Cone Penetration Testing 2018 – Hicks, Pisanò & Peuchen (Eds)
© 2018 Delft University of Technology, The Netherlands, ISBN 978-1-138-58449-5

Cone penetration testing on liquefiable layers identification and liquefaction potential evaluation

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ABSTRACT: This paper presents the results of liquefaction potential evaluation for various sandy sites, with high seismic risk, where soil liquefaction is a major concern for all structures supported on these kinds of soils. There are many methods available for these calculations, based on different site investigation techniques. The Cone Penetration Test (CPTU) provides ideal data for this purpose, due to its repeatability and reliability. CPTU based methods on soil liquefaction assessment are important not only to identify liquefiable layers, but also their state in situ. This paper looks at results of liquefaction analyses on different sites susceptible to liquefaction, using CPTU based methods and also compares them with methods that are Standard Penetration Test (SPT) based, but using SPT data derived from correlations to CPTU results.

1 INTRODUCTION

Evaluating the liquefaction characteristics of soils is one of the major challenges in geotechnical engineering, when it comes to the design of structures supported on saturated or partially saturated sandy and silty soils. In response to an earthquake shaking or sudden stress changes the strength and stiffness of these soils can be dramatically reduced. Over the years, many advances have occurred in evaluating the liquefaction potential of soils. Most importantly, there has been significant advancement since the early 1980s in CPT—based liquefaction potential identification procedures with the work of Robertson & Wride (1998), Moss et al. (2006) and Idriss & Boulanger (2008, 2010). Also, developments have taken place in SPT—based procedures, the most recent updates include those by Idriss & Boulanger (2008, 2010) (Idriss & Boulanger, 2014).

To evaluate the potential for soil liquefaction it is important to determine the soil stratigraphy and in-situ state of the deposits (Lunne et al. 1997). As they are able to identify all types of soils, CPTU and SPT are the most commonly used methods for site investigations in all kinds and sizes of projects. CPTU's ability to define a continuous soil profile, to identify thin layers, its repeatability and also accuracy of data acquisition makes it an ideal test for soil characterisation, and especially liquefaction potential evaluation. All methods used in this paper evaluate liquefaction potential by comparing the earthquake-induced cyclic stress ratio (CSR) with the cyclic resistance ratio (CRR) of the soil. The soil's CRR is correlated to CPTU and SPT penetration resistances after application of procedural and overburden stress corrections (Idriss & Boulanger, 2008, 2014). The liquefaction potential is evaluated by using a deterministic relationship expressed as a factor of safety (FoS), defined as the ratio of the capacity of soil to resist liquefaction, CRR, to the seismic demand imposed on it, CSR (Seed & Idriss, 1971), which predicts liquefaction of soils for values FoS≤1.0. CRR is calculated for a 7.5 magnitude earthquake and scaled to the design earthquake by a magnitude scaling factor (MSF).

In this paper, FoS has been computed applying the most widely used CPTU and SPT based liquefaction triggering procedures—for CPTU: Robertson & Wride (1998), Jefferies & Been (2006), Idriss & Boulanger (2008) and Idriss & Boulanger (2008) using fines content, FC determined from Robertson & Wride (1998). For SPT: Cetin et al. (2004), Idriss & Boulanger (2004) and Youd & Idriss

(2001). In the end, to predict the potential of liquefaction to cause near surface damage at the sites considered in this paper, the liquefaction potential index, LPI (Iwasaki et al, 1978, 1981, 1982) is calculated based on the method developed by Toprak & Holzer (2003).

This paper uses selected data from sites susceptible to liquefaction, where in situ site investigations using CPTU tests were carried out, with great success on identifying the soils' geotechnical properties and locating the liquefiable silty sandy layers within the soil profiles. The purpose of the paper is to suggest that the use of CPTU to identify liquefiable layers is reliable and the results obtained from liquefaction triggering procedures are very satisfactory, and in good agreement with SPT based methods.

