

Liquefaction Potential Evaluation by SDMT

M. Maugeri

University of Catania, Italy

P. Monaco

University of L'Aquila, Italy

Keywords: Liquefaction, Seismic Dilatometer (SDMT), Horizontal Stress Index, Shear Wave Velocity

ABSTRACT: The seismic dilatometer (SDMT) permits to obtain parallel independent evaluations of liquefaction resistance CRR from the horizontal stress index K_D and from the shear wave velocity V_S . The use of V_S for evaluating CRR is well known. Correlations CRR- K_D have also been developed in the last two decades, stimulated by the recognized sensitivity of K_D to a number of factors which are known to increase liquefaction resistance – such as stress state/history, prestraining, aging, cementation, structure – and its correlation to relative density and state parameter. The authors have collected in the recent years, using SDMT, a large amount of parallel measurements of K_D and V_S in different saturated sandy soils. Using such data an evaluation has been made of the CRR- K_D and CRR- V_S correlations. Additional verification, supported by more real-life liquefaction case histories where V_S and K_D are known, is desirable.

1 INTRODUCTION

The seismic dilatometer (SDMT), a tool initially conceived for research, is gradually entering into use in routine geotechnical investigations, allowing the parallel accumulation of numerous data.

SDMT provides, among other measurements, two parameters that previous experience has indicated as bearing a significant relationship with the liquefaction resistance of sands. Such parameters are the horizontal stress index K_D , whose use for liquefaction studies was summarized by Monaco et al. (2005), and the shear wave velocity V_S , whose relationship with liquefaction resistance has been illustrated by several Authors (Robertson et al. 1992, Robertson & Wride 1997, Andrus & Stokoe 1997, 2000, Andrus et al. 2003, 2004).

For evaluating liquefaction potential during earthquakes, within the framework of the simplified penetration tests vs case histories based approach (Seed & Idriss 1971 procedure), it is important to use redundant correlations and more than one test.

The SDMT has the advantage, in comparison with the standard penetration test SPT and the cone penetration test CPT (in its basic non-seismic configuration without V_S measurement), to measure two independent parameters, such as K_D and V_S . Hence independent evaluations of liquefaction resistance at each test depth can be obtained from K_D and from V_S according to recommended CRR- K_D and CRR- V_S

correlations. On the other hand, CPT- and SPT-based correlations are supported by large databases, while SDMT correlations are based on a smaller database.

The writers have collected in the recent years, using SDMT, a large amount of parallel measurements of K_D and V_S in different sandy soils. Taking into account such data, an evaluation of the CRR- K_D and CRR- V_S correlations has been made.

2 CURRENT METHODS FOR EVALUATING LIQUEFACTION POTENTIAL USING THE SIMPLIFIED PROCEDURE

The "simplified procedure", introduced by Seed & Idriss (1971), is currently used as a standard of practice for evaluating the liquefaction resistance of soils. This method requires the calculation of two terms: (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 overburden stresses and r_d = stress reduction coefficient dependent on depth, generally in the range ≈ 0.8 to 1.

The liquefaction resistance CRR is generally evaluated from in situ tests. The 1996 NCEER and 1998 NCEER/NSF workshops (summary report by Youd & Idriss 2001) reviewed the state-of-the-art of the Seed & Idriss (1971) "simplified procedure" and recommended revised criteria for routine evaluation of CRR from various in situ tests, including the cone penetration test CPT, the standard penetration test SPT (both widely popular, because of the extensive databases and past experience) and shear wave velocity V_s measurements.

Further contributions on CRR from CPT-SPT were recently provided by Seed et al. (2003) and Idriss & Boulanger (2004).

According to the various methods, CRR is evaluated from in situ measurements by use of charts where CRR is plotted as a function of a normalized penetration resistance or shear wave velocity. 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.

Several Authors have pointed out the importance of using redundant correlations for evaluating liquefaction potential. Robertson & Wride (1998) warned that CRR evaluated by CPT (preferred over SPT, due to its 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 '96 and '98 NCEER workshops (Youd & Idriss 2001) concluded that, where possible, two or more tests should be used for a more reliable evaluation of CRR.

Idriss & Boulanger (2004) observed that the reliability of any liquefaction evaluation depends directly on the quality of the site characterization, and it is often the synthesis of findings from several different procedures that provides the most insight and confidence in making final decisions. For this reason, the practice of using a number of in situ testing methods should continue to be the basis for standard practice, and the allure of relying on a single approach (e.g. CPT-only procedures) should be avoided.

As evaluating CRR from laboratory or calibration chamber (CC) testing, the major obstacle is to obtain 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 noted e.g. by Porcino & Ghionna 2002.

3 EVALUATION OF CRR FROM THE DMT HORIZONTAL STRESS INDEX K_D

3.1 *Theoretical/experimental basis of the correlation CRR- K_D*

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. Comparative studies have indicated that K_D is noticeably reactive to factors such as stress state/history (σ_h , OCR), pure prestraining, aging, cementation, 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, a low K_D signals that none of the above factors is high, i.e. the sand is loose, uncemented, in a low K_0 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 K_D as an index of liquefaction resistance, listed by Monaco et al. (2005), 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 Jendebly (1992) found DMT \approx twice more sensitive than CPT to densification), suggests that the DMT may also sense 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. 1) 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 a) 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. 2. This correlation has been strongly confirmed by datapoints

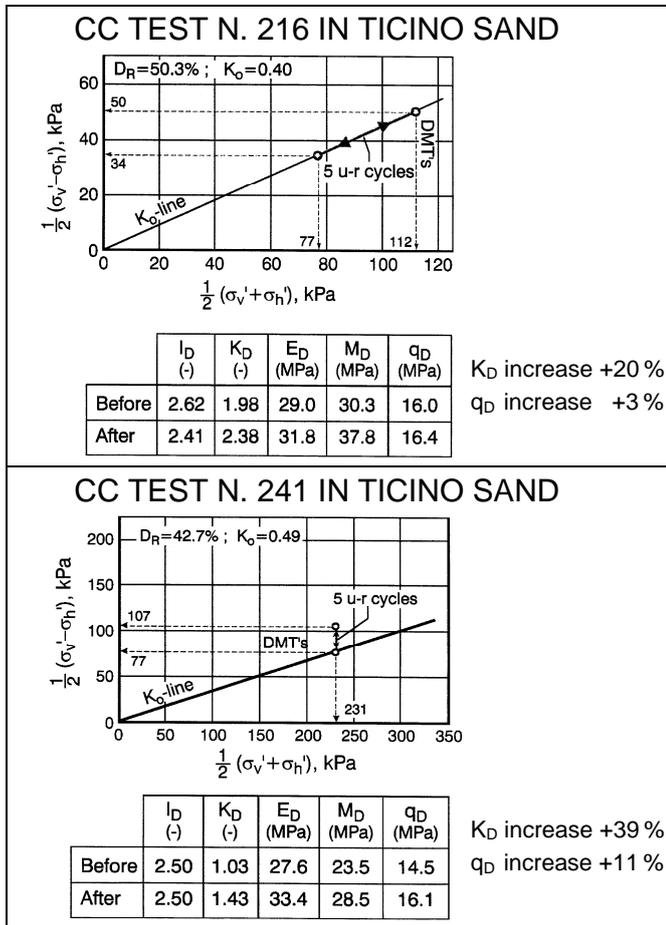


Fig. 1. Results of CC testing (prestraining cycles) showing the higher sensitivity of K_D to prestraining than penetration resistance q_D (Jamiolkowski & Lo Presti 1998)

