EVALUATING LIQUEFACTION POTENTIAL BY SEISMIC DILATOMETER (SDMT) ACCOUNTING FOR AGING/STRESS HISTORY

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ABSTRACT

The seismic dilatometer (SDMT) permits to obtain two parallel independent estimates of liquefaction resistance CRR, one from the horizontal stress index K_D and one from the shear wave velocity V_S. The use of V_S for evaluating CRR is well known. Correlations CRR-K_D have been developed in the last two decades, stimulated by the recognized sensitivity of K_D to factors which are known to increase liquefaction resistance – stress history, prestraining/aging, cementation, structure – and its correlation to relative density and state parameter. This paper provides further insight into the ability of K_D to reflect aging in sands, a factor that recent research has indicated as having a first order of magnitude influence on liquefaction behaviour. In addition, recent SDMT experience has pointed out the high sensitivity of K_D to "non-textbook" OCR crusts in NC sands. These findings lend additional support to a well-based CRR-K_D correlation.

Keywords: Liquefaction, Aging, Seismic Dilatometer, Horizontal Stress Index, Shear Wave Velocity

INTRODUCTION

The seismic dilatometer (SDMT), initially conceived for research, is gradually entering into use in current site investigation practice. SDMT routinely provides, among other measurements, pairs of profiles of two parameters – the horizontal stress index K_D and the shear wave velocity V_S – that previous experience has indicated as bearing a significant relationship with the liquefaction resistance of sands. Hence SDMT permits to obtain two parallel independent estimates of CRR from K_D and V_S, using CRR-K_D and CRR-V_S correlations, where CRR is the cyclic liquefaction resistance – a basic input in the commonly used Seed and Idriss (1971) simplified procedure. The use of V_S for liquefaction is well known. Correlations CRR-K_D have 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 – difficult to sense by other tests – such as stress history, prestraining/aging, cementation, structure, and by K_D's relationship with relative density and state parameter. A summary of the available knowledge on the subject and the latest version of the CRR-K_D correlation, based on all previous data, can be found in Monaco et al. (2005). Comparisons of CRR values predicted by CRR-K_D and CRR-V_S correlations were presented by Maugeri and Monaco (2006). This paper provides further insight into the ability of the SDMT, in particular the K_D parameter, to reflect aging, stress history and other characteristics that have a major influence on the liquefaction resistance of natural sand deposits, as emphasized by recent research.

THE SEISMIC DILATOMETER (SDMT)

The seismic dilatometer (SDMT) is a combination of the standard flat dilatometer (DMT) equipment (Marchetti 1980, TC16 2001) with a seismic module for the down-hole measurement of the shear wave velocity V_S. First introduced by Hepton (1988), the SDMT was subsequently improved at Georgia Tech, Atlanta, USA (Martin and Mayne 1997, 1998, Mayne et al. 1999).

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A new "true-interval" SDMT system (Figure 1) has been recently developed in Italy. The seismic module (Figure 1a) is a cylindrical element placed above the DMT blade, equipped with two receivers located at 0.5 m distance. The signal is amplified and digitized at depth. The shear wave source at the surface (Figure 1b) is a pendulum hammer which hits horizontally a steel rectangular base pressed vertically against the soil and oriented with its long axis parallel to the axis of the receivers, so that they can offer the highest sensitivity to the generated shear wave. The "true-interval" two-receiver test configuration avoids possible inaccuracy in the determination of the "zero time" at the hammer impact, sometimes observed in the "pseudo-interval" one-receiver configuration. Moreover, the couple of seismograms recorded by the two receivers at a given test depth (Figure 1b) corresponds to the same hammer blow and not to different blows in sequence, not necessarily identical. Hence the repeatability of V_S measurements is considerably improved (observed V_S repeatability about 1 m/s). The shear wave velocity V_S (Figure 1b) is obtained as the ratio between the difference in distance between the source and the two receivers ($S_2 - S_1$) and the delay of the arrival of the impulse from the first to the second receiver (Δt). V_S measurements are obtained every 0.5 m of depth. The determination of the delay from the seismograms obtained by SDMT is generally well-conditioned (Figure 1c). V_S measurements obtained by SDMT have been validated by comparison with V_S obtained by other methods at various test sites. As an example, Figure 2 shows good agreement between the profiles of V_S obtained by SDMT and by seismic cone (SCPT), cross-hole and SASW at the site of Fucino (Italy), a well-documented NC clay research test site, extensively investigated at the end of the '80s (AGI 1991).
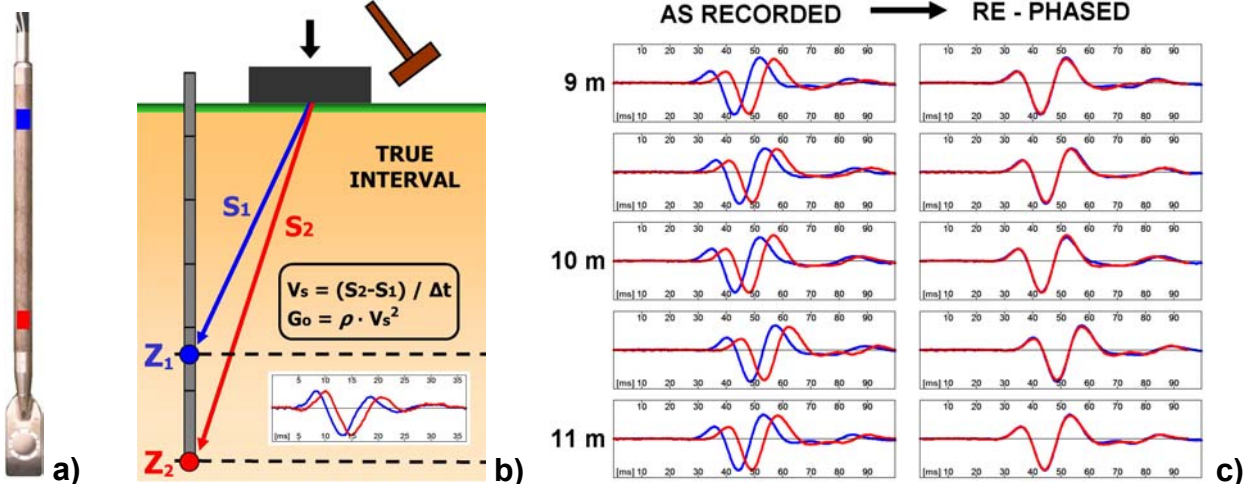

