Sensitivity of CPT and DMT to stress history and aging in sands for liquefaction assessment

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ABSTRACT**:** Sand liquefaction resistance depends on a large number of factors, some of which are arduous to detect. Without the possibility of retrieving undisturbed samples in sands and reproducing their natural structure in the laboratory, evidence of stress history, aging and similar factors – not easy to capture - must be obtained from in situ tests. This paper deals with the possibilities offered by CPT and DMT to capture stress history and aging. Consideration is also given to the fact that even the state parameter ψ may be an incomplete indicator of the liquefaction resistance CRR, since ψ, according to its definition, does not contain the possible benefits of stress history and aging to liquefaction resistance.

1 INTRODUCTION

Sand liquefaction resistance depends on a large number of factors. A possible list includes: relative density D_r, in-situ K_o, stress and strain history, aging, bonding, structure. Some of these factors have substantial influence on liquefaction resistance. For example, most natural soils are microstructured so that, at a given void ratio, they can sustain stresses higher than could the same material without microstructure. At the same time, however, some of these factors are arduous to detect. Detecting them by laboratory testing is not viable in practice, since taking undisturbed samples in sand for laboratory testing can be complicated and prohibitively expensive.

Testing on sand specimens reconstituted even at exactly the same in situ density is “highly questionable" (Ladd, 1977). Different reconstitution methods result in different fabric and structure, and loss of natural bonding. Moreover estimating D_r in situ may involve considerable error. The different structure of natural and reconstituted specimen can result in highly different behaviour. Experiments by Høeg et al. (2000) showed that natural silty sands exhibited a dilative behaviour, while reconstituted specimens with the same void ratio exhibited a contractive behaviour, which is a big difference when assessing liquefaction resistance. Given the impossibility of analysing in the laboratory aging, bonding and similar factors, they must be deducted from in situ tests. This paper discusses the capability of CPT and DMT to capture stress history and aging.