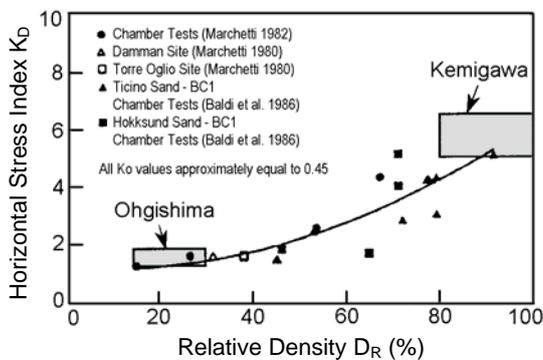


Fig. 2. Correlation K_D - D_R for NC uncemented sands (Reyna & Chameau 1991), also including Ohgishima and Kemigawa datapoints obtained by Tanaka & Tanaka (1998) on high quality frozen samples

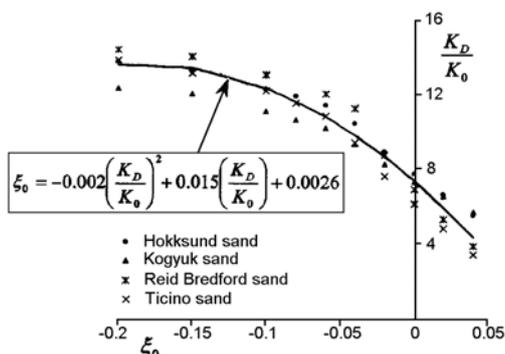


Fig. 3. Average correlation K_D - in situ state parameter ξ_0 (Yu 2004)

added by subsequent research, in particular by additional K_D - D_R datapoints (shaded areas in Fig. 2) 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 is 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 e - $\ln p'$ plot) governs the tendency of a sand to increase or decrease in volume when sheared, hence it is strongly related to liquefaction resistance. More rational methods for evaluating CRR would require the use of the state parameter (see e.g. studies by Boulanger 2003 and Boulanger & Idriss 2004, incorporating critical state concepts into the analytical framework used to evaluate liquefaction potential). Recent research supports viewing K_D from DMT as an index reflecting the in situ state parameter ξ_0 . Yu (2004) identified the average correlation K_D - ξ_0 shown in Fig. 3 (study on four well-known reference sands). Clearly relations K_D - ξ_0 as the one shown by Yu (2004) strongly encourage efforts to develop methods to assess liquefiability by DMT.

- Physical meaning of K_D

Despite the complexity of the phenomena involved in the blade penetration, the reaction of the soil against the face of the blade could be seen as an indicator of the soil reluctance to a volume reduction. Clearly a loose collapsible soil will not strongly contrast a volume reduction and will oppose a low σ'_h (hence a low K_D) to the insertion of the blade. Moreover such reluctance is determined at the existing ambient stresses increasing with depth (apart an alteration of the stress pattern in the vicinity of the blade). Thus, at least at an intuitive level, a connection is expectable between K_D and the state parameter.

3.2 CRR- K_D curves

Fig. 4 (Monaco et al. 2005) summarizes the various correlations developed to estimate CRR from K_D , expressed in form of CRR- K_D boundary curves separating possible "liquefaction" and "no liquefaction" regions.

Previous CRR- K_D curves were formulated by Marchetti (1982), Robertson & Campanella (1986) and Reyna & Chameau (1991) - the last one including liquefaction field performance datapoints (Imperial Valley, South California). Coutinho & Mitchell (1992), based on Loma Prieta (San Francisco Bay) 1989 earthquake liquefaction datapoints, proposed a slight correction to the Reyna & Chameau (1991) correlation.

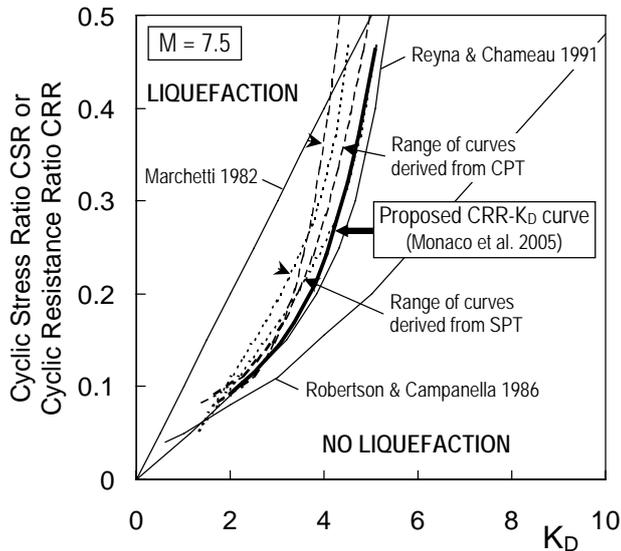


Fig. 4. CRR- K_D curves for evaluating liquefaction resistance from DMT (Monaco et al. 2005)

A new tentative correlation for evaluating CRR from K_D , to be used according to the Seed & Idriss (1971) "simplified procedure", was formulated by Monaco et al. (2005) by combining previous CRR- K_D correlations with the vast experience incorporated in current methods based on CPT and SPT (supported by extensive field performance databases), translated using the relative density D_R as intermediate parameter.

Additional CRR- K_D curves were derived by translating current CRR-CPT and CRR-SPT curves (namely the "Clean Sand Base Curves" recommended by the '96 and '98 NCEER workshops, Youd & Idriss 2001) into "equivalent" CRR- K_D curves via relative density. D_R values corresponding to the normalized penetration resistance in the CRR-CPT and CRR-SPT curves, evaluated using current correlations (D_R - q_c by Baldi et al. 1986 and Jamiolkowski et al. 1985 b, D_R - N_{SPT} by Gibbs & Holtz 1957), were converted into K_D values using the K_D - D_R correlation by Reyna & Chameau (1991) in Fig. 2. The "equivalent" CRR- K_D curves derived in this way from CPT and SPT (dashed lines in Fig. 4) plot in a relatively narrow range, very close to the Reyna & Chameau (1991) curve.