Figure 1. (a) DMT blade and seismic module. (b) Schematic layout of the seismic dilatometer test. (c) Example of seismograms obtained by SDMT at various test depths at the site of Fucino, Italy – as recorded and re-phased according to the calculated delay.
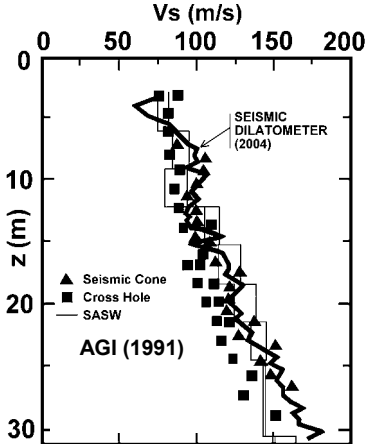

Figure 2. Comparison of V_S profiles obtained by SDMT and by other in situ seismic tests (AGI 1991) at the research site of Fucino, Italy

CURRENT METHODS FOR EVALUATING LIQUEFACTION POTENTIAL

The "simplified procedure", introduced by Seed and Idriss (1971), is currently used as a standard of practice for evaluating the liquefaction potential. 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 equation:

$$\text{CSR} = \tau_{av}/\sigma'_{v0} = 0.65\,(a_{max}/g)\,(\sigma_{v0}/\sigma'_{v0})\,r_d \tag{1}$$

where τ_{av} = average cyclic shear stress, a_{max} = peak horizontal acceleration at ground surface generated by the earthquake, g = acceleration of gravity, σ_{v0} and σ'_{v0} = total and effective overburden stresses and r_d = stress reduction coefficient dependent on depth, mostly in the range ≈ 0.8 to 1. The liquefaction resistance CRR is generally evaluated from in situ tests. Procedures for evaluating CRR from the cone penetration test CPT, the standard penetration test SPT (both widely popular, because of the extensive databases and past experience) and V_S measurements were recommended by the 1996 NCEER and 1998 NCEER/NSF workshops (Youd and Idriss 2001). Further contributions on CRR from CPT-SPT can be found e.g. in Seed et al. (2003) and Idriss and Boulanger (2004). CRR is generally evaluated from in situ measurements (normalized to overburden stress) by use of charts in which the CRR curves separate two regions – "liquefaction" and "no liquefaction" – including data obtained at sites where surface effects of liquefaction were or were not observed in past earthquakes.

The use of "redundant" correlations for a more reliable estimate of CRR is generally recommended. E.g. Robertson and Wride (1998) recommended to estimate CRR by more than one method for medium- to high-risk projects, while CRR from CPT-only (preferred to SPT) may be adequate for low-risk, small-scale projects. The '96-'98 NCEER workshops (Youd and Idriss 2001) recommended that, where possible, two or more tests should be used. Idriss and Boulanger (2004) warned that using a number of in situ tests should be the basis for standard practice and the allure of relying on a single approach (e.g. CPT-only) should be avoided.

