Cone Penetration Testing on liquefiable layers identification and liquefaction potential evaluation

E. Anamali[1], L. Dhimitri[1], D. Ward[1] & J.J.M Powell[2]

1 – In Situ Site Investigation
2- Geolabs ltd

Introduction

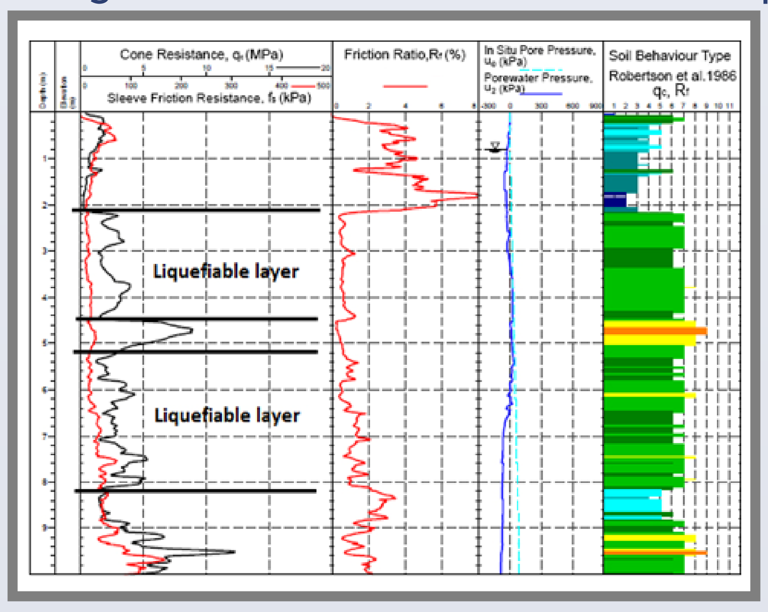
Evaluating liquefaction characteristics of soils is one of the challenges for design of structures supported on saturated & partially saturated sandy & silty soils. In response to an earthquake, the strength and stiffness of these soils is reduced. Significant advancement in evaluating the liquefaction potential by CPT & SPT- based identification procedures has been with the work of Robertson & Wride, Moss et al., Idriss & Boulanger.

Determining the soil stratigraphy and in-situ state of deposits are important for liquefaction potential evaluation. CPTU's ability to define a continuous soil profile, to identify thin layers, its repeatability and accuracy of data acquisition makes it an ideal test for this purpose.

Liquefaction potential is evaluated by using selected data from sites susceptible to liquefaction, where CPTU tests were carried out with great success on locating the liquefiable silty sandy layers within soil profiles, by comparing the earthquake-induced cyclic stress ratio, CSR with the cyclic resistance ratio, CRR of the soil, which is correlated to CPTU and SPT penetration resistances. A deterministic relationship expressed as a factor of safety, FoS defined as the ratio of soils' capacity to resist liquefaction, CRR, to the seismic demand imposed on it, CSR is used. Liquefaction is predicted if FoS≤1.0. CRR is calculated for a 7.5 magnitude earthquake, scaled to the design earthquake by a magnitude scaling factor, MSF.

Sites Specific Data Processing

Data basis: 50 CPTU tests from 8 sites, 8m - 40m depth, in areas susceptible to liquefaction, with high evaluated seismic risk *M=6.9 - 7.5 and PGA* = 0.273g - 0.3g. The fig. below presents a typical CPTU profile from one site. The tab presents a summary of the geotechnical data used to assess liquefaction potential, for liquefiable layers only.



Sites	IC (var.)*	IC (av.)	FC_1 (av.)	FC_2 (av.)	N_{160} (var.)*	N_{160} (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