2 SITES SPECIFIC DATA PROCESSING

2.1 *Geotechnical conditions*

For the purpose of this paper, results from 50 CPTU tests (from 8.0 m to 40.0 m depth) carried out as part of geotechnical site investigation programs for 8 different sites, in areas susceptible to liquefaction, are considered. All sites are mainly sand and silty sand deposits with a high evaluated seismic risk. The groundwater level is measured close to the ground surface, varying from site to site from 0.8 m to 2.0 m, for all sites, except site A, where ground water level is 10.0 m below ground surface. According to geophysical test results carried out on these sites, the earthquake magnitudes vary from $M = 6.9$ to $M = 7.5$, and the peak horizontal accelerations at the ground surface generated by the earthquakes, *PGA*, vary from 0.273 g to 0.3 g.

To include a summary table for all tests, presenting the geotechnical properties and all results from liquefaction analyses, would take too much space, but full data details are available from the authors, for all interested readers. Summary tables of some important parameters are presented below.

Figure 1 shows a typical CPTU profile from one of the sites considered, where the liquefiable layers are easily distinguished.

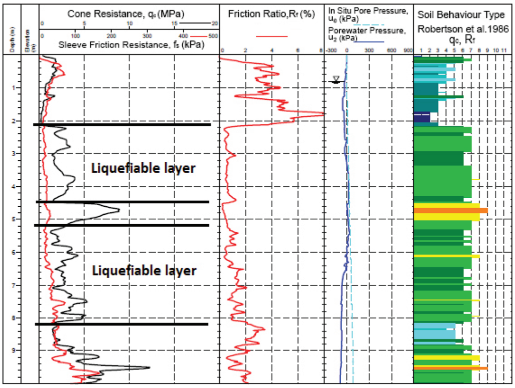

Figure 1. Typical CPTU profile (T1 CPT 01).

2.2 *Soil behavior type index, I_c, fines content, FC, and penetration resistance from SPT, $(N_1)_{60}$*

The response of soils to seismic loading varies with soil type and state, including void ratio, stress history, etc. It is possible to estimate soil type and grain characteristics directly from CPTU results (Lunne et al. 1997) and also an idea of derived fines content, FC. Boulanger & Idriss (2004) correctly distinguished between *sand-like* and *clay-like* soils behaviour (Robertson & Cabal, 2015). The soil behaviour type index, I_c for the calculations in this paper is defined using Robertson & Wride (1998) method, which suggests estimating behaviour characteristics using the normalized soil behaviour chart SBT_n of Robertson (1990). Robertson & Wride (1998) suggested that the boundary between *sand-like* and *clay-like* behaviour is around $I_c = 2.60$. Furthermore, Robertson (2009) suggested that when $I_c \leq 2.50$ soils are assumed to behave as *sand-like* and when $I_c > 2.70$ soils behave as *clay-like*. For values in between, $2.5 < I_c \leq 2.70$, soil behaviour is represented as a transition from predominately *sand-like* to predominately *clay-like* (Robertson & Cabal, 2015). Robertson & Wride (1998) suggested zones in which soils are susceptible to liquefaction based on the normalized soil behaviour chart, Robertson (1990), and so the chart was updated showing the zones of potential liquefaction/ softening based on CPTU data (Robertson & Cabal, 2015).

All data from CPTU tests used for calculations in this paper are printed out in the updated chart, considering different values of FC, which are calculated based on 2 different methods: FC_1 by Robertson & Wride (1998) and FC_2 by Suzuki et al. (1998).

$FC \leq 15\%$, which corresponds to $I_c < 2.05$; $15\% < FC \leq 35\%$, which corresponds to $2.05 < I_c \leq 2.6$; $35\% < FC \leq 55\%$, which corresponds to $2.6 < I_c \leq 2.95$.

The SPT penetration resistance, N_{60} used in the SPT-based liquefaction triggering procedures is defined from Robertson & Wride (1998) and Jefferies & Davies (1993). Both methods derive it from CPTU data. The reason why it is preferred to derive N_{60} from CPTU, rather than SPT itself, is because the data from CPTU are *more reliable and continuous*, so giving a larger data basis.

Table 1 presents a summary of derived geotechnical parameters from the different sites that are needed to assess liquefaction potential; only data from liquefiable layers are considered.