As to evaluating CRR from laboratory or calibration chamber 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 (Porcino and Ghionna 2002), since in situ fabric/cementation/aging affect greatly CRR.

EVALUATION OF CRR FROM THE SHEAR WAVE VELOCITY V_S

The use of V_S as an index of liquefaction resistance has been illustrated by several Authors. The most popular CRR-V_S correlation (Figure 3) was proposed by Andrus and Stokoe (2000) for uncemented Holocene-age soils, based on a database including 26 earthquakes and more than 70 test sites. CRR is obtained as a function of an overburden-stress corrected shear wave velocity $V_{S1} = V_S\,(p_a/\sigma'_{v0})^{0.25}$, where V_S = measured shear wave velocity, p_a = atmospheric pressure (≈ 100 kPa), σ'_{v0} = initial effective vertical stress (same units as p_a). Andrus et al. (2004) introduced age correction factors to extend the original correlation by Andrus and Stokoe (2000) to soils older than Holocene. Their CRR-V_{S1} relationship (curves in Figure 3, for various fines contents) is approximated by the equation:

$$\text{CRR} = \left[0.022\left(\frac{K_{a1}V_{S1}}{100}\right)^2 + 2.8\left(\frac{1}{V_{S1}^* - K_{a1}V_{s1}} - \frac{1}{V_{S1}^*}\right)\right]K_{a2} \tag{2}$$

where V_{S1}^* = limiting upper value of V_{S1} for liquefaction occurrence ($V_{S1}^* = 200$ m/s for the curve for fines content ≥ 35 %, $V_{S1}^* = 215$ m/s for the curve for fines content ≤ 5 %, V_{S1}^* varies linearly from 200 to 215 m/s for fines content between 35 and 5 %), K_{a1} = factor to correct for high V_{S1} values caused by aging, K_{a2} = factor to correct for influence of age on CRR. Magnitude scaling factors should be used to scale Eq. 2 (for magnitude $M_w = 7.5$ earthquakes) to different magnitudes. Both K_{a1} and K_{a2} are 1 for
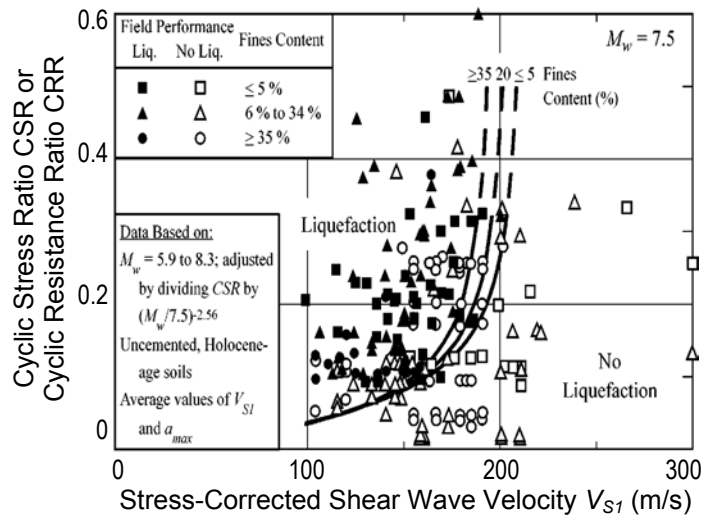
Figure 3. Curves for evaluating CRR from shear wave velocity V_S for clean, uncemented soils with liquefaction data from compiled case histories (Andrus and Stokoe 2000)

uncemented soils of Holocene age. For older soils, suggested K_{a1} values (mostly in the range 0.6 to 0.8) are derived from SPT-V_{S1} relationships (e.g. Ohta and Goto 1978, Rollins et al. 1998, or site specific). Lower-bound values of K_{a2} (1.1 to 1.5) are based on the study by Arango et al. (2000). Andrus et al. (2004) remarked, however, the high associated uncertainty and the need of additional work to quantify the influence of age on CRR, as well as on V_S.

EVALUATION OF CRR FROM THE DMT HORIZONTAL STRESS INDEX K_D

Marchetti (1982) and later studies (Robertson and Campanella 1986, Reyna and Chameau 1991) suggested that the horizontal stress index K_D from DMT ($K_D = (p_0 - u_0) / \sigma'_{v0}$) is a suitable index parameter of liquefaction resistance. Comparative studies have indicated that K_D is noticeably reactive to stress history, prestraining/aging, cementation, structure – all factors increasing liquefaction resistance (scarcely felt by q_c from CPT, see e.g. Huang and Ma 1994, and in general by cylindrical-conical probes). As noted by Robertson and 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 findings supporting a well-based CRR-K_D correlation (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 Jendeby 1992 found DMT ≈ twice more sensitive than CPT), suggests that the DMT may also sense sand liquefiability. A liquefiable sand may be regarded as a "negatively compacted" sand, plausibly the DMT sensitivity holds both in the positive and the negative range.

