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Sand liquefiability assessment by Flat Dilatometer Test (DMT)

Évaluation de la susceptibilité à la liquéfaction des sables par l'essai de dilatomètre (DMT)

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ABSTRACT
The aims of this paper are: (1) To summarize the available knowledge on the use of the flat dilatometer test (DMT) for evaluating sand liquefiability. (2) To formulate a new tentative correlation for evaluating the cyclic resistance ratio CRR from the DMT horizontal stress index K_D, to be used according to the "simplified procedure" (Seed & Idriss 1971). The proposed CRR-K_D correlation combines previous CRR-K_D curves with current correlations for evaluating CRR from CPT and SPT, translated using the relative density D_r as intermediate parameter.

RÉSUMÉ
Les objectifs de cet article sont: (1) Résumer la connaissance disponible sur l'emploi de l'essai de dilatomètre (DMT) pour évaluer la susceptibilité à la liquéfaction des sables. (2) Formuler une nouvelle corrélation préliminaire pour évaluer le rapport de résistance cyclique CRR de l'indice de tension horizontal K_D de DMT, pour être utilisé selon la "procédure simplifiée" (Seed & Idriss 1971). La corrélation CRR-K_D proposée combine des courbes CRR-K_D précédentes avec les corrélations courantes pour évaluer CRR de CPT et de SPT, traduites en utilisant la densité relative D_r comme paramètre intermédiaire.

1 INTRODUCTION

Over the past 30 years the methodology termed the "simplified procedure", introduced by Seed & Idriss (1971), has evolved as a standard of practice for evaluating the liquefaction resistance of soils. The "simplified procedure" requires the calculation of two variables: (1) the seismic demand on a soil layer generated by the earthquake, or cyclic stress ratio CSR, and (2) the capacity of the soil to resist liquefaction, or cyclic resistance ratio CRR. If CSR is greater than CRR, liquefaction can occur.

The cyclic stress ratio CSR is calculated by the following equation (Seed & Idriss 1971):

$$CSR = \tau_{av}/\sigma'_{vo} = 0.65\,(a_{max}/g)\,(\sigma_{vo}/\sigma'_{vo})\,r_d \quad (1)$$

where τ_{av} = average cyclic shear stress, a_{max} = peak horizontal acceleration at ground surface generated by the earthquake, g = acceleration of gravity, σ_{vo} and σ'_{vo} = total and effective vertical overburden stresses, respectively, and r_d = stress reduction coefficient dependent on depth.

The 1996 NCEER and 1998 NCEER/NSF workshops (see summary report by Youd & Idriss 2001) reviewed the state-of-the-art of the Seed & Idriss (1971) "simplified procedure" and recommended the use of in situ tests for routine evaluation of the liquefaction resistance CRR. Criteria for various tests, in particular the cone penetration test CPT and the standard penetration test SPT (both widely popular because of the extensive databases and past experience), were revised and updated. As to evaluating CRR from laboratory or calibration chamber (CC) testing, the major drawback is the difficulty of obtaining undisturbed samples, unless non-routine sampling techniques (e.g. ground freezing) are used. The adequacy of using reconstituted sand specimens, even "exactly" at the same "in situ density", is questionable (in situ fabric / cementation / aging affect significantly CRR), as emphasized by Porcino & Ghionna (2002).

This paper illustrates the potential of the flat dilatometer test (DMT) as an alternative or integration to other in situ tests in liquefaction studies. The aims of this paper are: (1) To review the available knowledge on sand liquefiability assessment by use of DMT. (2) To propose a new tentative correlation for evaluating the liquefaction resistance from DMT, to be used according to the Seed & Idriss (1971) "simplified procedure", by combining previous DMT correlations with current methods based on CPT and SPT (supported by past experience), using the relative density D_r as intermediate parameter.

2 CURRENT METHODS FOR EVALUATING LIQUEFACTION RESISTANCE BY CPT AND SPT

The liquefaction resistance CRR is commonly evaluated from CPT or SPT results by use of charts where CRR is plotted as a function of a normalized penetration resistance. The CRR curve separates two regions of the plot – "liquefaction" and "no liquefaction" – including data obtained at sites where surface effects of liquefaction were or were not observed in past earthquakes.