2 THREE CASES Of SENSITIVITY OF CPT AND DMT TO STRESS HISTORY AND AGING IN SANDS

2.1 CASE 1: Sensitivity of K_D to prestressing – Florida Calibration Chamber

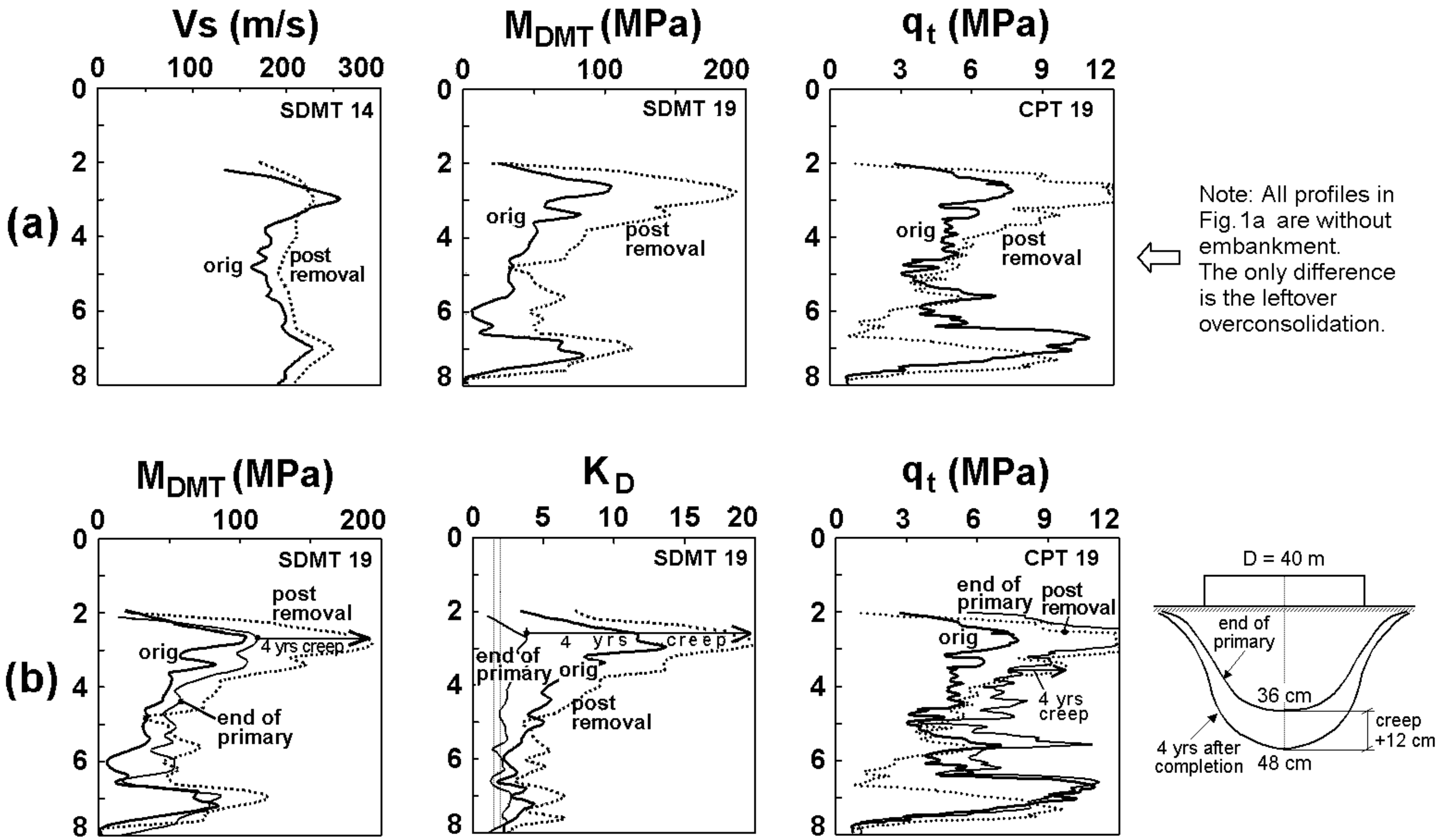
One of the most difficult factors to detect in soils is prestressing (or prestraining). Lambrechts and Leonards (1978) measured on laboratory triaxial sand specimens both the initial modulus and q_t before and after prestressing along the K_o line. They found that prestressing increased the initial moduli by one order of magnitude, but increased q_t negligibly. Marchetti (1982) performed similar experiments in the Florida calibration chamber. The dilatometer blade was inserted in the sand in two stages. The top half of the specimen was penetrated in its just deposited NC state, the lower half after prestressing. The results indicate that prestressing increased considerably K_D (K_D = (po-uo)/σ'$_{vo}$) but negligibly E_D. M_{DMT} also increased considerably, as M_{DMT} is interpreted from both E_D and K_D. The indication from the above experiments was that K_D is considerably more sensitive than q_t (and E_D) to prestressing.

2.2 CASE 2: Sensitivity of CPT and DMT to aging – Enel Milano Calibration Chamber

Jamiolkowski and Lo Presti (1998), using the large calibration chamber, showed that K_D is much more sensitive to cyclic prestraining than the penetration resistance q_D of the DMT blade, and presumably of the cone penetration resistance. Both q_D and K_D were measured before and after prestraining the sand in the chamber. The prestraining consisted of increasing both the vertical and horizontal stress maintaining a constant K_o, then removing both increases, thereby returning to the same initial stress state before the DMT testing – five cycles. In a series of tests of this type the increase in K_D caused by prestraining was found ≈ 3 to 7 times the increase in q_D. Cycles of prestraining may be viewed as a type of "simulated aging" (at least for the mechanical *non-chemical* mechanism responsible of aging, consisting in the grains gradually slipping into a more stable configuration). Prestraining speeds the slippage of particles, which would otherwise occur over long periods of time. The indication from the above results was that K_D is considerably more sensitive to *aging* than penetration resistance.

2.3 CASE 3: Reaction of K_D and q_t to stress history and aging under a full scale embankment.

The Treporti (Venezia) embankment was a full-scale cylindrical heavily instrumented test embankment (40 m diameter, 6.7 m high, applied load 104 kPa) built on the highly stratified sandy and silty deposits typical of the Venezia lagoon. The attention is concentrated here on the sand layer between 2 and 8 m depth. The site is geologically normally consolidated (K_D ~2), though various phenomena (like desiccation and sea level fluctuations) have produced overconsolidation-like effects in the top few meters. The embankment was initiated in 2002 and completed in 6 months. It applied its load for 4 years, and was removed in 2007-2008. All the materials at the site, silts and sands, were freely draining, and never generated excess pore pressure. Hence the end of construction coincided essentially with end of



Note: All profiles in Fig. 1a are without embankment. The only difference is the leftover overconsolidation.