The updated chart, Robertson & Cabal (2015), used for classification of liquefiable soils in all sites considered is based on the normalized cone resistance,Q_{tn} (see Robertson & Cabal 2015), (Figs. 2a, b, c) calculated using a stress exponent that varies with soil type via I_c, whereas the recommended chart for estimating $CRR_{7.5}$ is based on a normalized cone resistance based on a variable stress exponent, updated to allow for a variation of the stress exponent with both SBT_n, I_c and effective overburden stress (Robertson 2009, Robertson & Cabal 2015).

Soils are divided into coarse grained soils: CD & CC, cyclic liquefaction possible depending on level and duration of cyclic loading and strength loss possible depending on loading and ground geometry *(I_c<2.50);* and fine-grained soils: FD & FC, cyclic softening possible depending on level and duration of cyclic loading and strength loss possible depending on soil sensitivity, loading and ground geometry *(I_c>2.70)* (Robertson & Cabal, 2015).

The data presented in Figures 2 a, b, c, are for values of fines content varying from FC < 15%, 15%< FC ≤35% and 35%< FC ≤55%, respectively.

Table 1. Summary of geotechnical parameters.

	I_c	I_c	FC_1	FC_2	N_{160}	N_{160}
Sites	(var.)*	(av.)	(av.)	(av.)	(var.)*	(av.)
A	1.74–3.49	2.61	23.07	24.59	1–26	11.25
G	1.42–3.28	2.35	13.87	17.24	1–20	10.95
H	1.53–3.25	2.39	15.94	19.12	2–20	10.04
L	1.43–2.86	2.42	28.4	28.50	5–20	10.08
P	1.39–3.41	2.40	17.13	19.55	2–28	13.11
S	1.55–3.29	2.42	36.11	32.85	1–20	4.448
T1	1.50–3.30	2.40	35.73	32.40	2–21	5.873
T2	1.81–3.63	2.72	51.05	44.37	1–21	4.730

* Variation of the values (min-max) for each site

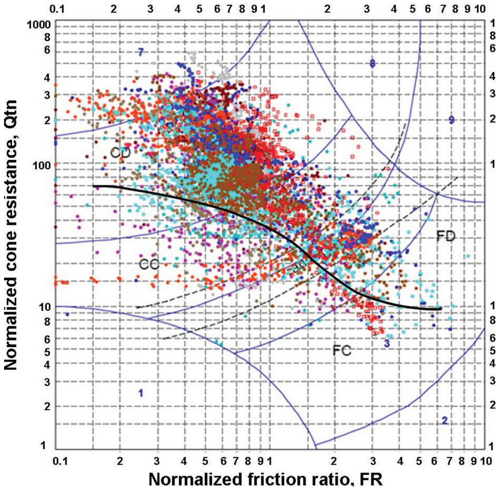

Figure 2a. Normalized SBT_n chart, Q_{tn}-FR using general large strain “soil behavior descriptors” for FC≤15%.

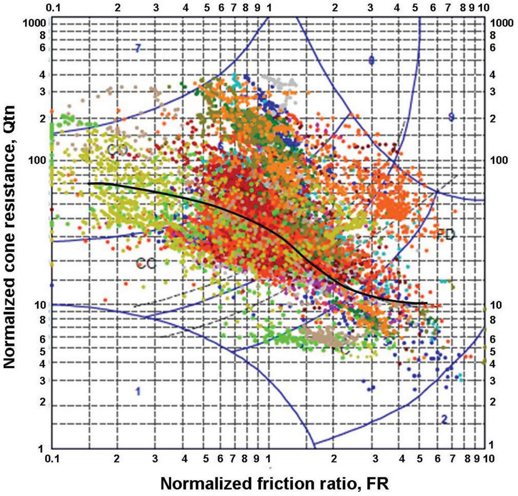

Figure 2b. Normalized SBT_n chart, Q_{tn}-FR using general large strain “soil behavior descriptors” for 15 < FC ≤ 35%.