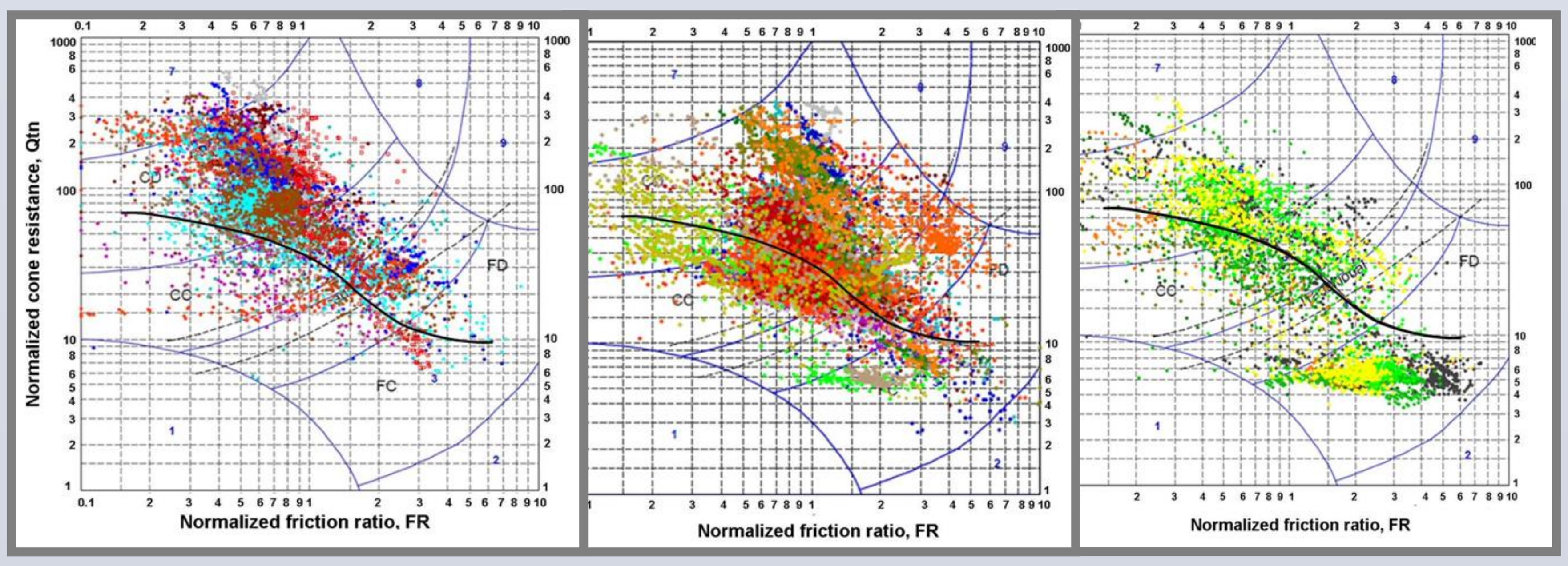
Response of soils to seismic loading varies with soil type, state, void ratio, stress history, etc. The soil behaviour type index, I_c is defined using Robertson & Wride (1998) method, estimating behaviour characteristics by the normalized soil behaviour chart SBT_n Robertson (1990), for I_c=2.60 - the boundary between *sand-like* & *clay-like* soils behaviour. Robertson (2009) suggested: I_c≤2.50 - *sand-like* behaviour; I_c>2.70 - *clay-like* behaviour; 2.5<I_c≤2.70 - transition behaviour from *sand-like* to *clay-like*.

Based on the above, Robertson (1990) SBT_n chart was updated for classification of liquefiable soils, showing zones of potential liquefaction/ softening, based on normalized cone resistance, Q_{tn}. Fines content, FC are calculated using 2 methods, Robertson & Wride (1998) and Suzuki et al. (1998), considering these correspondences:

FC≤15% - I_c<2.05; 15%< FC ≤35% - 2.05<I_c≤2.6; 35%< FC ≤55% - 2.6<I_c≤2.95.

3 charts below present the data from all CPTU tests used for the purpose of this paper. Soils are divided in 2 groups: 1-Coarse grained CD&CC: (*I_c<2.50)*; 2-Fine grained FD&FC: (*I_c>2.70)*, with FC varying FC<15%, 15%<FC≤35% & 35%<FC≤55%, respectively.

Cyclic liquefaction possible depending on level and duration of cyclic loading & strength loss possible depending on loading and ground geometry for both groups.



Considering the S shaped line as a boundary for dilative and contractive soils: points plotting above the line represent dilative soils & below it represent contractive soils.