Interpretations based on CPT are generally expressed in form of charts where CRR is plotted vs a dimensionless, normalized cone penetration resistance $q_{c1N} = (p_a/\sigma'_{vo})^n\,(q_c/p_a)$, where q_c is the measured cone penetration resistance and p_a is a reference pressure (1 atm of pressure in the same units of σ'_{vo}), with n generally ≈ 0.5 to 1. The curve currently recommended for evaluating CRR from CPT (Youd & Idriss 2001, Robertson 2004) is the "CPT Clean Sand Base Curve" shown in Fig. 1. Criteria based on SPT are largely embodied in the "SPT Clean Sand Base Curve" shown in Fig. 2 (Youd & Idriss 2001), where CRR is plotted vs $(N_1)_{60}$ = SPT blowcount normalized to an overburden pressure of 100 kPa and a hammer energy ratio of 60%.

Both the CPT and the SPT recommended CRR curves apply to magnitude 7.5 earthquakes. For magnitudes smaller or larger than 7.5, magnitude scaling factors (a recommended range is indicated in Youd & Idriss 2001) are used to scale the base curves upward or downward on CRR vs q_{c1N} or $(N_1)_{60}$ plots.

3 THEORETICAL/EXPERIMENTAL BASE SUPPORTING THE USE OF DMT FOR ESTIMATING LIQUEFIABILITY

Marchetti (1982) and later studies (Robertson & Campanella 1986, Reyna & Chameau 1991) suggested that the horizontal stress index K_D from DMT ($K_D = (p_o - u_o)/\sigma'_{vo}$) is a suitable parameter to evaluate the liquefaction resistance of sands.

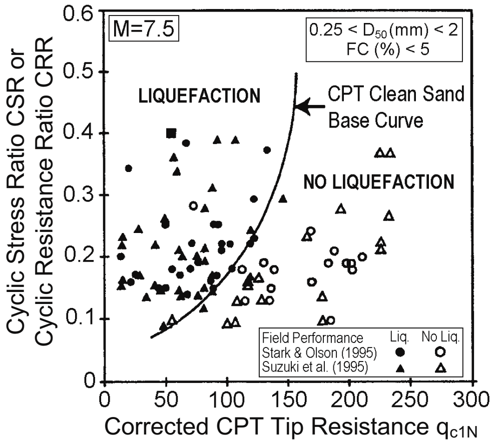


Fig. 1. Recommended curve for evaluating CRR from CPT (Youd & Idriss 2001)

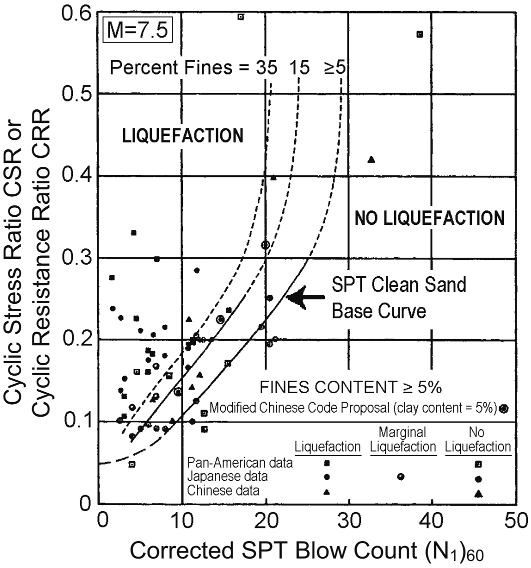


Fig. 2. Recommended curve for evaluating CRR from SPT (Youd & Idriss 2001)

Comparative studies have indicated that K_D is noticeably reactive to factors such as stress state/history (σ_h, OCR), aging, pure prestraining, cementation and structure – all factors increasing liquefaction resistance. Such factors are scarcely felt e.g. by q_c from CPT (see e.g. Huang & Ma 1994) and, in general, by cylindrical-conical probes. As noted by Robertson & Campanella (1986), it is not possible to separate the individual contribution of each factor on K_D. On the other hand, when K_D is low, none of the above factors is high, i.e. the sand is loose, uncemented, in a low horizontal stress environment and has little stress history. A sand under these conditions may liquefy or develop large strains under cyclic loading.