Figure 1. Treporti (Venezia) Test Embankment. All profiles are for the sand layer 2 to 8 m depth. (a) Influence on the various parameters of the overconsolidation caused by the embankment. (b) How the various parameters reacted to stress history and aging.

primary consolidation. Subsequent settlements were due to creep, not to consolidation. CPT and DMT soundings were executed: (1) before construction (2) at the end of contruction and (3) after complete removal. The results are presented in Fig. 1. Fig. 1a focuses on the sensitivity of CPT and DMT to the effects of overconsolidation, and Fig. 1b on the sensitivity to the effects of aging.

Fig. 1a compares the profiles of shear wave velocity, V_S, M_{DMT}, and q_t with the post-removal profile. All the soundings in Fig.1a were executed from “green grass”, i.e. without embankment, the only difference being the overconsolidation caused by the embankment. By observing the pre-construction profile and the post-removal profiles is can be noted that the overconsolidation is reflected almost negligibly by V_S (or G_o), to a maximum degree by M_{DMT}, to a medium degree by q_t. It is worth noting the “parallelism” between the in situ trend and laboratory results (e.g. Yamashita et al. 2000). Yamashita et al (2000) showed that the benefit of overconsolidation on modulus is practically negligible at small strains, maximum at “operative” strains, modest at high strains.

Fig. 1b compares the profiles of M_{DMT}, K_D, q_t with the end-of-construction and the final (i.e. post-removal) profiles. The last scheme in Fig. 1b shows the settlements under the embankments at the end of construction (end of primary) and after 4 years of permanence of the embankment. In the 4 years the settlement under the centre increased from an end-of-primary value of 36 cm to 48 cm, i.e. a surprisingly large 12 cm additional settlement due to creep. By comparing the end-of-primary profiles of M_{DMT}, K_D, and q_t with the after 4-years-creep profiles it can be noted that the 4-years-creep effects are most vividly reflected by K_D (and to some extent by M_{DMT}). The data presented suggest that DMT (in particular K_D) is considerably more sensitive than CPT to stress history and aging, which, as already noted, influence considerably liquefaction resistance.

The influence of stress history on liquefaction was emphasized by Baldi et al. (1985): "reliable predictions [of liquefiability] in complex stress-history deposits require the development of some new in situ device [other than CPT or SPT] more sensitive to the effects of past stress and strain histories". The quantitatively important influence of aging on liquefaction is discussed in the next section.

3 INFLUENCE OF AGING ON LIQUEFACTION RESISTANCE

Leon et al. (2006) explicitly highlighted the importance of aging when assessing liquefaction potential. They pointed out that commonly used correlations for estimating the cyclic resistance ratio, CRR (from SPT, CPT, V_S) were derived mostly for young or freshly deposited sands, where the aging effect is negligible or anyway smaller than in older soils, and are not strictly valid in older sands. They also observed that penetration resistance is a poor indicator of the in situ conditions of sand deposits when aging is found. The poor ability of SPT and CPT to capture the effects of aging is ascribed by Leon et al. (2006) to their insufficient sensitivity to detect minor changes in soil fabric that can increase liquefaction resistance, since the disturbance during these tests may destroy or seriously damage the microstructure effects that result from aging. In the sands studied by Leon et al. (2006), ignoring aging effects and using a CRR evaluated from in situ tests *insensitive* to aging (SPT, CPT, V_S) underestimated CRR by a large 60 %.

4 INDICATIONS EMERGING FROM THE REPORTED DATA

As observed by Monaco and Schmertmann (2007), disregarding aging is equivalent to omitting a primary parameter in the CRR correlations. This omission may explain the frequently observed dispersion of the CRR predictions, ultimately leading to the generally accepted recommendation "evaluate CRR by as many methods as possible" (e.g. Youd et al, 2001).

Since the data previously reported suggest that K_D is more sensitive to stress history and aging than other parameters obtained in situ, it would seem that K_D might have a chance to be uniquely well correlated to CRR. Of course this expectation needs field verification.

5 COMMENTS ON METHODS FOR EVALUATING CRR

5.1 CRR from q_t

At present, the basic method to evaluate liquefaction is to use CPT with the most recently developed correlations between CRR and 'clean sand equivalent' normalized cone resistance, $Q_{tn,cs}$ (Robertson, 2009). Reviews of the methods to determine the 'clean sand equivalent' can be found in Schnaid (2009) and Mayne et al. (2009). Mayne et al (2009) also present alternative correlations to CRR having the particularity that they contain multiple curves, rather than a unique curve. Mayne et al (2009) also suggest the possibility of multiple CRR-Q_{t1n} curves, depending on the various sands. A possible reason of this multiplicity could be that a different structure, all things being equal, may result in a similar q_t but in a different CRR. Since ignoring aging and structure is equivalent to omitting an important parameter, it could be that the multiple curves would be reunited in a narrower band, if aging and structure were taken into account. This reunion might perhaps occur by using K_D, which is sensitive to these factors.