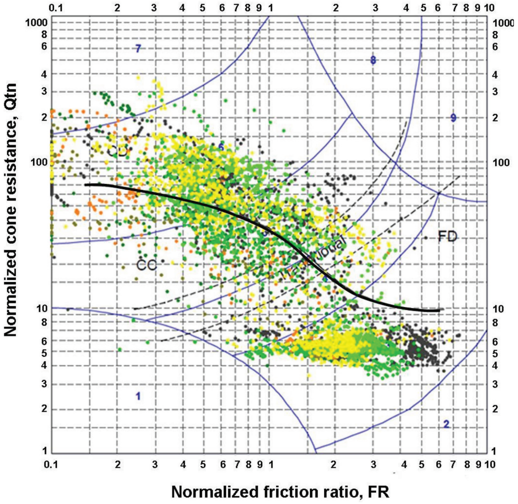

Figure 2c. Normalized SBT_n chart, Q_{tn}-FR using general large strain “soil behavior descriptors” for 35 < FC ≤ 55%.

All points plotting above the transitional zone ($2.5<I_c \leq 2.70$) represent soils under drained conditions and all points plotting below it represent soils under undrained conditions. Considering the *S* shaped line as a boundary for dilative and contractive soils, all points plotting above it represent dilative soils, whereas all points plotting below this curve represent contractive soils.

3 LIQUEFACTION ANALYSIS

3.1 *Methods and data input*

As mentioned above the liquefaction potential based on CPTU data is evaluated from the value of Factor of Safety (FoS), obtained by the following 4 methods:

1. FoS_1-Robertson & Wride (1998), which uses CSR as proposed by Seed & Idriss (1971) (called CSR_1 in the figures) and CRR, proposed by Robertson & Wride (1998), using FC_1;
2. FoS_2-Jefferies & Been (2006), which uses CSR as proposed by Seed & Idriss (1971) (called CSR_1 in the figures) and CRR proposed by Jefferies & Been (2006), using FC_2;
3. FoS_3-Idriss & Boulanger (2008), which uses CSR as proposed by Idriss & Boulanger (2008) (and called CSR_2 in the figures) and CRR proposed by Idriss & Boulanger (2008) using FC_2;
4. FoS_4-Idriss and Boulanger (2008), which uses CSR as proposed by Idriss & Boulanger (2008) (and called CSR_2 in the figures) and CRR proposed by Idriss & Boulanger (2008) using FC_1.

Liquefaction potential based on SPT values (estimated from the CPTU results) is evaluated from the value of Factor of Safety (FoS), obtained by the following 3 methods:

1. FoS_1-Cetin et al. (2004), which uses CSR proposed by Seed & Idriss (1971), where stress reduction factor, r_d is used after Cetin et al. (2014) and CRR, proposed by Cetin et al. (2004) deterministic;
2. FoS_2-Idriss & Boulanger (2004), which uses CSR and CRR proposed by Idriss & Boulanger (2004);
3. FoS_3-Youd et al. (2001), which uses CSR and CRR proposed Youd et al. (2001).

Figure 3 presents liquefaction analysis results based the data from a CPTU test.

3.2 *Results of calculations*

All CPTU data based calculations for this paper are computed using Datgel-CPT Tool gINT. All SPT data based calculations are computed using Settle^{3D} Version 4.0-Liquefaction Analysis.

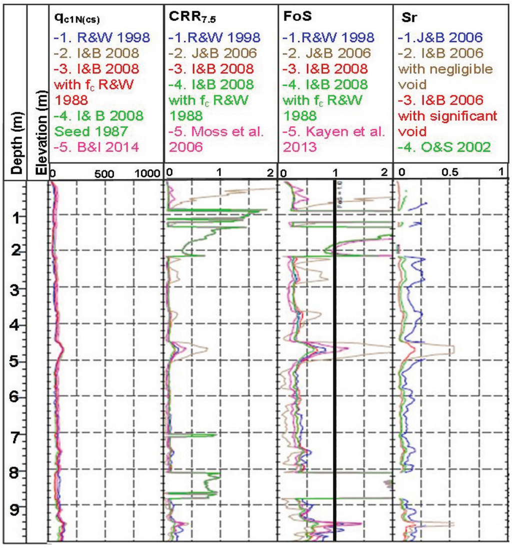

Figure 3. Results of CPTU liquefaction analysis(T1 CPT 01).

Table 2 presents a summary of the results from all sites from the liquefaction analyses, expressed by the average value of FoS from each method of calculation, based on CPTU and SPT data and Liquefaction Potential Index, LPI results derived from FoS_1 for both CPTU and SPT based methods.

