig. 5 and 6, respectively. In these figures, the deduced values of Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR) are shown. Every time that CSR is larger than CRR liquefaction may occur. Comparing these two figures (up to 15m depth), it can be observed that site SCO3 shows more layers of potentially liquefiable soil than in location BSA3 although both locations are less than 30m apart from each other.

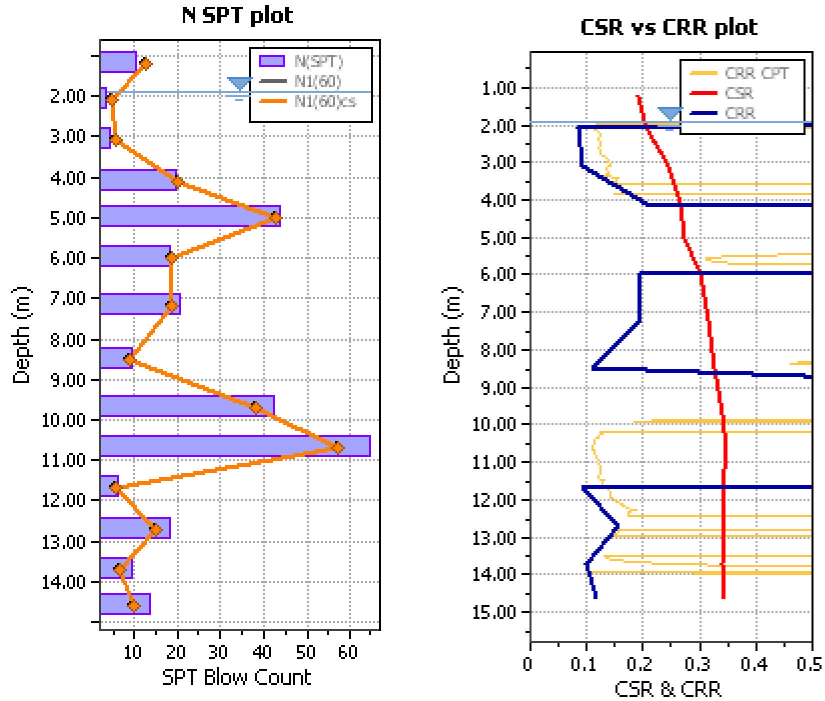

Fig. 5-Comparison of CSR and CRR at site SC-03 using Seed et al., 2004.

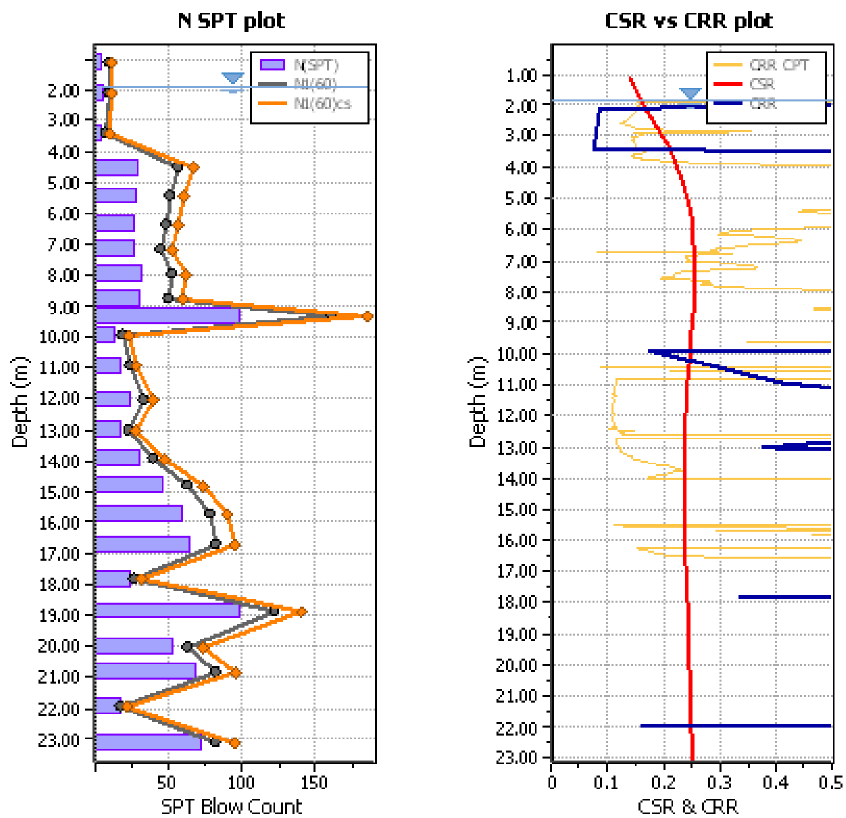

Fig. 6- Comparison of CSR and CRR at site BSA-3 using Seed et al., 2004.