The most significant factors supporting the use of DMT for evaluating sand liquefiability are:

Sensitivity of DMT in monitoring soil densification

The high sensitivity of the DMT in monitoring densification, demonstrated by several studies (e.g. Schmertmann et al. 1986 and Jendeby 1992 found DMT ≈ twice more sensitive than CPT to densification), suggests that the DMT may be a sensitive tool also for sensing sand liquefiability. In fact a liquefiable sand may be regarded as a sort of "negatively compacted" sand, and it appears plausible that the DMT sensitivity holds both in the positive and in the negative range.

Sensitivity of DMT to prestraining

CC research on Ticino sand (Jamiolkowski & Lo Presti 1998, Fig. 3) has shown that K_D is much more sensitive to prestraining – one of the most difficult effects to detect by any method – than the penetration resistance (the increase in K_D caused by prestraining was found ≈ 3 to 7 times the increase in penetration resistance q_D). On the other hand, Jamiolkowski et al. (1985) had already observed that reliable predictions of liquefaction resistance of sand deposits of complex stress-strain history require the development of some new in situ device (other than CPT or SPT), more sensitive to the effects of past stress-strain histories.

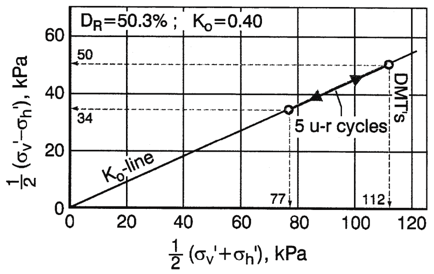
Correlation K_D – Relative density

In NC uncemented sands, the relative density D_r can be derived from K_D according to the correlation by Reyna & Chameau (1991) shown in Fig. 4. This correlation has been confirmed by datapoints added by subsequent research. In particular, it has received a strong confirmation by additional K_D -D_r datapoints (shaded areas in Fig. 4) obtained by Tanaka & Tanaka (1998) at the sites of Ohgishima and Kemigawa, where D_r was determined on high quality frozen samples.

Correlation K_D – In situ state parameter

The state parameter concept represents an important step forward from the conventional relative density concept in characterizing soil behavior, combining the effects of both relative density and stress level in a rational way. The state parameter (vertical distance between the current state and the critical state line in the usual v - ln p' plot) governs the attitude of a sand to increase or decrease in volume when sheared, hence it is strongly related to liquefaction resistance. Recent research supports viewing K_D from DMT as an index reflecting the in situ state parameter ξ_o. Yu (2004) identified the average correlation K_D-ξ_o shown in Fig. 5 (study regarding four well-known reference sands). Clearly relations K_D-ξ_o as the one shown by Yu (2004) strongly encourage efforts to develop methods to assess liquefiability by DMT.

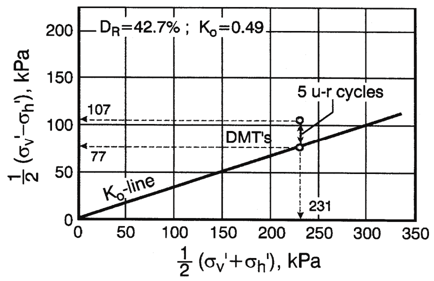
CC TEST N. 216 IN TICINO SAND



	I_D (-)	K_D (-)	E_D (MPa)	M_D (MPa)	q_D (MPa)
Before	2.62	1.98	29.0	30.3	16.0
After	2.41	2.38	31.8	37.8	16.4

K_D increase +20 %
q_D increase +3 %

CC TEST N. 241 IN TICINO SAND



	I_D (-)	K_D (-)	E_D (MPa)	M_D (MPa)	q_D (MPa)
Before	2.50	1.03	27.6	23.5	14.5
After	2.50	1.43	33.4	28.5	16.1

K_D increase +39 %
q_D increase +11 %

Fig. 3. Results of CC testing (prestraining cycles) showing the higher sensitivity of K_D to prestraining than penetration resistance (Jamiolkowski & Lo Presti 1998)

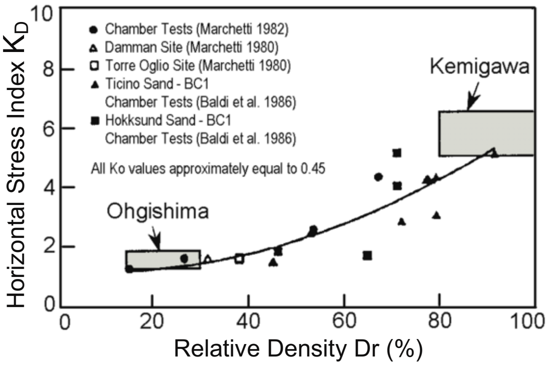


Fig. 4. Correlation K_D-D_r for NC uncemented sands (Reyna & Chameau 1991), also including Ohgishima and Kemigawa datapoints obtained by Tanaka & Tanaka (1998) on high quality frozen samples