A new tentative CRR- K_D curve (bold line in Fig. 4), approximated by the equation:

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

was proposed by Monaco et al. (2005) as "slightly conservative average" interpolation of the curves derived from CPT and SPT.

The proposed CRR- K_D curve should be used in the same way as other methods based on the Seed & Idriss (1971) procedure: (1) Enter K_D in Fig. 4 (or Eq. 2) to evaluate CRR. (2) Compare CRR with the cyclic stress ratio CSR generated by the earthquake calculated by Eq. 1.

This CRR- K_D curve (Eq. 2) applies to magnitude $M = 7.5$ earthquakes, as the CRR curves for CPT and SPT from which it was derived. For magnitudes other than 7.5, magnitude scaling factors (e.g. Youd & Idriss 2001, Idriss & Boulanger 2004) should be applied.

Also, the proposed CRR- K_D curve applies properly to "clean sand" (fines content $\leq 5\%$), as its "parent" CRR-CPT and CRR-SPT curves. No further investigation on the effects of higher fines content has been carried out so far, also due to the lack of reference field performance liquefaction data.

Of course, the method is affected by the same restrictions which apply, in general, to the Seed & Idriss (1971) procedure (level to gently sloping ground, limited depth range).

4 EVALUATION OF CRR FROM SHEAR WAVE VELOCITY V_S

The use of the shear wave velocity V_S as an index of liquefaction resistance has been illustrated by several Authors (Robertson et al. 1992, Robertson & Wride 1997, Andrus & Stokoe 1997, 2000, Andrus et al. 2003, 2004).

The V_S based procedure for evaluating CRR, which follows the general format of the Seed & Idriss (1971) "simplified procedure", has advanced significantly in recent years, with improved correlations and more complete databases, and is included by the '96 and '98 NCEER workshops (Youd & Idriss 2001) in the list of the recommended methods for routine evaluation of liquefaction resistance.

According to Andrus & Stokoe (2000), the use of V_S as a field index of liquefaction resistance is soundly based, because both V_S and CRR are similarly influenced by many of the same factors (e.g. void ratio, effective confining stresses, stress history and geologic age).

As today, the V_S based correlation currently recommended is the one formulated by Andrus et al. (2004) shown in Fig. 5, modified after the correlation obtained Andrus & Stokoe (2000) for unconsolidated Holocene-age soils with various fines contents, based on a database including 26 earthquakes and more than 70 measurement sites. CRR is plotted as a function of an overburden-stress corrected shear wave velocity $V_{S1} = V_S (p_a / \sigma'_{vo})^{0.25}$, where V_S = measured shear wave velocity, p_a = atmospheric pressure (≈ 100 kPa), σ'_{vo} = initial effective vertical stress in the same units as p_a .

The relationship CRR- V_{S1} in Fig. 5, for magnitude $M_w = 7.5$, is approximated by the equation:

$$CRR_{7.5} = \left[0.022 \left(\frac{K_{a1} V_{S1}}{100} \right)^2 + 2.8 \left(\frac{1}{V_{S1}^* - K_{a1} V_{S1}} - \frac{1}{V_{S1}^*} \right) \right] K_{a2} \quad (3)$$

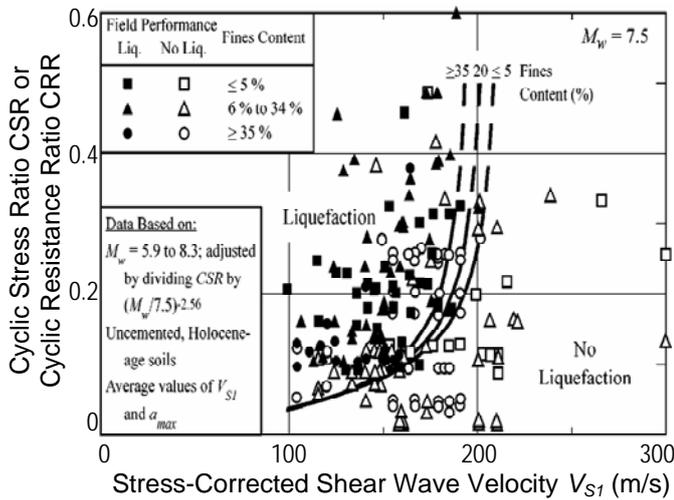


Fig. 5. Recommended curves for evaluating CRR from shear wave velocity V_S for clean, uncemented soils with liquefaction data from compiled case histories (Andrus et al. 2004)

where V_{S1}^* = limiting upper value of V_{S1} for liquefaction occurrence, assumed to vary linearly from 200 m/s for soils with fines content of 35 % to 215 m/s for soils with fines content of 5 % or less, K_{a1} = factor to correct for high V_{S1} values caused by aging, K_{a2} = factor to correct for influence of age on CRR.

Both K_{a1} and K_{a2} are 1 for uncemented soils of Holocene age. For older soils the SPT- V_{S1} equations by Ohta & Goto (1978) and Rollins et al. (1998) suggest average K_{a1} values of 0.76 and 0.61, respectively, for Pleistocene soils (10,000 years to 1.8 million years). Lower-bound values of K_{a2} are based on the study by Arango et al. (2000).

The CRR curves in Fig. 5 apply to magnitude $M_w = 7.5$ earthquakes and should be scaled to other magnitude values through use of magnitude scaling factors.

5 MINIMUM "NO LIQUEFACTION" K_D AND V_{S1} VALUES

In many everyday problems, a full seismic liquefaction analysis can be avoided if the soil is clearly liquefiable or 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 safe against liquefaction ($M = 7.5$ earthquakes) is indicated in TC16 (2001):

- Non seismic areas, i.e. very low seismic: $K_D > 1.7$
- 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 K_D values are marginal values, to be factorized by an adequate safety factor.

Such K_D values were identified based on the Reyna & Chameau (1991) CRR- K_D curve and on in-

dications given by Marchetti (1997) for non seismic areas, and were substantially confirmed by the CRR- K_D curve by Monaco et al. (2005) in Fig. 4.

Limiting upper values of V_{S1} for liquefaction occurrence for areas of different seismicity could be correspondingly derived from the CRR- V_{S1} curve (for clean sand) in Fig. 5.