Liquefaction Analysis

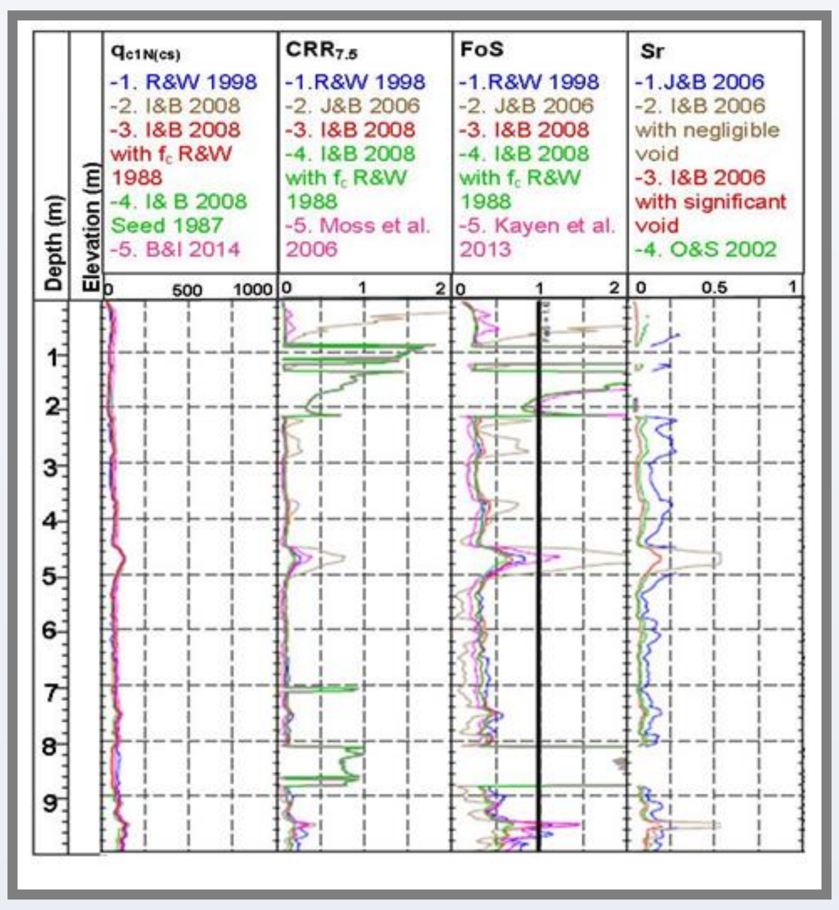
CPTU- based liquefaction potential is evaluated from FoS, obtained by 4 methods:

FoS_1-Robertson & Wride (1998); FoS_2-Jefferies & Been (2006); FoS_3-Idriss & Boulanger (2008); FoS_4-Idriss and Boulanger (2008).

SPT (from CPTU) - based liquefaction potential is evaluated from FoS by 3 methods:

FoS_1-Cetin et al. (2004); FoS_2-Idriss & Boulanger (2004); FoS_3-Youd et al. (2001).

In the fig. below is presented a typical profile of liquefaction analysis using CPTU data. In the tab. below is presented a summary of the results for all sites, from the liquefaction analyses, expressed by the average FoS from each method of calculation.