5.2 CRR from Vs

The most popular among the CRR-V_S correlations is the one proposed by Andrus and Stokoe (2000) and by Andrus et al. (2004). However, these authors suggest that there is high uncertainty associated with the correlations.

Doubts about the validity of CRR-V_S correlations are also suggested by the Treporti field results in Fig. 1a. Those results indicate scarce reactivity of V_S to stress history, hence, a scarce aptitude to correlate to CRR, considerably influenced by stress history. Doubts about possible CRR-V_S correlations are also expressed by Jamiolkowski and Lo Presti (1992), who illustrate the lack of sensitivity of V_S to the strain or stress history (Fig 2). Finally, a concern is expressed by Andrus and Stokoe (2000) who note that, when using V_S to evaluate CRR, the V_S measurements are made at small strains, whereas liquefaction is a medium- to high-strain phenomenon. This concern is significant for bonded soils, in which V_S may be high due to (even weak) interparticle bonding, but these may be destroyed at medium-high strains. Weak interparticle bonding can increase V_S, while not necessarily increasing CRR. For the above reasons, when using the Seismic DMT (SDMT), which routinely provides two independent estimates of CRR, one from K_D, another one from V_S, it is believed that considerable more weight should be attributed to CRR derived from K_D.

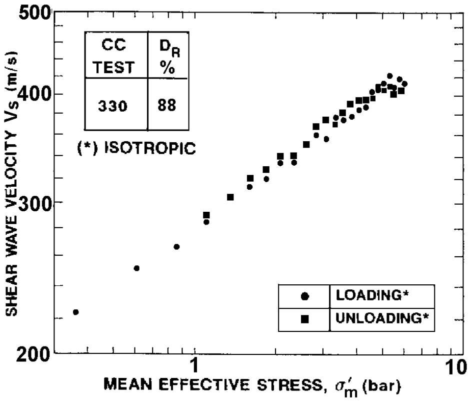


Figure 2. Vs measured on sand specimen in the calibration chamber during loading and unloading (Jamiolkowski and Lo Presti, 1992)

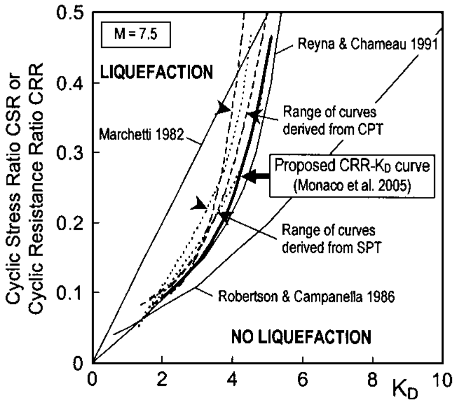


Figure 3. CRR-K_D curves for evaluating liquefaction resistance from DMT

5.3 CRR from K_D

Marchetti (1982) and later studies (Robertson and Campanella 1986, Reyna and Chameau 1991) suggested that K_D from DMT is a suitable index parameter of liquefaction resistance. K_D, besides being reactive to D_r and K_o, is noticeably reactive to stress history, prestraining, aging, cementation, structure, all factors increasing liquefaction resistance. Fig. 3 summarizes the various CRR-K_D correlations developed in the years. The latest is the bold curve in Fig. 3, derived by Monaco et al. (2005). Additional details on using K_D for evaluating CRR may be found in Monaco and Marchetti (2007). An extensive database of liquefaction-nonliquefaction CRR- K_D data is badly needed for better defining the location of the curve.

5.4 CRR from K_D via state parameter ψ

Recent research supports viewing K_D from DMT as an index linked to the in situ state parameter ψ. Yu (2004) identified the average correlation K_D - ψ shown in Fig. 4a (predictions for four well-known reference sands, falling in a narrow band). The state parameter (void ratio difference between the current state of the soil and critical state at the same effective mean normal stress p'), combines relative density and stress level, and is rightly considered a more rational parameter for correlations with CRR. However, ψ is a parameter difficult to determine, given the difficulty of accurate estimates of the void ratio in situ. Hence the desirability of methods for determining ψ in situ, such as the curve in Fig. 4a. It should be noted, however, that ψ alone is an incomplete indicator of the tendency of a sand to dilate or contract, and in general of the liquefiability. In fact, equality of ψ does not imply equality of CRR. The soil structure effect is missing in ψ, e.g. two soils from two identical deposits, having identical void ratio and ψ, but with only the second soil with structure, would have different CRR. To be related to CRR, ψ of the structured soil should be increased to match the increase of CRR due to the structure. On the other hand, despite the equality of ψ, K_D of the structured element would expectably be higher, due to the stress history and aging effects already incorporated in K_D, and could possibly be better related to CRR.