6 COMPARISON OF CRR FROM K_D AND CRR FROM V_S OBTAINED BY SDMT AT VARIOUS SAND SITES

6.1 SDMT K_D - V_S database in sands

The authors have collected in the recent years a large amount of parallel measurements of K_D and V_S in sands by use of the seismic dilatometer SDMT.

The first check that the authors found natural to carry out was to see if V_S and K_D are correlated, considering the intended use of both for predicting CRR. (Such check is independent from liquefaction occurrence). Several V_{S1} - K_D data pairs obtained by SDMT in sand layers/deposits (having material index $I_D > 2$) at various sites recently investigated in Italy and Europe are plotted in Fig. 6. The data shown in Fig. 6 suggest the following observations.

- Site-specific trend of the relationship V_{S1} - K_D

Fig. 6 shows a significant scatter of the V_{S1} - K_D data-points. Based on these data, no evident correlation – not even site specific – seems to exist between V_S and K_D in sands. The "trend" of the possible relationship between V_{S1} and K_D varies from one site to another.

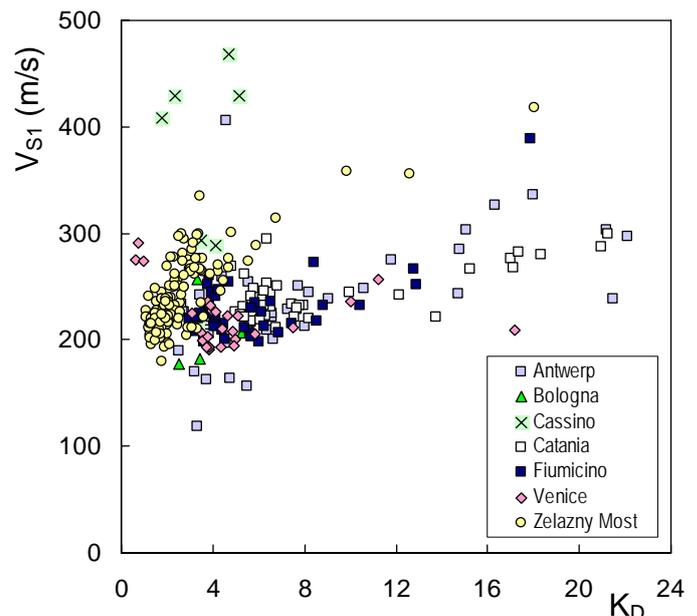


Fig. 6. V_{S1} - K_D data pairs obtained by SDMT in sands ($I_D > 2$) at various sites

E.g. at Zelazny Most, while V_{SI} varies in the range 200 to 300 m/s, K_D varies in a relatively narrow range, mostly ≈ 2 to 2.5. On the contrary at Catania, while V_{SI} is moderately variable (≈ 250 -300 m/s), K_D varies in a much larger range (≈ 5 to 20).

The high dispersion in Fig. 6 indicates that V_S and K_D reflect, besides possibly CRR, other properties, so V_S and K_D are not interchangeable for predicting CRR. Therefore different CRR estimates are to be expected.

– OCR and K_D crusts in sand

"Crust-like" K_D profiles – very similar to the typical K_D profiles found in OC desiccation crusts in clay – have been found at the top of most of the sand deposits investigated by SDMT. An example of K_D crusts (Catania) is shown in Fig. 7.

OCR in sand is often the result of a complex history of preloading or desiccation or other effects. Apart from quantitative estimates of OCR, the K_D profile generally shows some ability to reflect OCR in sand. Shallow K_D crusts may be also (in part) a consequence of their vicinity to ground surface, i.e. dilatancy effects. On the other hand, the K_D - D_R correlation by Reyna & Chameau (1991) shown in Fig. 2, developed for NC uncemented sands, provides $D_R = 100\%$ for a value of $K_D \approx 6$ -7. Values of K_D well above 6-7 have been observed in the shallow K_D crusts in most of the investigated sandy sites. This confirms that part of K_D is due to overconsolidation or cementation, rather than to D_R .

In the example shown in Fig. 7 it should be noted that, while the existence of a shallow desiccation crust in the upper ≈ 8 m is well highlighted by the K_D profile, the profile of V_S , moderately increasing with depth, is much more uniform and does not appear to reflect the shallow crust at all. A similar behavior has been observed at several of the investigated sites (e.g. Venice, Fig. 8). The fact that OCR crusts such as the one in Fig. 7 (believed by far not liquefiable) are unequivocally depicted by the high K_{DS} , but are almost unfelt by V_S , suggests a lesser ability of V_S to profile liquefiability.

– Role of the interparticle bonding

Fig. 6 shows that the Cassino data (top of Fig. 6) are somehow anomalous, in that high V_{SI} coexist with low K_{DS} . Many of the sands in that area are known to be volcanic and active in developing interparticle bonding (pozzolana).

A possible explanation could be the following: The shear wave travels fast in those sands thanks to the interparticle bonding, that is preserved because the strains are small. K_D , by contrast, is "low" because it reflects a different material, where the interparticle bonding has been at least partly destroyed by the strains produced by the blade penetration. On the other hand, pore-pressure build up and liquefaction are medium- to high-strain phenomena. Thus, for liquefiability evaluations, the K_D indications could possibly be more relevant.