The CPT—based methods used for these liquefaction analyses assess the $CRR_{7.5}$ by estimating the clean-sand equivalent normalized cone resistance, $(q_{c1\,N})_{cs}$, which depends on behaviour characteristics of the soils, fines content and many other factors, in order to avoid different results for $CRR_{7.5}$ in silty sands and clean sands. In Figure 4 is presented the distribution of data for various values of fines content, determined by I_c correlations. All the data plotted in the Figure 4 is from liquefiable layers only.

In Figure 5, results from different CPT—based methods are compared to the CRR curve derived from Idriss & Boulanger (2004). The results of these calculations are in good agreement with the triggering curve derived from Idriss & Boulanger (2004).

An updated graph from Idriss & Boulanger (2004) for our soil conditions is presented in Figure 6. The CRR curves are developed from the SPT—based methods mentioned above, using the necessary parameters for calculations, only for liquefiable layers of soils, for all sites considered in this paper. Curves 1 to 9 present the results, obtained from each calculation method for different fines content, as follows:

10%<FC < 15%; 15%<FC < 35%; 35%<FC < 55%. Curve 10 in this graph is the

Table 2. Summary of FoS and LPI from liquefaction analysis based from CPTU and SPT data.

	From CPTU analysis*					From SPT analysis*			
Sites	FoS_1	FoS_2	FoS_3	FoS_4	LPI	FoS_1	FoS_2	FoS_3	LPI
A	0.3	0.1	0.3	0.3	29	0.3	0.5	0.5	20
G	0.3	0.4	0.3	0.2	29	0.6	0.7	0.6	18
H	0.3	0.3	0.3	0.2	29	0.5	0.6	0.6	17
L	0.5	0.3	0.5	0.4	16	0.5	0.6	0.6	17
P	0.5	0.4	0.6	0.4	22	0.4	0.4	0.4	23
S	0.4	0.3	0.4	0.4	22	0.3	0.5	0.4	23
T1	0.4	0.4	0.4	0.4	26	0.3	0.5	0.4	22
T2	0.4	0.3	0.4	0.3	29	0.3	0.4	0.4	24

* Average of the values for each site, considering all liquefiable layers for each test.

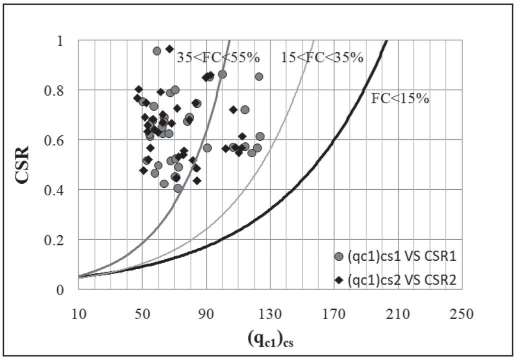

Figure 4. Results of CPT—based triggering correlations for the sites considered in this paper, for different values of FC (%) determined by I_c correlations.

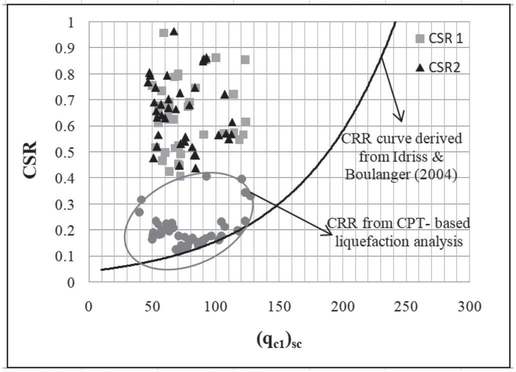

Figure 5. Distribution of data from CPT—based triggering correlations for the sites considered in this paper.

original Idriss & Boulanger (2004) curve, whereas curve 11 is obtained from SPT—based calculation methods carried out for the purpose of this paper. The CRR curves shift up to the left as the FC increases, with the maximum shift occurring for fines content varying from 35% to 55%. All the data points falling in the left side of the curves represent the liquefiable soils; meanwhile the data points in the right would represent the non liquefiable soils.