A note of caution: while a K_D - ψ curve derived for fresh sand could be conceptually unique (see Fig. 4a) , for structured sands it is expectable that there will be multiple K_D -

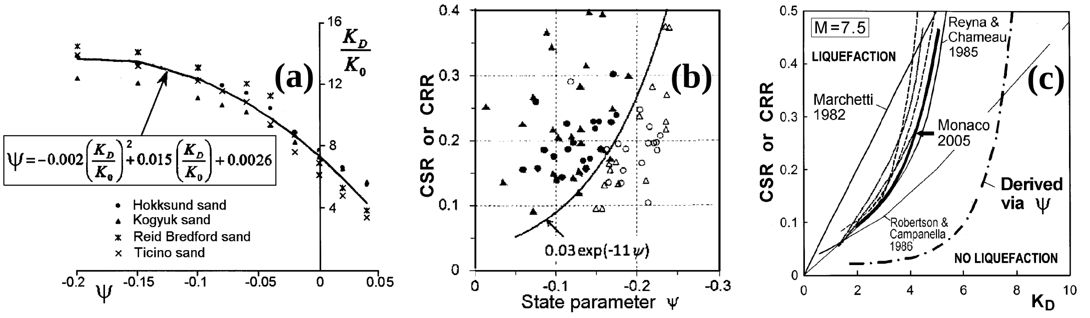


Figure 4. (a) Average correlation K_D - in situ state parameter ψ (Yu 2004). (b) CRR as a function of state parameter ψ (Jefferies and Been 2006) (c) K_D -CRR correlation "derived via ψ" , i.e.resulting from the combination of the equations in (a) and in (b).

Interestingly, a direct CRR- K_D correlation can be derived by combining the K_D - ψ correlation in Fig. 4 with the recently developed (Jefferies & Been, 2006) correlation CRR-ψ (Fig. 4b). By assuming K_o=0.5, the rightmost curve K_D -CRR in Fig. 4c is obtained. The location of the resulting curve appears somewhat irrealistic – it would predict liquefaction too often. The reason could be, at least in part, that the combined curve is based on two semi-theoretical curves derived for fresh sand. It is finally noted that, while the link K_D -ψ suggests in a generic way usefulness of K_D for liquefaction, the fact that ψ does not incorporate the benefits of structure, while K_D does, suggests the possibility (to be explored) that K_D might be an index even closer than ψ to CRR.

6 CONCLUSIONS

Liquefaction resistance depends on a large number of factors including: relative density D_r, in situ K_o, stress and strain history, aging, bonding, structure. Some of these factors, in particular stress history and aging, are very difficult to sense, both for the impossibility of reproducing the characteristic structure of natural sand in laboratory specimens, and for the scarce sensitivity of in situ penetration tests to such factors. The results reported in this paper, along with additional evidence presented, suggest that the parameter K_D is considerably more sensitive than q_t to stress history and aging, two factors strongly influencing the resistance to liquefaction. On the other hand this result was expectable, considering that the less disruptive insertion of the blade, compared with the cone, destroys less the effects of stress history and aging. Since ignoring aging is equivalent to omitting an important parameter in the correlations with CRR, it is not surprising that current correlations with CRR are dispersed or, as hypothesized by Mayne et al. (2000), may be multiple. It seems expectable, on the other hand, that, using as liquefaction index a parameter sensitive to aging and stress history, will results in correlations with CRR less dispersed than previous correlations.

Recent research has identified a link between K_D and state parameter ψ. In this regard it is noted that the state parameter alone is an incomplete indicator of the tendency of a sand to dilate or contract, and in general of the resistance to liquefaction.

In fact, equality of ψ does not imply equality of CRR. The structure effect is missing in ψ. To be related to CRR, ψ of a structured element should be increased to match the increased level of CRR due to the structure. It does not appear illogical to expect that K_D, being a parameter related to ψ, but at the same incorporating stress history and aging effects, could be uniquely well correlated with CRR.