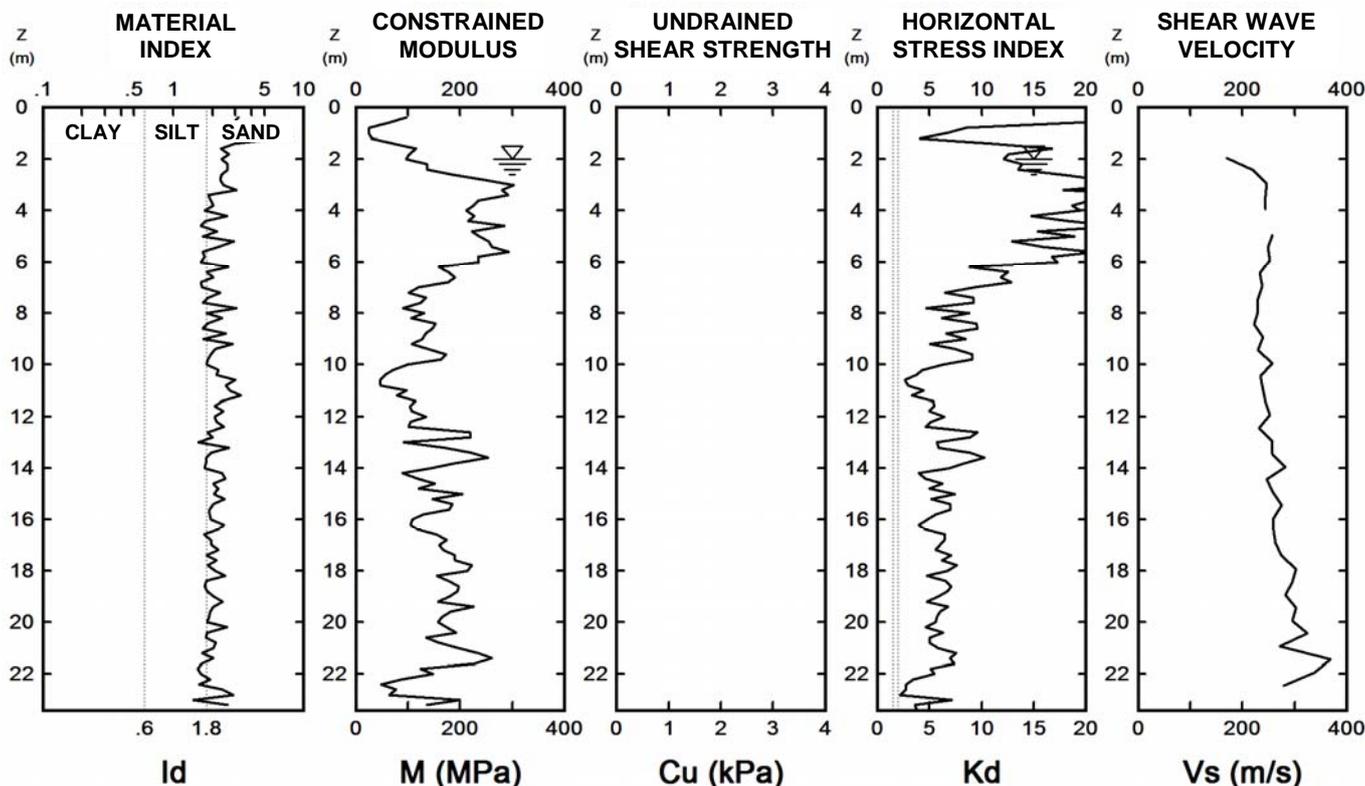


Fig. 7. SDMT results at the site of Catania (San Giuseppe La Rena), Italy

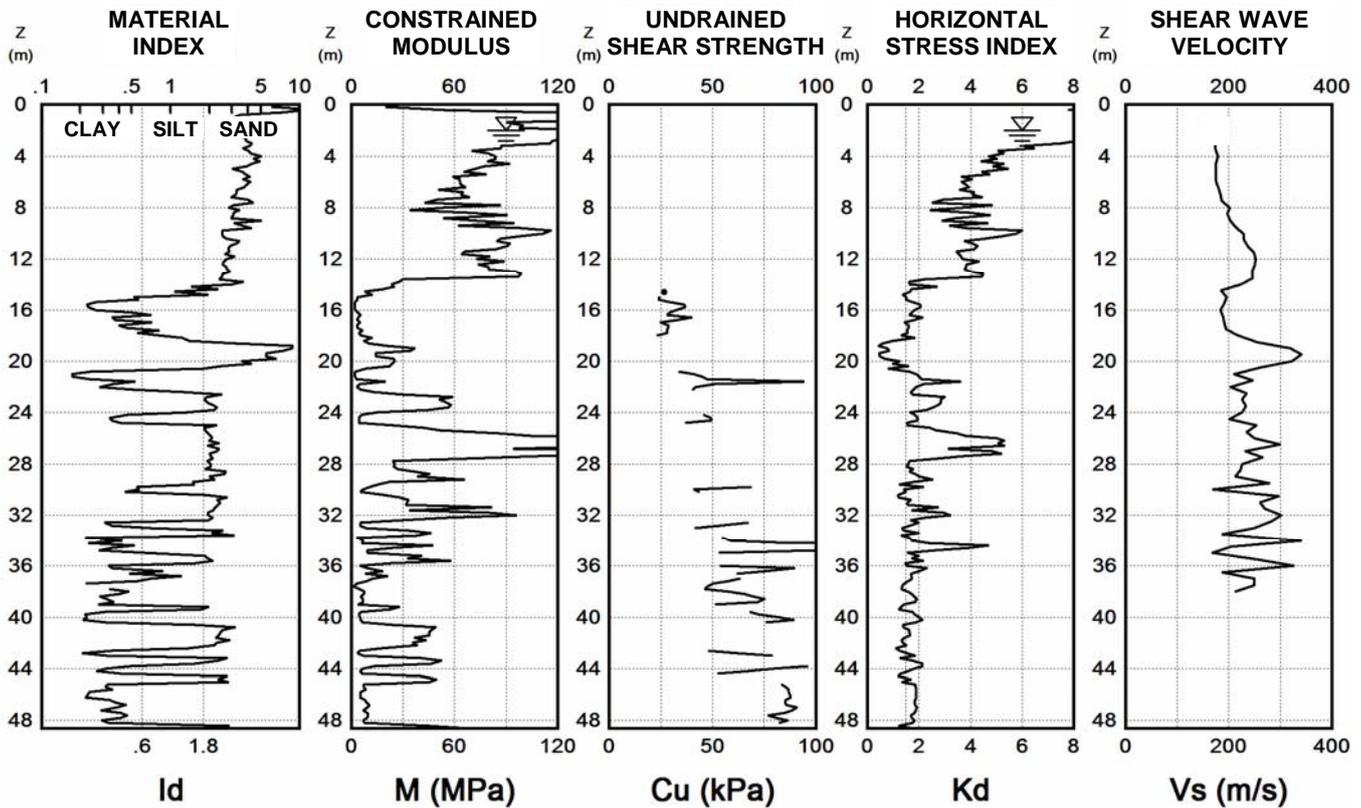


Fig. 8. SDMT results at the site of Venice, Italy

6.2 Comparison of CRR predicted by V_S and by K_D

In order to evaluate the consistency of liquefaction resistance predicted by V_S and by K_D for a given sand, the CRR- V_S method by Andrus et al. (2004) and the CRR- K_D method by Monaco et al. (2005), previously described, have been compared (indirectly) by constructing a relationship between V_{SI} and K_D implied by the CRR- V_{SI} curve for $FC \leq 5\%$ in Fig. 5 (assuming both aging correction factors K_{a1} and $K_{a2} = 1$) and the CRR- K_D curve in Fig. 4. Both curves apply to magnitude $M_w = 7.5$ earthquakes and clean sands. This CRR-equivalence curve was obtained by combining Eqns. 2 and 3 and then eliminating CRR.

The advantage of studying such V_{SI} - K_D relationship is that it provides a comparison of the two liquefaction evaluation methods without needing to calculate CSR. Hence data from sites not shaken by earthquakes can also be used to assess the consistency between the two methods. This option is particular helpful, in view of the lack of documented liquefaction case histories including DMT data.