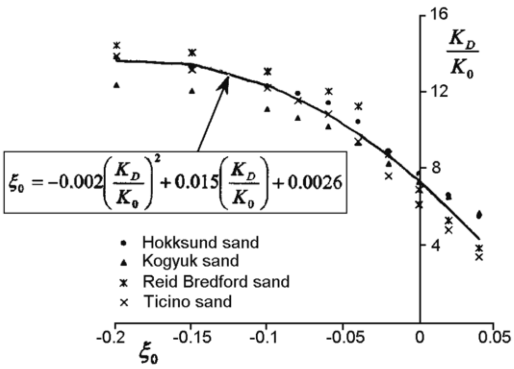


Fig. 5. Average correlation K_D - in situ state parameter ξ_o (Yu 2004)

Comments on evaluating liquefiability by CPT and SPT

Theoretical and experimental research (e.g. Sladen 1989, Yu & Mitchell 1998) has demonstrated that, contrary to what was attempted by Been et al. (1987), the correlation q_c-state parameter for CPT is not unique, but strongly dependent on the stress level. Sladen (1989) showed that ignoring the non-unicity of the correlation q_c -state parameter in design can lead, in some circumstances, to catastrophic consequences (e.g. the Nerlerk subsea liquefaction flow slides). In view of the possibility of large errors in CRR estimated from q_c, Sladen (1989) concluded that, while the CPT is ideal for providing a qualitative profile of sand deposits, future research should be probably directed towards other tools. Robertson & Wride (1998) warned that CRR evaluated by CPT (preferred to SPT, due to the poor repeatability) may be adequate for low-risk, small-scale projects, while for medium- to high-risk projects they recommended to estimate CRR by more than one method. Accordingly, the 1996 and 1998 NCEER workshops (Youd & Idriss 2001) concluded that, where possible, two or more tests should be used for a more reliable evaluation of liquefaction resistance.

Comments on evaluating liquefiability by V_s measurements

The NCEER workshops (Youd & Idriss 2001) list the shear wave velocity V_s as a possible quantity to assess sand liquefiability. The seismic dilatometer SDMT, currently in use in the last years, provides V_s measurements, hence offers the possibility to estimate CRR from V_s. However, in the authors' opinion, methods for evaluating CRR from K_D should be preferred, since K_D is more sensitive than V_s to factors such as stress history and aging, which greatly increase the liquefaction resistance.

4 SUMMARY OF EXISTING CRR-K_D CORRELATIONS

Fig. 6 summarizes the various correlations developed to estimate CRR from K_D, leading to the definition of CRR-K_D boundary curves separating possible "liquefaction" and "no liquefaction" regions. The central CRR-K_D curve by Reyna & Chameau (1991) in Fig. 6 supersedes the previous ones (Marchetti 1982, Robertson & Campanella 1986), as it includes liquefaction field performance datapoints (Imperial Valley, South California).

5 TRANSLATION OF CRR-CPT AND CRR-SPT CORRELATIONS INTO CRR-K_D CORRELATIONS USING D_r AS INTERMEDIATE PARAMETER

The specific contribution of this paper is to supplement the existing knowledge on evaluation of CRR by DMT, summarized in Fig. 6. Such supplement consists in additional CRR-K_D curves derived from current methods for evaluating CRR by CPT and SPT (supported by extensive field performance databases). The CRR curves recommended for CPT and SPT are translated into "equivalent" CRR-K_D curves, using the relative density D_r as intermediate parameter. The procedure is the following:

1) Evaluate D_r corresponding to the values of the normalized cone penetration resistance q_{c1N} for the "CPT Clean Sand Base Curve" in Fig. 1 using various D_r-q_c correlations (Baldi et al. 1986, Jamiolkowski et al. 1985).
2) Evaluate D_r corresponding to the values of the normalized SPT blowcount $(N_1)_{60}$ for the "SPT Clean Sand Base Curve" in Fig. 2 using the D_r -N_{SPT} correlation by Gibbs & Holtz (1957), assuming a range of σ'_{vo} values relevant to common liquefaction conditions (depths ≈ 5 to 15 m, water table close to ground surface).
3) Estimate the values of K_D corresponding to the above calculated values of D_r using the K_D -D_r correlation by Reyna & Chameau (1991) shown in Fig. 4.
4) Plot the CRR-K_D curves derived from CPT and SPT (Fig. 6).