In order to verify the above expectation, it is not possible to use as reference for calibration the CRRs from laboratory or from penetration tests. The only way appears the accumulation, in the CRR- K_D correlation, of real life experimental liquefaction- nonliquefaction data. Good field evidence is better than somewhat flawed theories and laboratory results.

7 REFERENCES

Andrus, R. D. & Stokoe K. H. II. 2000, Liquefaction resistance of soils from shear-wave velocity. *J. Geotech. Geoenv. Engrg.*, ASCE, 126(11) : 1015-1025.

Andrus, R. D., Stokoe, K. H. II., Juang, C. H. 2004. Guide for Shear-Wave-Based Liquefaction Potential Evaluation. *Earthquake Spectra*, 20(2) : 285-305.

Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M. & Pasqualini, E. 1985. Penetration Resistance and Liquefaction of Sands. Proc. *11th ICSMFE*, San Francisco, 4 : 1891-1896

Høeg, K., Dyvik, R., Sandbækken, G. 2000. Strength of undisturbed versus reconstituted silt and silty sand specimens. *J. Geotech. Geoenv. Engrg.*, ASCE, 126 (7) : 606-617.

Jamiolkowski,M. & Lo Presti, D. 1992. Discussion on paper : Correlation between Liquefaction Resistance and Shear Wave Velocity. *Soils and Foundations* 32 (2) : 145-148.

Jamiolkowski, M. & Lo Presti, D. (1998). DMT research in sand. What can be learned from calibration chamber tests. *1st Int. Conf. on Site Characterization ISC'98*, Atlanta. Oral presentation.

Jefferies, M. & Been, K. 2006. *Soil Liquefaction A Critical State Approach*. Taylor and Francis Group, London: 480 p.

Ladd, C.C., Foot, R., Ishihara K., Schlosser F. & Poulos H.G. 1977. Stress-Deformation and Strength Characteristics, *Proc.9th ICSMFE.* Tokyo, 2, : 421-497.

Lambrechts, J.R. & Leonards, G.A. 1978. Effects of Stress History on Deformation of Sand, *ASCE J. GED*, 104, GT11 : 1371-1387.

Leon, E., Gassman, S.L., Talwani, P. 2006. Accounting for Soil Aging When Assessing Liquefaction Potential. *J. Geotech. Geoenv. Engrg.,* ASCE, 132(3), 363-377.

Marchetti, S. 1982 Detection of liquefiable sand layers by means of quasi-static penetration probes. *ESOPT II* Amsterdam 2 : 689-695.

Mayne, P.W., Coop, M.R., Springmanm S.M., Huang, A., Zornberg, J.G. 2009 Geomaterial behavior and testing. *Proc. 17th ICSMGE* Alexandria, Egypt,4 : 2777-2872. Eds Hamza et al.

Monaco, P. & Marchetti, S. 2007. Evaluating liquefaction potential by seismic dilatometer (SDMT) accounting for aging/stress history. *Proc. 4th Int. Conf. on Earthquake Geotechnical Engineering*, Thessaloniki .Paper #1626 : 12p.

Monaco, P., Marchetti, S., Totani, G., Calabrese, M. 2005. Sand liquefiability assessment by Flat Dilatometer Test (DMT). *Proc.16th ICSMGE*, Osaka, 4, 2693-2697.

Monaco, P. & Schmertmann, J. H. 2007. Discussion of Accounting for Soil Aging When Assessing Liquefaction Potential by Leon, E. et al. (in *J. Geotech. Geoenv. Engrg.,* ASCE, 2006, 132(3): 363-377). *J. Geotech. Geoenv. Engrg.*, ASCE, 133(9) : 1177-1179.

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. & 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. 2009. Performance based earthquake design using the CPT. Proc. of IS-Tokyo, International Conference on Performance-based design in Earthquake Geotechnical Engineering-from case history to practice. Tokyo.

Schnaid F. 2009. *In Situ Testing in Geomechanics – the main tests*. Taylor and Francis Group, London: 327 p.

Yamashita, S. Jamiolkowski M. & Lo Presti D. 2000. Stiffness Nonlinearity of Three Sands. *J. Geotech. Geoenv. Engrg.*, ASCE, 126(10): 929–938

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. *J. GGE*, ASCE, 127(4) : 297-313.

Yu, H.S. 2004. In situ soil testing: from mechanics to interpretation. 1st J.K. Mitchell Lecture, *Proc. 2nd Int. Conf. on Site Characterization ISC-2*, Porto. 1 : 3-38.