Note that a similar procedure was adopted by Andrus & Stokoe (2000) for comparing CRR from V_S vs CRR from SPT. In that case, however, the database consisted of V_S and SPT data from various sites where liquefaction had actually occurred during past earthquakes.

The CRR-equivalence curve is shown in Fig. 9. Also shown in Fig. 9, superimposed to the curve, are field V_{SI} - K_D data pairs obtained by SDMT at several

sandy sites. Such V_{SI} - K_D data pairs are those plotted in Fig. 6, excluding the V_{SI} - K_D data pairs belonging to shallow (OC) K_D crusts, where it is often found $K_D > 10$. Also, the datapoints shown in Fig. 9 are limited to a maximum depth of 15 m (usual depth range for liquefaction occurrence), also to take into account the limits of applicability of the Seed & Idriss (1971) simplified procedure.

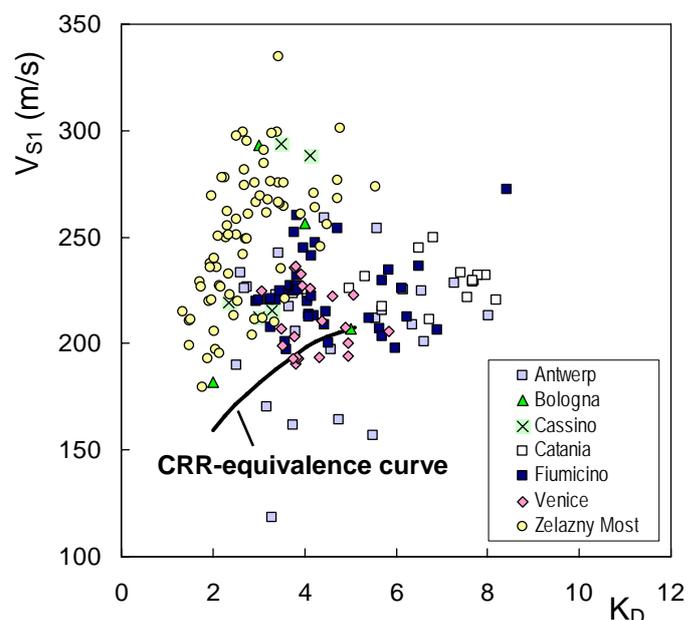


Fig. 9. CRR-equivalence curve between the correlations CRR- V_{SI} (Andrus et al. 2004) and CRR- K_D (Monaco et al. 2005) for clean sands and $M_w = 7.5$

In practice, the comparison is limited to the sand layers "more likely to liquefy", i.e. excluding OC crusts and deep layers. In this way, the scatter of the V_{SI} - K_D datapoints is somewhat reduced (though not substantially), if compared to Fig. 6.

The meaning of Fig. 9 is the following. When the V_{SI} - K_D data point lies on the CRR-equivalence curve, both the CRR- V_{SI} and the CRR- K_D methods provide similar predictions of liquefaction resistance. When the data point plots below this curve, the V_{SI} method provides the more conservative prediction. When the data point plots above the curve, the K_D method provides the more conservative prediction.

Fig. 9 shows that the two methods here considered for evaluating CRR from V_S and from K_D would provide substantially different predictions of CRR. In general, the V_{SI} method predicts CRR values less conservative than the K_D method.

Another inconsistency observed between the two methods concerns the limiting values of V_{SI} and K_D for which liquefaction occurrence can be definitely excluded (asymptotes of the CRR- V_{SI} curve in Fig. 5 and of the CRR- K_D curve in Fig. 4). Such values are respectively $V_{SI}^* = 215$ m/s and $K_D^* = 5.5$ (for clean sands and $M_w = 7.5$). E.g. at Zelazny Most (see Fig. 9), while V_{SI} values (mostly > 215 m/s) suggest "no liquefaction" in any case, K_D values (≈ 2 -2.5) indicate that liquefaction may occur above a certain seismic stress level.

7 CRR- K_D VS CRR- V_S AT LOMA PRIETA 1989 EARTHQUAKE LIQUEFACTION SITES

A preliminary validation of the proposed CRR- K_D curve (Fig. 10) was obtained by Monaco et al. (2005) from comparison with field performance liquefaction datapoints from various sites investigated after the Loma Prieta 1989 earthquake ($M_w = 7$), 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. 10 were calculated based on data contained in the report by Mitchell et al. (1994), which includes the results of DMTs performed 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.

A detailed description of the DMT investigation and an assessment of liquefaction potential based on previous CRR- K_D correlations for the Loma Prieta 1989 earthquake had been presented by Coutinho & Mitchell (1992).

Fig. 10 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 non classified as "liquefaction" or "non-liquefaction" site by Mitchell et al. (1994) plots very close to the proposed CRR- K_D boundary curve (scaled for $M_w = 7$).

V_S measurements at the liquefaction sites investigated after the Loma Prieta 1989 earthquake, reported by Mitchell et al. (1994), were obtained by seismic cone SCPT, SASW, cross-hole and up-hole tests. (The seismic dilatometer had not been developed yet at the time of the investigation).

V_S data obtained by the above methods were used to calculate the CSR- V_{SI} datapoints shown in Fig. 11. Like the corresponding CSR- K_D datapoints in Fig. 10, all the CSR- V_{SI} datapoints are located on the "liquefaction" side, on the left of the CRR- V_{SI} curve (Andrus et al. 2004), scaled for $M_w = 7$.

In this case the liquefaction potential evaluations by K_D (Fig. 10) and by V_{SI} (Fig. 11) are in reasonably good agreement, as also indicated by the "indirect" comparison shown in Fig. 12.