2.2. CPT liquefaction evaluation

Similarly, five CPT soundings were performed in the same area (see Fig. 1). Four of these soundings are practically identical, but CPT-5 shows lower cone tip resistance between 3m and 6.5m depth. CPT 5 is located further North-West to the Site B.

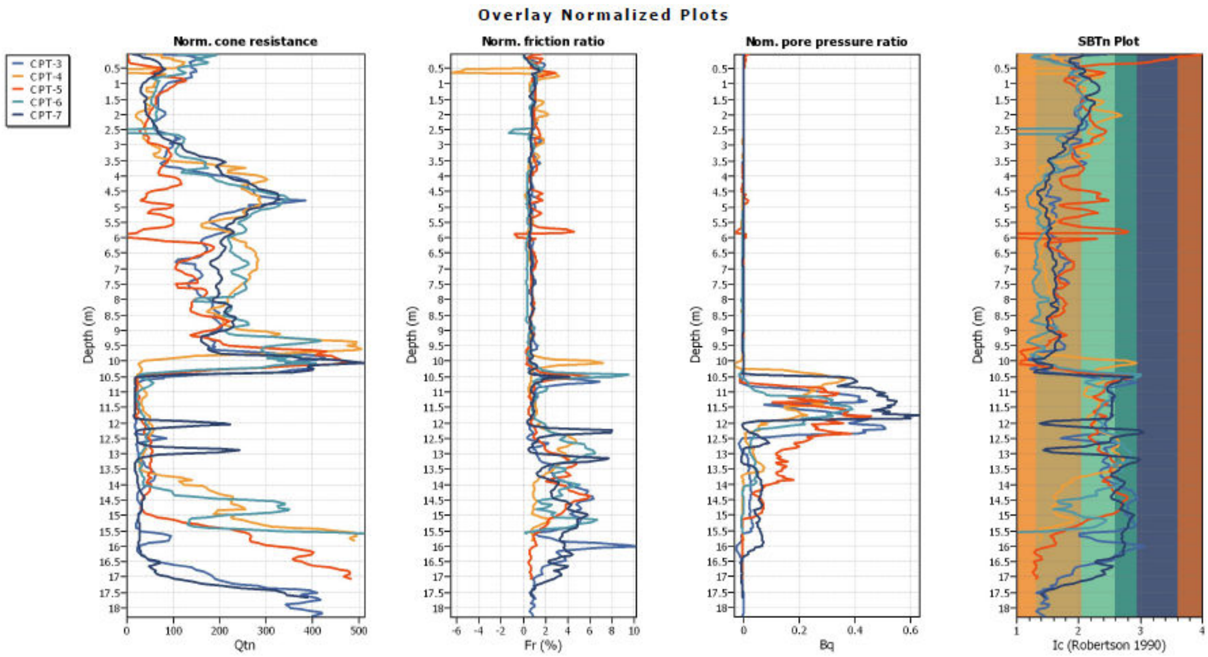

Fig. 7- CPT soundings

Liquefaction potential analyses are performed using values adopted previously for the Chilean 1985 earthquake and CPT data analyzed with Boulanger and Idriss (2014) procedure. CPT soundings show basically the same liquefiable layers amongst all CPT data (except CPT 5 that shows higher liquefaction potential than the others). In comparison to SPT results, CPT analysis shows to be more consistent, and thicker layers of liquefiable soil are predicted (see Fig. 8).