It could be observed that the above procedure basically relies on estimation of D_r from CPT and SPT, which, as widely recognized, is affected by many uncertainties. For this reason D_r was evaluated by more than one method, e.g. for the CPT two different D_r-q_c correlations recommended for current practice (Lunne et al. 1997) were used. As pointed out before, more rational interpretations would require the use of the in situ state parameter, rather than D_r. On the other hand, such interpretations are not sufficiently well-established at present. However, since the aim of this study was to locate a possible *range* of CRR-K_D curves, the results obtained may be considered adequate as a first approach. Fig. 6 shows that the CRR-K_D curves derived from the CRR curves recommended for CPT and SPT plot in a relative narrow range, very close to the Reyna & Chameau (1991) curve.

A tentative conservative average CRR-K_D curve is proposed (bold line in Fig. 6), approximated by the following equation:

$$CRR = 0.0107\, K_D^3 - 0.0741\, K_D^2 + 0.2169\, K_D - 0.1306 \quad (2)$$

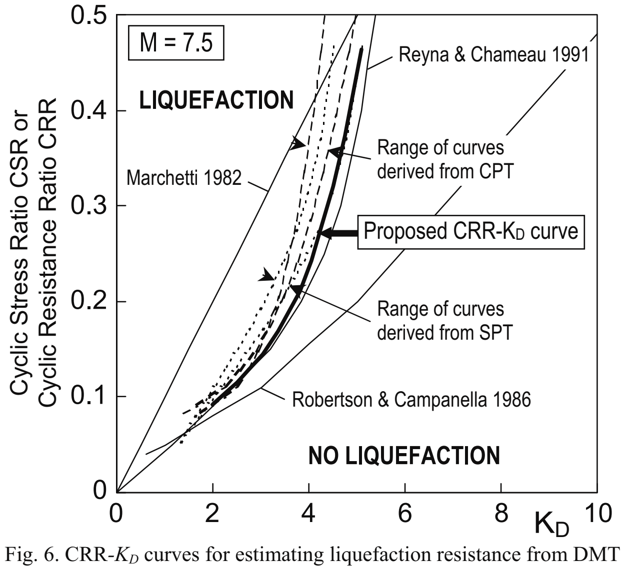


Fig. 6. CRR-K_D curves for estimating liquefaction resistance from DMT

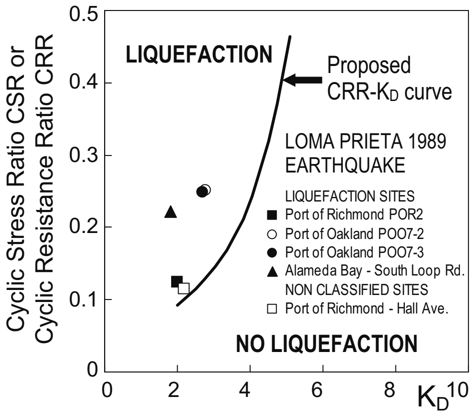


Fig. 7. Comparison of proposed CRR-K_D curve and Loma Prieta 1989 earthquake liquefaction datapoints (Mitchell et al. 1994)

Fig. 6 could be used exactly in the same way as other methods based on the "simplified procedure" (Seed & Idriss 1971): (1) Enter K_D in Fig. 6 (or Eq. 2) to evaluate CRR. (2) Compare CRR with the cyclic stress ratio CSR generated by the earthquake calculated by Eq. 1.

The proposed CRR-K_D curve applies to magnitude M = 7.5 earthquakes. For magnitudes smaller or larger than 7.5, magnitude scaling factors should be applied (possibly the same ranges recommended in Youd & Idriss 2001). Of course the method proposed for evaluating CRR by DMT is affected by the same restrictions which limit, in general, the validity of the Seed & Idriss (1971) method (level to gently sloping ground conditions, limited depth range, clean sand).