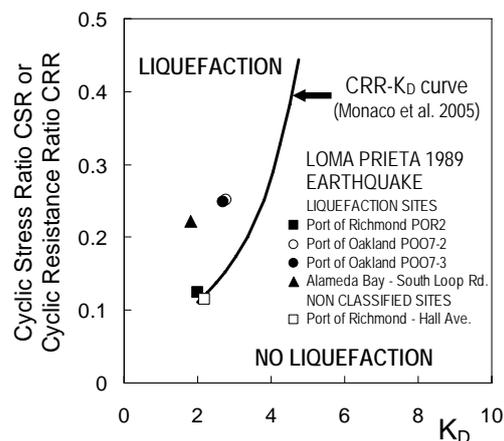


Fig. 10. Comparison of CRR- K_D curve by Monaco et al. (2005) and Loma Prieta 1989 earthquake liquefaction datapoints (after Mitchell et al. 1994)

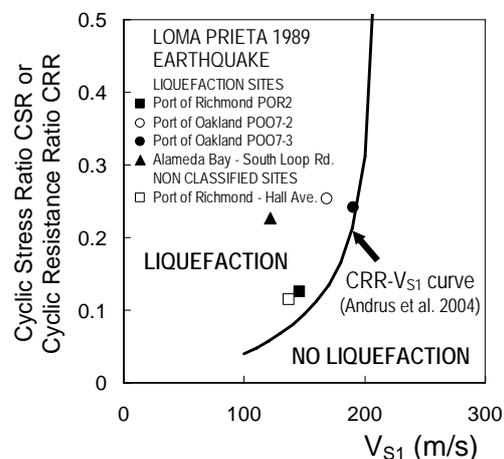


Fig. 11. Comparison of CRR- V_{SI} curve by Andrus et al. (2004) and Loma Prieta 1989 earthquake liquefaction datapoints (after Mitchell et al. 1994)

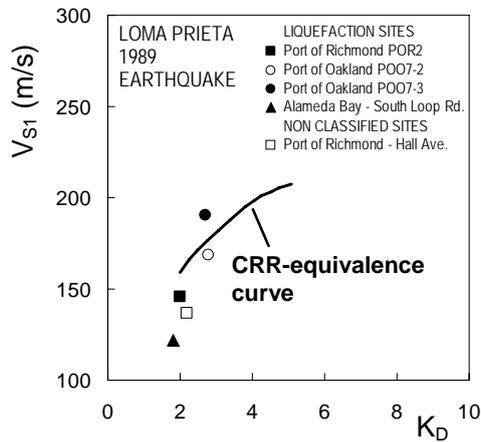


Fig. 12. Loma Prieta 1989 earthquake liquefaction V_{S1} - K_D data pairs superimposed to the CRR-equivalence curve

8 COMMENTS ON EVALUATION OF CRR FROM V_S AND K_D VS CRR FROM OTHER METHODS

The reliability of CRR evaluated from V_S compared to CRR evaluated by other methods has been discussed by various Authors.

According to Seed et al. (2003), V_S based CRR correlations provide less reliable estimates than SPT and CPT based correlations, not only because the V_S based field case history database is considerably smaller than that available for SPT and CPT correlation development, but also because V_S is a very small-strain measurement and correlates poorly with a much "larger-strain" phenomenon such as liquefaction. Seed et al. (2003) conclude that current V_S based CRR correlations are best employed either conservatively or as preliminary rapid screening tools to be supplemented by other methods.

According to Idriss & Boulanger (2004), V_S based liquefaction correlations provide a valuable tool that ideally should be used in conjunction with SPT or CPT, if possible. An interesting question, however, is which method should be given greater weight when parallel analyses by SPT, CPT, and/or V_S procedures produce contradictory results. A particularly important point to consider is the respective sensitivity of SPT, CPT and V_S measurements to the relative density of the soil. E.g. changing D_R of a clean sand from 30% to 80% would be expected to increase the SPT blowcount by a factor of ≈ 7.1 and the CPT tip resistance by a factor of ≈ 3.3 (using D_R correlations proposed by Idriss & Boulanger 2004). In contrast, the same change in D_R would be expected to change V_S only by a factor of ≈ 1.4 based on available correlations. Given that D_R is known to have a strong effect on the cyclic and post-cyclic loading behavior of a saturated sand, it appears that V_S measurements would be the least sensitive for distinguishing among different types of behavior. For this reason, Idriss & Boulanger (2004) conclude that it may be more appropriate to view the V_S case history data-

base as providing bounds that identify conditions where liquefaction is potentially highly likely, highly unlikely and where it is uncertain whether or not liquefaction should be expected. As such, there is still a need for an improved understanding of V_S based correlations and an assessment of their accuracy relative to SPT and CPT based correlations. In the mean time, Idriss & Boulanger (2004) recommend that greater weight be given to the results of SPT or CPT based liquefaction evaluations (for materials without large particle sizes).

The considerations expressed by Idriss & Boulanger (2004) for CRR from CPT/SPT vs CRR from V_S could be extended to CRR from K_D . According to the K_D - D_R correlation by Reyna & Chameau (1991) in Fig. 2, a change in D_R from 30% to 80% would increase K_D from ≈ 1.5 to ≈ 4.2 , i.e. a factor of ≈ 2.8 , indicating a higher sensitivity of K_D than V_S to relative density.

Moreover, research has shown that K_D is more sensitive than V_S to factors such as stress history, aging, cementation, structure, which greatly increase, for a given D_R , liquefaction resistance and, incidentally, are felt considerably more than by penetration resistance.

Particularly relevant to this point is the discussion by Pyke (2003). The Author recalled that Seed (1979) had listed five factors which were known, or could be reasonably assumed, to have a similar effect on penetration resistance and liquefaction potential, but these were never intended to be equalities. In particular, two of these factors – overconsolidation and aging – are likely to have a much greater effect on increasing liquefaction resistance than they do on penetration resistance. Thus soils that are even lightly OC or more than several decades old may have a greater resistance to liquefaction than indicated by the current correlations, which are heavily weighted by data from hydraulic fills and very recent streambed deposits.

Hence, in the authors' opinion, when using V_S and K_D from SDMT for parallel evaluations of liquefaction resistance, the CRR- K_D method should be given greater weight – in principle – than the V_S based method, in case of contradictory CRR predictions from the two methods. However, since the CRR- K_D correlation is based on a limited liquefaction case history database, considerable additional verification is needed.

9 CONCLUSIONS

The seismic dilatometer SDMT offers an alternative or integration to current methods for evaluating the liquefaction resistance of sands based on CPT or SPT, within the framework of the simplified penetration tests vs case histories based approach (Seed & Idriss 1971 procedure).

This opportunity appears attractive, since "redundancy" in the evaluation of CRR by more than one method is generally recommended.

Parallel independent evaluations of liquefaction resistance can be obtained from the horizontal stress index K_D and from the shear wave velocity V_S according to recommended CRR- K_D and CRR- V_S correlations. The use of V_S as an index of liquefaction resistance is well known. The basis for correlating liquefaction resistance to K_D , illustrated in detail in this paper, includes the sensitivity of K_D to a number of factors which are known to increase liquefaction resistance – such as stress state/history, prestraining, aging, cementation, structure – and its correlation to relative density and state parameter.

A preliminary validation of the recommended CRR- K_D method was obtained from comparison with field performance datapoints obtained at liquefaction sites investigated after the Loma Prieta 1989 earthquake. In that case the CRR- K_D and CRR- V_S correlations provided similar estimates.