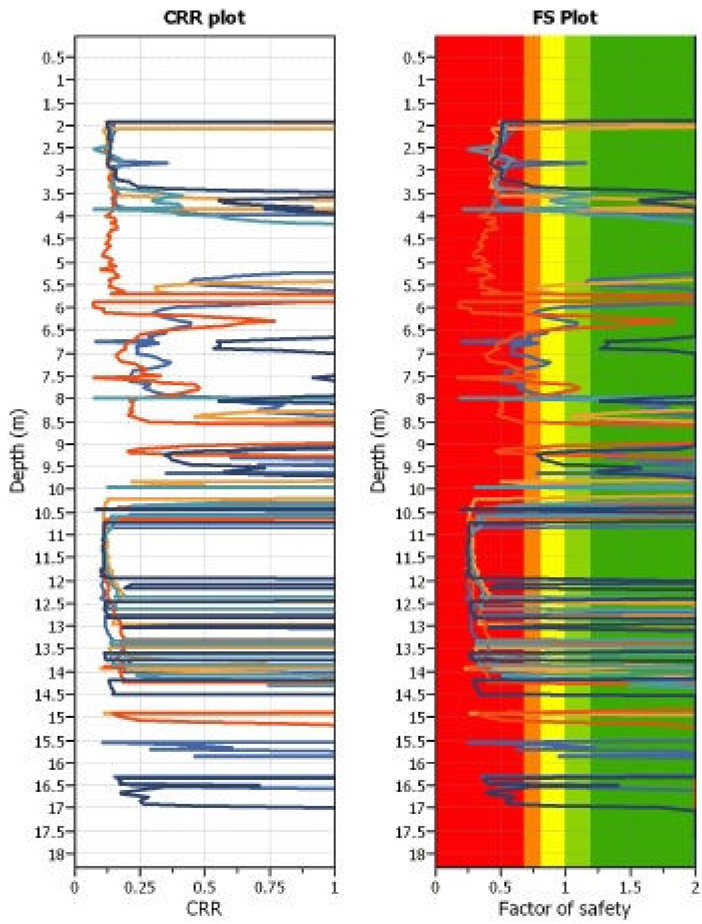

Fig. 8- Deduced factor of safety using CPT soundings

2.3. Vs liquefaction assessment

A seismic CPT was also performed at site C. The results of shear wave velocity are shown in Fig. 9. With the same earthquake data used before and the Youd et al. 2001 (NCEER-1998)) method, the soil liquefaction potential are deduced and shown in Fig. 9. The results of CSR and CRR are very coarse as seismic CPT measurements were carried out every 2m. However, the method also shows layers susceptible to liquefaction up to a depth of 10m.

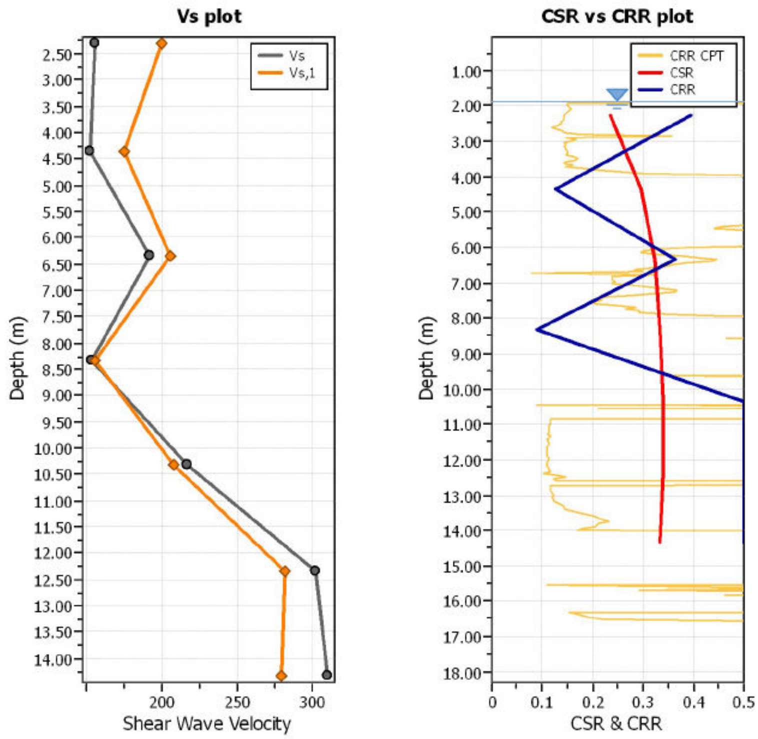

Fig. 9- Comparison of CSR and CRR using shear wave velocities.

3. Liquefaction settlement evaluation using CPT soundings

Once susceptibility to cyclic liquefaction was evaluated, CPT soundings are considered to evaluate settlements. t is believed that CPT-based approach is generally conservative (Robertson and Cabal, 2012).