A preliminary verification of the proposed CRR-K_D curve is shown in Fig. 7, which includes liquefaction field performance datapoints obtained at various sites after the Loma Prieta 1989 earthquake (M = 7.1), in the San Francisco Bay region (to the authors' knowledge, one of the few documented liquefaction cases with DMT data). The CSR-K_D datapoints in Fig. 7 were calculated based on data contained in the report by Mitchell et al. (1994), which includes the results of DMTs conducted after the earthquake at several locations where soil liquefaction had occurred (mostly in hydraulic sandfills), along with data on soil stratigraphy, water table, depths of soil layers likely to have liquefied, a_{max} estimated or measured from strong motions recordings. Fig. 7 shows that the datapoints obtained at sites where liquefaction had occurred are correctly located in the "liquefaction" side of the plot. One datapoint relevant to a site not classified as "liquefaction" or "non-liquefaction" site by Mitchell et al. (1994) plots very close to the proposed CRR-K_D boundary curve.

6 TENTATIVE IDENTIFICATION OF MINIMUM "NO LIQUEFACTION" K_D VALUES

In many everyday problems, a full seismic liquefaction analysis can be avoided if the soil is clearly liquefiable or clearly non liquefiable. Guidelines of this type would be practically helpful to engineers. A tentative identification of minimum values of K_D for which a clean sand (natural or sandfill) is adequately safe against liquefaction for areas of different seismicity (M = 7.5 earthquakes) is indicated in TC16 (2001):

– Non seismic areas: $K_D > 1.7$
– Low seismicity areas ($a_{max}/g = 0.15$): $K_D > 4.2$
– Medium seismicity areas ($a_{max}/g = 0.25$): $K_D > 5.0$
– High seismicity areas ($a_{max}/g = 0.35$): $K_D > 5.5$

The above values of K_D were identified based on the Reyna & Chameau (1991) CRR-K_D curve.

As to non seismic areas, the following indications were given by Marchetti (1997): (1) For $K_D > 1.7$ liquefaction is definitely not a problem. (2) For $K_D < 1.3$ (unless sporadic/isolated) liquefaction is definitely a problem, some kind of soil improvement is necessary. (3) For $1.3 < K_D < 1.7$ additional study is necessary. (Various studies have indicated that the Zelazny Most Tailing Dam in Poland, in a non seismic region, having typically K_D = 1.5, is marginally safe against liquefaction. Yet such dam is standing, possibly it would be definitely safe for say K_D = 1.7).

From comparison with the proposed CRR-K_D curve shown in Fig. 6, the above values of K_D appear reasonably conservative.

7 CONCLUSIONS

The DMT offers an alternative to current methods for estimating the liquefaction resistance of sands from CPT or SPT. Theoretical and experimental research over the last 20 years has shown that the horizontal stress index K_D from DMT is noticeably reactive to factors that greatly increase liquefaction resistance, such as past stress-strain history, aging, cementation and structure. On the other hand, such factors are scarcely felt by other tests (e.g. by q_c from CPT). The available experience supports viewing K_D as a suitable parameter to assess sand liquefiability.

A tentative correlation is proposed for evaluating the cyclic resistance ratio CRR from K_D according to the "simplified procedure" (Seed & Idriss 1971), by combining previous CRR-K_D correlations with the vast experience that has led to today used methods for evaluating CRR from CPT and SPT, using the relative density as intermediate parameter. A preliminary verification of the proposed method was obtained from comparison with field performance datapoints obtained at liquefaction sites investigated after the Loma Prieta 1989 earthquake (Mitchell et al. 1994). Obviously considerable additional verification is needed.

REFERENCES

Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M. & Pasqualini, E. 1986. Interpretation of CPT and CPTUs. 2nd part: Drained penetration of sands. *Proc. 4th Int. Geotech. Seminar*, Singapore, 143-156.

Been, K., Crooks, J.H.A., Becker, D.E. & Jefferies, M.G. 1987. The cone penetration test in sand. II General inference of state. *Géotechnique*, 37(3), 285-299.

Gibbs, K.J. & Holtz, W.G. 1957. Research on determining the density of sands by spoon penetration testing. *Proc. IV ICSMFE*, 1, 35-39.

Huang, A.B. & Ma, M.Y. 1994. An analytical study of cone penetration tests in granular material. *Can. Geotech. Jnl*, 31(1), 91-103.