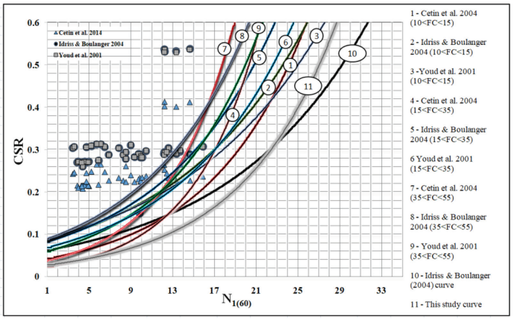

Figure 6. Results of SPT—based triggering correlations from different methods used for liquefaction potential evaluation of the sites considered in this paper, for different values of FC (%) determined by I_c correlations.

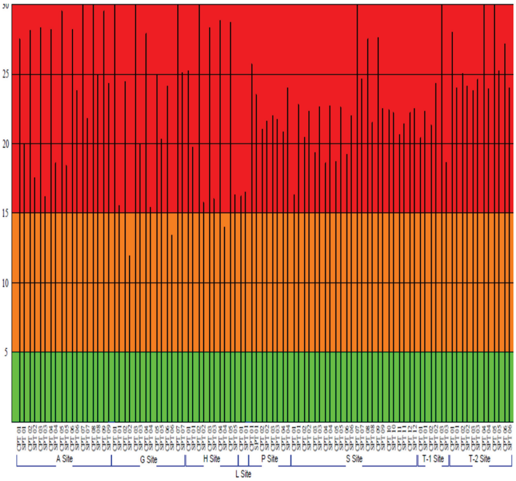

Figure 7. Distribution of LPI results obtained by Robertson & Wride (1998) method for all sites.

To predict the potential of liquefaction to cause damage at the surface level, Liquefaction Potential Index, LPI is evaluated for each test using the predicted factors of safety, taking into account depth of the tests (the soils below 20.0 m depth are not considered in LPI evaluation) and thickness of the layers (Iwasaki et al. 1978).

In Figure 7 are presented the results obtained by the LPI evaluation, based on the method proposed by Toprak & Holzer (2003).

The risk from liquefaction phenomena, based on LPI results is categorized as:

Low risk—LPI ≤ 5- green band;
High risk- 5 < LPI ≤ 15- orange band;
Very high risk—LPI > 15- red band.

As presented in the Figure 7, the LPI mostly shows zones with high to very high risk for liquefaction potential. The results are consistent with the low factors of safety obtained by all methods of calculations based on both the CPTU and the SPT derived data.

4 CONCLUSION

Data from 50 CPTU tests, carried out in 8 different sites susceptible to liquefaction have been used to perform the analyses presented in this paper, with the main focus on the use of CPTU to identify the liquefiable layers and evaluate the liquefaction potential of sandy and silty deposits. 7 different methods to assess the liquefaction potential in terms of the factor of safety, FoS, based on CPTU and SPT penetration resistance data, were used and all results obtained were compared to each other. SPT penetration resistance was derived from CPTU data, because CPTU tests provide continuous and more reliable data in terms of penetration resistance. The input values for these calculations were corrected for soil behavior characteristics, fines content and other factors, which might affect the results for different kind of soils. All liquefiable layers along the soils profile were detected by all methods used in this paper, and similar values of FoS and LPI are obtained.

Curves derived from cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) results obtained from these calculations are in good agreement with curves derived from historic CPTU and SPT data basis from Idriss & Boulanger (2004), predicting higher potential of liquefaction in cohesionless soils with higher content of fines. The CRR values obtained by CPT—based methods are higher than CRR values obtained from SPT—based methods, but also the CSR values from CPT—based methods are app. 30% higher than CSR values evaluated from SPT—based methods. For the relative performance between CPTU and SPT based methods, CPT—based liquefaction triggering procedures are less conservative, although they may lead to lower values of FoS, in cases of predicted factors of safety lower than 0.5.

To conclude, providing continuous data and having the ability to define all the thin layers within a soil profile and their geotechnical parameters makes CPTU a reliable and useful test for liquefaction potential evaluation. But, considering that all CPT—based methods are simplified procedures, the results obtained should be used carefully, in accordance with the sites and projects specifics.

ACKNOWLEDGMENTS

The authors would like to thank their colleagues at *In Situ Site Investigation* for the data basis of CPTU tests and *Datgel* who helped with the updated graphs presented in this paper.

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