Post-earthquake settlements are calculated considering the 1985 Chilean earthquake, as shown previously. Cliq software (version 1.7) is used, this software uses Zhang et al. (2002) method to estimate post-earthquake volumetric strains with leveled ground. This approach combines CPT based method to determine liquefaction potential with laboratory test results on clean sand to evaluate liquefaction induced volumetric strains.

Using the same CPT liquefaction assessment method as previously (Boulanger and Idriss, 2014), fines content according to Robertson and Wride (1998), and cut-off of I_c = 2.6, the post liquefaction settlement are deduced. Details about these parameters are found in Robertson and Cabal (2012) and Zhang et al. (2002). The values deduced at this site are shown for each CPT sounding in Fig. 10.

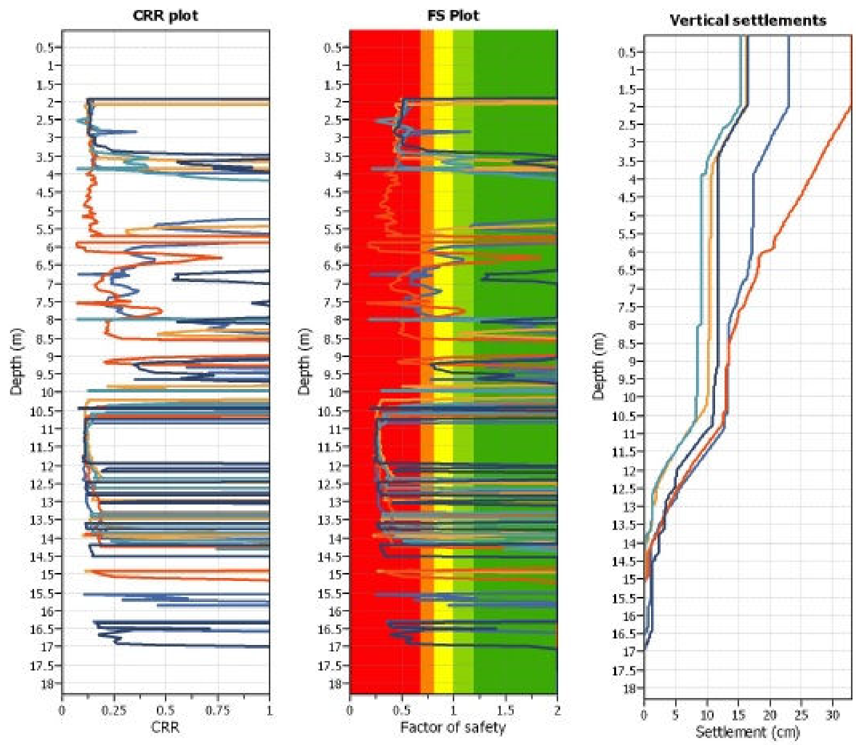

Fig. 10- Post-earthquake settlement estimation from CPT tests.

Additionally, Fig. 11 shows the effect of using a different maximum surface acceleration (from 0.3g) in the deduced post-earthquake settlement. As it can be observed, most of the soundings show a relatively flat curve for acceleration larger than 0.3g.

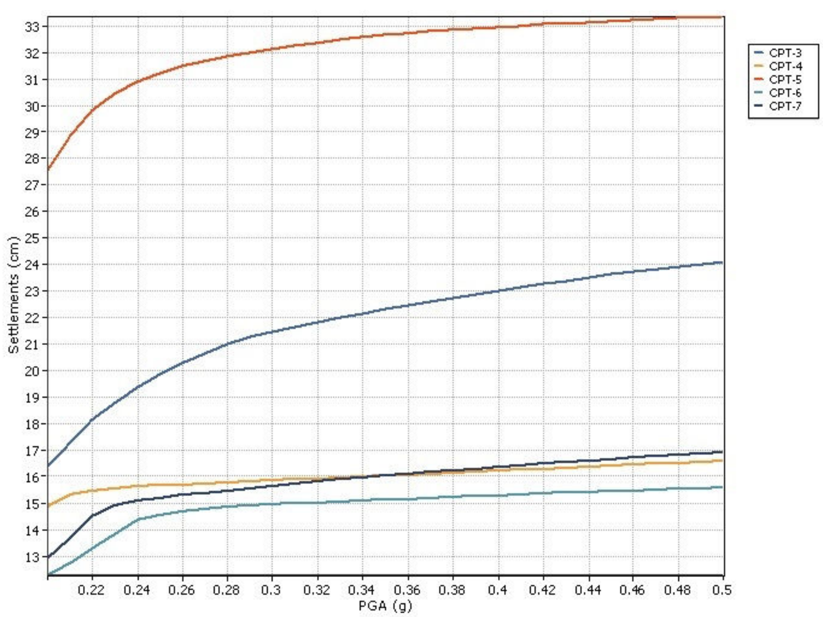

Fig. 11- Settlement estimation versus maximum ground acceleration.