Jamiolkowski, M., Baldi, G., Bellotti, R., Ghionna, V., & Pasqualini, E. 1985. Penetration resistance and liquefaction of sands. *Proc. XI I-CSMFE*, San Francisco, 4, 1891-1896.

Jamiolkowski, M., Ladd, C.C., Germaine, J.T. & Lancellotta, R. 1985. New developments in field and laboratory testing of soils. SOA Report, *Proc. XI ICSMFE*, San Francisco, 1, 57-153.

Jamiolkowski, M. & Lo Presti, D.C.F. 1998. Oral presentation. *1st Int. Conf. on Site Characterization ISC'98*, Atlanta.

Jendeby, L. 1992. Deep Compaction by Vibrowing. *Proc. Nordic Geotechnical Meeting NGM-92*, 1, 19-24.

Lunne, T., Robertson, P.K. & Powell, J.J.M. 1997. Cone Penetration Testing in Geotechnical Practice. Blackie Academic.

Marchetti, S. 1982. Detection of liquefiable sand layers by means of quasi-static penetration tests. *Proc. 2nd European Symp. on Penetration Testing*, Amsterdam, 2, 689-695.

Marchetti, S. 1997. The Flat Dilatometer: Design Applications. Keynote Lecture, *Proc. 3rd Int. Geotech. Engrg. Conference*, Cairo, 421-448.

Mitchell, J.K., Lodge, A.L., Coutinho, R.Q., Kayen, R.E., Seed, R.B., Nishio, S. & Stokoe, K.H. 1994. Insitu test results from four Loma Prieta earthquake liquefaction sites: SPT, CPT, DMT and shear wave velocity. *Report No. UCB/EERC-94/04*, Earthquake Engineering Research Center, Univ. of California, Berkeley.

Porcino, D. & Ghionna, V.N. 2002. Liquefaction of coarse grained sands by laboratory testing on undisturbed frozen samples (in Italian). *Proc. Annual Meeting Italian Geot. Res. IARG 2002*, Naples.

Reyna, F. & Chameau, J.L. 1991. Dilatometer Based Liquefaction Potential of Sites in the Imperial Valley. *Proc. 2nd Int. Conf. on Recent Adv. in Geot. Earthquake Engrg. and Soil Dyn.*, St. Louis, 385-392.

Robertson, P.K. 2004. Evaluating soil liquefaction and post-earthquake deformations using the CPT. *Proc. 2nd Int. Conf. on Site Characterization ISC-2*, Porto, 1, 233-249.

Robertson, P.K. & Campanella, R.G. 1986. Estimating Liquefaction Potential of Sands Using the Flat Plate Dilatometer. *ASTM Geotechn. Testing Journal*, 9(1), 38-40.
Robertson, P.K. & Wride, C.E. 1998. Evaluating cyclic liquefaction potential using the cone penetration test. *Can. G. Jnl*, 35(3), 442-459.
Schmertmann, J.H., Baker, W., Gupta, R. & Kessler, K. 1986. CPT/DMT Quality Control of Ground Modification at a Power Plant. *Proc. In Situ '86, ASCE Spec. Conf. on "Use of In Situ Tests in Geotechn. Engineering"*, Virginia Tech, Blacksburg, ASCE Geotechn. Special Publ. No. 6, 985-1001.
Seed, H.B. & Idriss, I.M. 1971. Simplified procedure for evaluating soil liquefaction potential. *Jnl GED* ASCE, 97(9), 1249-1273.
Sladen, J.A. 1989. Problems with interpretation of sand state from cone penetration test. *Géotechnique*, 39(2), 323-332.
Tanaka, H. & Tanaka, M. 1998. Characterization of Sandy Soils using CPT and DMT. *Soils and Foundations*, 38(3), 55-65.
TC16 - Marchetti, S., Monaco, P., Totani, G. & Calabrese, M. 2001. The Flat Dilatometer Test (DMT) in Soil Investigations - A Report by the ISSMGE Committee TC16. 41 pp.
Youd, T.L. & Idriss, I.M. 2001. Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils. *Jnl GGE* ASCE, 127(4), 297-313.
Yu, H.S. 2004. In situ soil testing: from mechanics to interpretation. *Proc. 2nd Int. Conf. on Site Characterization ISC-2*, Porto, 1, 3-38.
Yu, H.S. & Mitchell, J.K. 1998. Analysis of cone resistance: review of methods. *Jnl GGE* ASCE, 124(2), 140-149.