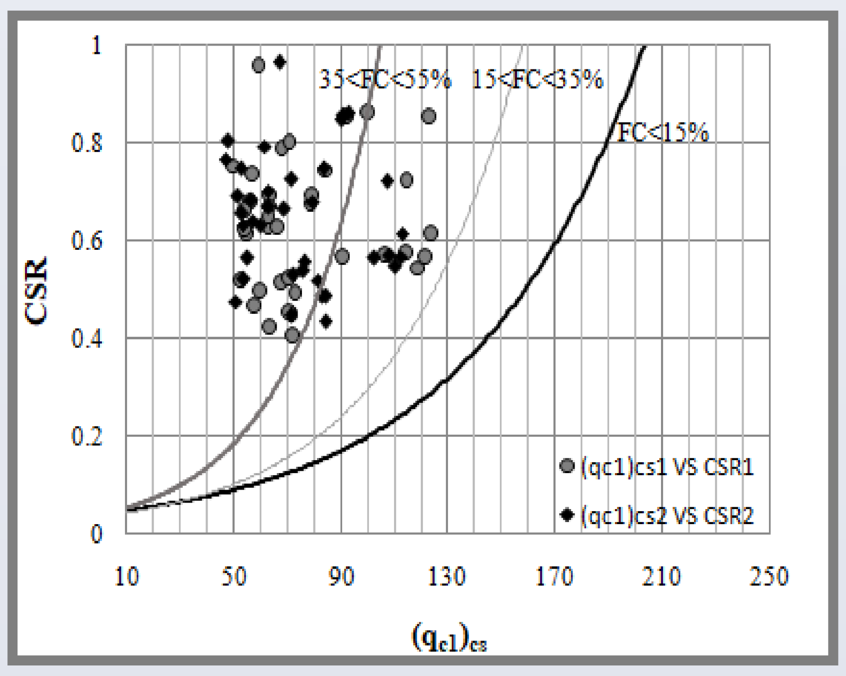


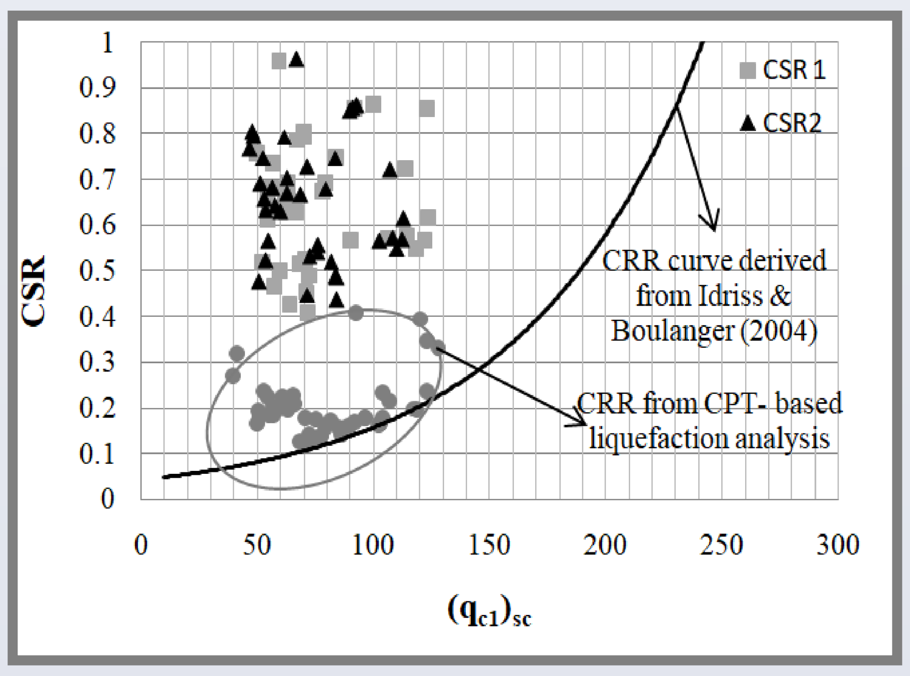
Sites	from CPTU analysis* FoS_1	FoS_2	FoS_3	FoS_4	from SPT analysis* FoS_1	FoS_2	FoS_3
A	0.3	0.1	0.3	0.3	0.3	0.5	0.5
G	0.3	0.4	0.3	0.2	0.6	0.7	0.6
H	0.3	0.3	0.3	0.2	0.5	0.6	0.6
L	0.5	0.3	0.5	0.4	0.5	0.6	0.6
P	0.5	0.4	0.6	0.4	0.4	0.4	0.4
S	0.4	0.3	0.4	0.4	0.3	0.5	0.4
T1	0.4	0.4	0.4	0.4	0.3	0.5	0.4
T2	0.4	0.3	0.4	0.3	0.3	0.4	0.4

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

CPTU data based calculations are computed using Datgel-CPT Tool gINT. SPT data based calculations are computed using Settle3D V. 4.0-Liquefaction Analysis.

CPTU based methods used for the liquefaction analyses assess the $CRR_{7.5}$ by estimating the clean-sand equivalent normalized cone resistance, $(q_{c1N})_{cs}$ depending on soils behaviour, FC and other factors, to avoid different $CRR_{7.5}$ results in different sands. Figs below present the distribution of data for various values of FC, determined by I_c and CPT- based results compared to CRR curve from Idriss & Boulanger (2004), respectively.





The fig. below presents the updated Idriss & Boulanger (2004) graph. (Updated for our soil conditions, CRR obtained from SPT- based methods).