3.1. Comparison with observed settlement during 1985 Chilean earthquake

As mentioned before, settlements observed after the 1985 Chilean earthquake were in the order of 10 cm in a nearby site (Site A). A comparison of measured and observed settlements are shown in Fig. 12. This means that the method used is conservative as suggested by Robertson and Cabal 2012.

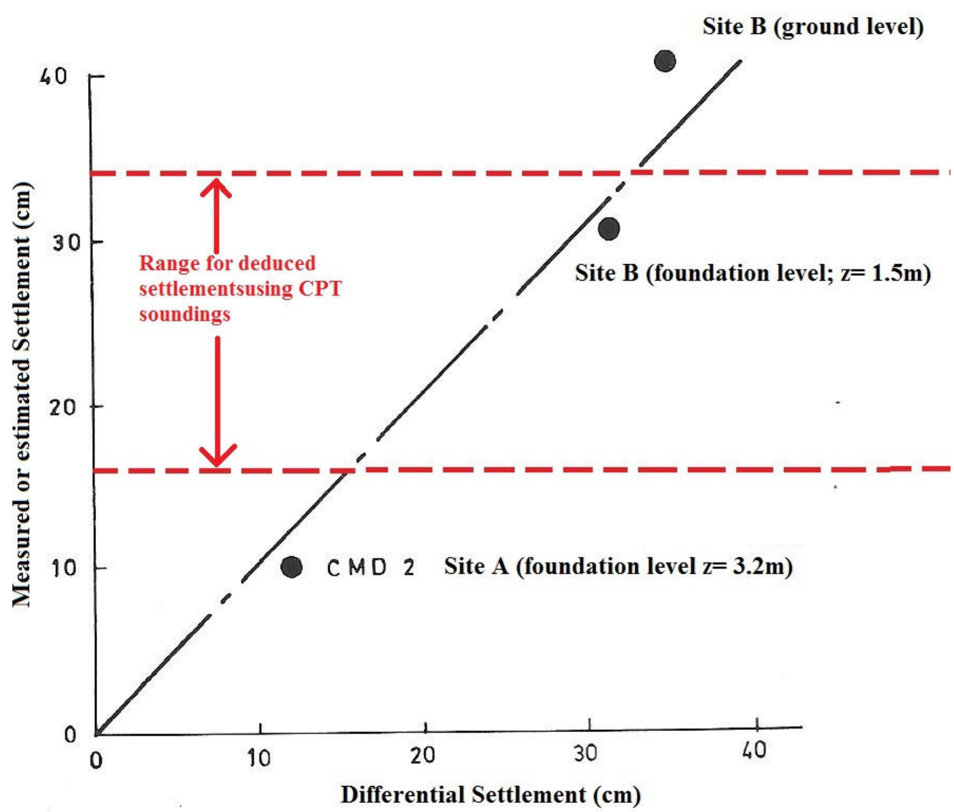

Fig- 12. Measured settlements on the field versus estimated settlements from CPT. Data points according to Ortigosa (1986).

4. Summary and Conclusions

A site exploration was performed in a zone close to a site where previous liquefaction was observed and post-earthquake settlements measured. CPT, SPT and CPT downhole tests were carried out on the site.

The following specific conclusions are drawn, with regard to the in-situ test results on this real project:

(1) SPT testing results without energy measurements show a considerable scatter and therefore different layers susceptible to liquefaction in the site.

(2) CPT results are very similar between the different soundings and therefore they show a very similar pattern of susceptible layers to liquefaction.

(3) SPT, CPT and Vs measurements all detect the presence of potentially liquefiable soils.

(4) CPT estimation of vertical settlement show larger values than the observed settlements in a nearby site during the 1985 Chilean earthquake.

CPT testing shows to be a promising and adequate in-situ testing to estimate settlements, due to strong earthquakes, that are common in Chile. Additional research is necessary to be able to estimate more accurately the vertical settlements post-earthquake.

5. Acknowledgements

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6. References

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