In general, however, estimates of CRR by V_S have been found to be less conservative than by K_D , leaving open the question which CRR should be given greater weight. The authors would propend to give greater weight to CRR by K_D for the following reasons:

- OCR crusts, believed to be very unlikely to liquefy, are unequivocally depicted by the high K_D s, but are almost unfelt by V_S . This suggests a lesser ability of V_S to profile liquefiability.
- V_S measurements are made at small strains, whereas pore-pressure build up and liquefaction are medium- to high-strain phenomena. Thus in cemented soils V_S can be "misleadingly" high thanks to interparticle bonding, that is eliminated at medium and high strains. By contrast, K_D is measured at considerably higher strains than V_S .
- Many indications suggest at least some link between K_D and state parameter, which is probably one of the closest proxy of liquefiability.
- K_D is sensitive not only to D_R but also to factors such as stress history, aging, cementation, structure, that greatly increase liquefaction resistance.

The above obviously deserves considerable additional verification, supported by more well documented real-life liquefaction case histories where V_S and K_D are known.

ACKNOWLEDGMENTS

The authors wish to thank Roberto Quental Coutinho for kindly providing the Loma Prieta DMT liquefaction data report.

Diego Marchetti is also acknowledged for providing the SDMT data at various sites.

REFERENCES

- Andrus, R.D. & Stokoe, K.H., II. 1997. Liquefaction resistance based on shear wave velocity. *Proc. NCEER Workshop on Evaluation of Liquefaction Resistance of Soils, Technical Report NCEER-97-0022*, T.L. Youd & I.M. Idriss, eds., National Center for Earthquake Engineering Research, Buffalo, 89-128.
- Andrus, R.D. & Stokoe, K.H., II. 2000. Liquefaction resistance of soils from shear-wave velocity. *Jnl GGE, ASCE*, 126(11), 1015-1025.
- Andrus, R.D., Stokoe, K.H., II, Chung, R.M. & Juang, C.H. 2003. Guidelines for evaluating liquefaction resistance using shear wave velocity measurements and simplified procedures. *NIST GCR 03-854*, National Institute of Standards and Technologies, Gaithersburg.
- 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.
- Arango, I., Lewis, M.R. & Kramer, C. 2000. Updated liquefaction potential analysis eliminates foundation retrofitting of two critical structures. *Soil Dyn. Earthquake Eng.*, 20, 17-25.
- 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.
- Boulanger, R.W. 2003. High overburden stress effects in liquefaction analysis. *Jnl GGE, ASCE*, 129(12), 1071-1082.
- Boulanger, R.W. & Idriss, I.M. 2004. State normalization of penetration resistance and the effect of overburden stress on liquefaction resistance. *Proc. 11th Int. Conf. on Soil Dynamics & Earthquake Engineering & 3rd Int. Conf. on Earthquake Geotechnical Engineering*, Berkeley, 484-491.
- Coutinho, R.Q. & Mitchell, J.K. 1992. Evaluation of Dilatometer Based Methods for Liquefaction Potential Assessment Using Loma Prieta Earthquake Data. Internal Report of Research Project (unpublished).
- 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. *Canadian Geotech. Jnl*, 31(1), 91-103.
- Idriss, I.M. & Boulanger, R.W. 2004. Semi-empirical procedures for evaluating liquefaction potential during earthquakes. *Proc. 11th Int. Conf. on Soil Dynamics & Earthquake Engineering & 3rd Int. Conf. on Earthquake Geotechnical Engineering*, Berkeley, 32-56.
- Jamiolkowski, M., Baldi, G., Bellotti, R., Ghionna, V. & Pasqualini, E. 1985 a. Penetration resistance and liquefaction of sands. *Proc. XI ICSMFE*, San Francisco, 4, 1891-1896.
- Jamiolkowski, M., Ladd, C.C., Germaine, J.T. & Lancellotta, R. 1985 b. 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.
- Jendebly, L. 1992. Deep Compaction by Vibrowing. *Proc. Nordic Geotechnical Meeting NGM-92*, 1, 19-24.
- 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.

- Monaco, P., Marchetti, S., Totani, G. & Calabrese, M. 2005. Sand liquefiability assessment by Flat Dilatometer Test (DMT). *Proc. XVI ICSMGE*, Osaka, 4, 2693-2697.
- 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.
- Ohta, Y. & Goto, N. 1978. Empirical shear wave velocity equations in terms of characteristic soil indexes. *Earthquake Eng. Struct. Dyn.*, 6, 167-187.
- Pike, R. 2003. Discussion of "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils" by Youd, T.L. et al. (in *Jnl GGE ASCE*, 2001, 127(10), 817-833). *Jnl GGE ASCE*, 129(3), 283-284.
- 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. & 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., Woeller, D.J. & Finn, W.D.L. 1992. Seismic cone penetration test for evaluating liquefaction potential under cyclic loading. *Canadian Geotech. Jnl*, 29, 686-695.
- Robertson, P.K. & Wride, C.E. 1997. Cyclic liquefaction and its evaluation based on SPT and CPT. *Proc. NCEER Workshop on Evaluation of Liquefaction Resistance of Soils, Technical Report NCEER-97-0022*, T.L. Youd & I.M. Idriss, eds., National Center for Earthquake Engineering Research, Buffalo, 41-88.
- Robertson, P.K. & Wride, C.E. 1998. Evaluating cyclic liquefaction potential using the cone penetration test. *Canadian Geotech. Jnl*, 35(3), 442-459.
- Rollins, K.M., Diehl, N.B. & Weaver, T.J. 1998. Implications of V_S -BPT (N_1)₆₀ correlations for liquefaction assessment in gravels. *Geotechnical Earthquake Engineering and Soil Dynamics III*, Geotech. Special Pub. No. 75, P. Dakoulas, M. Yegian & B. Holtz, eds., ASCE, I, 506-517.
- 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. 1979. Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes. *Jnl GED*, ASCE, 105(2), 201-255.
- Seed, R.B., Cetin, K.O., Moss, R.E.S., Kammerer, A.M., Wu, J., Pestana, J.M., Riemer, M.F., Sancio, R.B., Bray, J.D., Kayen, R.E. & Faris, A. 2003. Recent advances in soil liquefaction engineering: a unified and consistent framework. *Keynote Presentation 26th Annual ASCE Los Angeles Geotechnical Spring Seminar, Long Beach*. Report No. EERC 2003-06.
- Seed, H.B. & Idriss, I.M. 1971. Simplified procedure for evaluating soil liquefaction potential. *Jnl GED*, ASCE, 97(9), 1249-1273.
- 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. *Proc. Int. Conf. on In Situ Measurement of Soil Properties and Case Histories, Bali*, 95-131.
- 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.