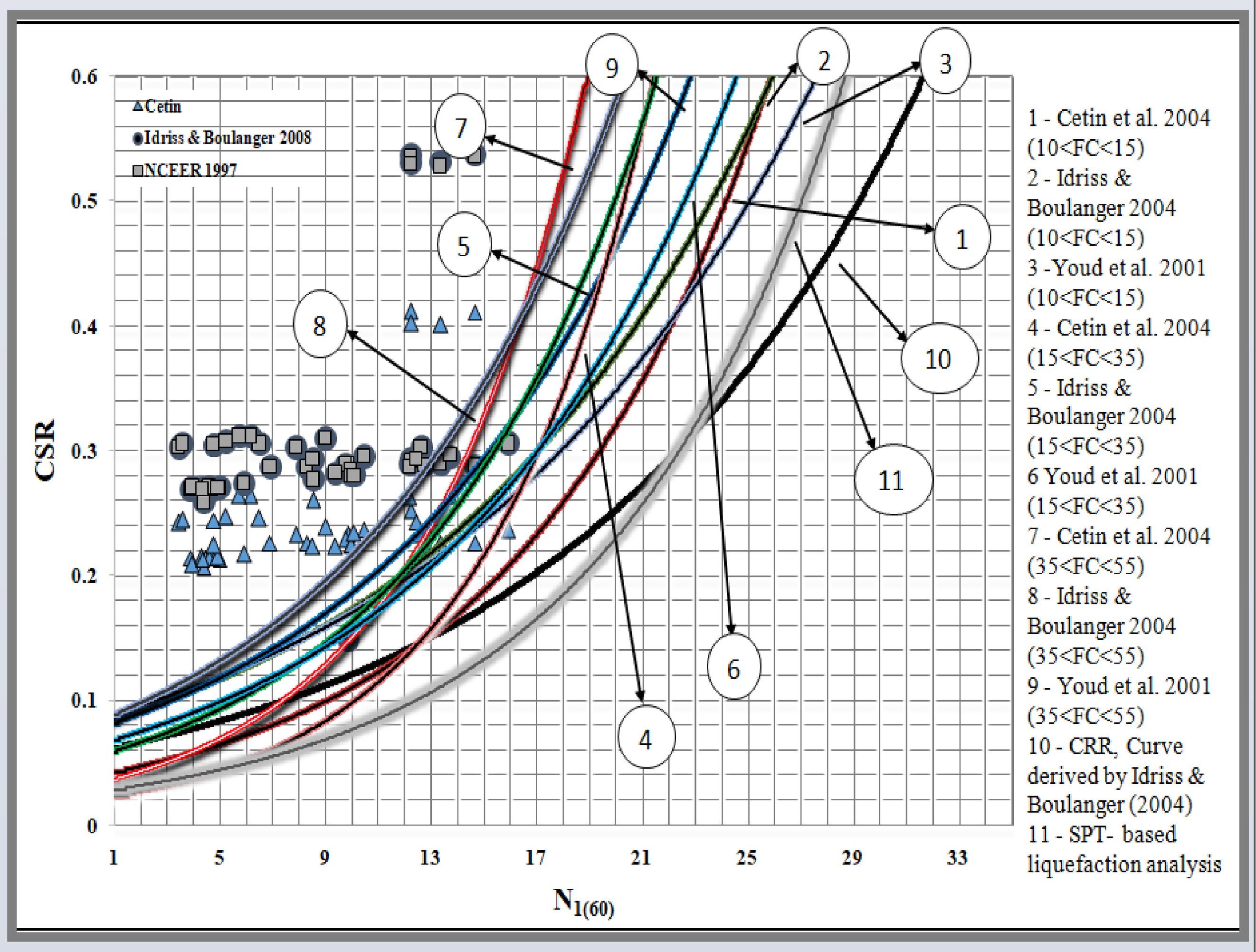
Curves 1 – 9: results from each method for different FC values;

Curve 10: original I&B (2004) curve;

Curve 11: SPT- based methods results.

CRR curves shift up to the left as the FC increases, with maximum shift occurring for FC 35% - 55%.

Data points falling in the left side of the curves represent liquefiable soils.



Conclusions

- Data from 50 CPTU tests carried out in 8 different sites susceptible to liquefaction have been used for these analyses, 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 methods to assess the liquefaction potential based on CPTU & SPT resistance data were used and the results 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 were corrected for soil behavior type, fines content & other factors, which might affect results for different kind of soils.
- Curves derived from CSR & CRR results obtained from our 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 FC. CRR values evaluated by CPT- based methods are higher than CRR values from SPT- based methods. CSR values from CPT- based methods are app. 30% higher than CSR values from SPT- based methods. For the relative performance between CPTU & SPT based methods, CPT- based liquefaction triggering procedures are less conservative, although they may lead to lower values of FoS, in cases of predicted FoS<0.5.
- Providing continuous data and having the ability to define the thin layers and geotechnical parameters within a soil profile, makes CPTU reliable for liquefaction potential evaluation. But, the results should be carefully used, as CPTU- based methods are simplified procedures.

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