Sensitivity of DMT to prestraining
CC research by Jamiolkowski and Lo Presti (1998) has shown that K_D is much more sensitive to cyclic prestraining – one of the most difficult effects to detect by any method – than penetration resistance. Given the strong link of prestraining with aging, this point is discussed in more detail in the Section "Sensitivity of K_D to aging".

Correlation K_D - Relative density
The correlation by Reyna and Chameau (1991) for deriving the relative density D_R from K_D in NC uncemented sands (Figure 4a) has been strongly confirmed by subsequent research, in particular by additional K_D-D_R datapoints (shaded areas in Figure 4a) obtained by Tanaka and Tanaka (1998) at the sites of Ohgishima and Kemigawa, where D_R was determined on high quality frozen samples.
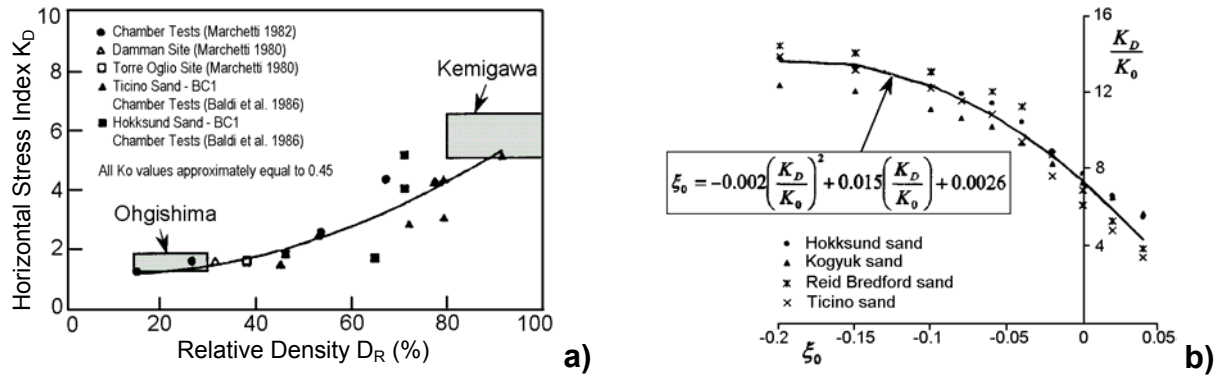
Figure 4. (a) Correlation K_D-D_R for NC uncemented sands (Reyna and Chameau 1991), also including Ohgishima and Kemigawa datapoints obtained by Tanaka and Tanaka (1998) on high quality frozen samples. (b) Average correlation K_D- in situ state parameter ξ_0 (Yu 2004).

Correlation K_D - In situ state parameter

The state parameter concept is an important step forward in characterizing soil behaviour, combining the effects of both relative density and stress level in a rational way. The state parameter (vertical distance between current state and 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 (e.g. Boulanger 2003, Boulanger and Idriss 2004). 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 Figure 4b (study on four well-known reference sands). 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 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 blade insertion. Moreover such *reluctance* is determined at 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.

Figure 5a (Monaco et al. 2005) summarizes the various correlations developed for estimating CRR from K_D, to be used according to the "simplified procedure". Previous CRR-K_D correlations were formulated by Marchetti (1982), Robertson and Campanella (1986) and Reyna and Chameau (1991) – the last one, including Imperial Valley (California) liquefaction field performance datapoints, was slightly corrected by Coutinho and Mitchell (1992) based on Loma Prieta 1989 earthquake datapoints. The latest CRR-K_D correlation (bold curve in Figure 5a), approximated by the equation:

$$\text{CRR} = 0.0107\,K_D^3 - 0.0741\,K_D^2 + 0.2169\,K_D - 0.1306 \qquad (3)$$

was formulated by Monaco et al. (2005) by combining previous CRR-K_D curves with the vast experience incorporated in current methods based on CPT and SPT (supported by extensive field performance databases), translated using the relative density as intermediate parameter. This CRR-K_D curve applies to magnitude M = 7.5 earthquakes (magnitude scaling factors should be applied for other magnitudes) and "clean sand" (no further investigation into the effects of higher fines content is currently available). The CRR-K_D correlation by Monaco et al. (2005) was preliminarily validated by comparison with field performance datapoints from various liquefaction sites investigated after the Loma Prieta 1989 earthquake (M_w = 7), in the San Francisco Bay area, one of the few documented liquefaction cases including DMT data (reports by Coutinho and Mitchell 1992, Mitchell et al. 1994).
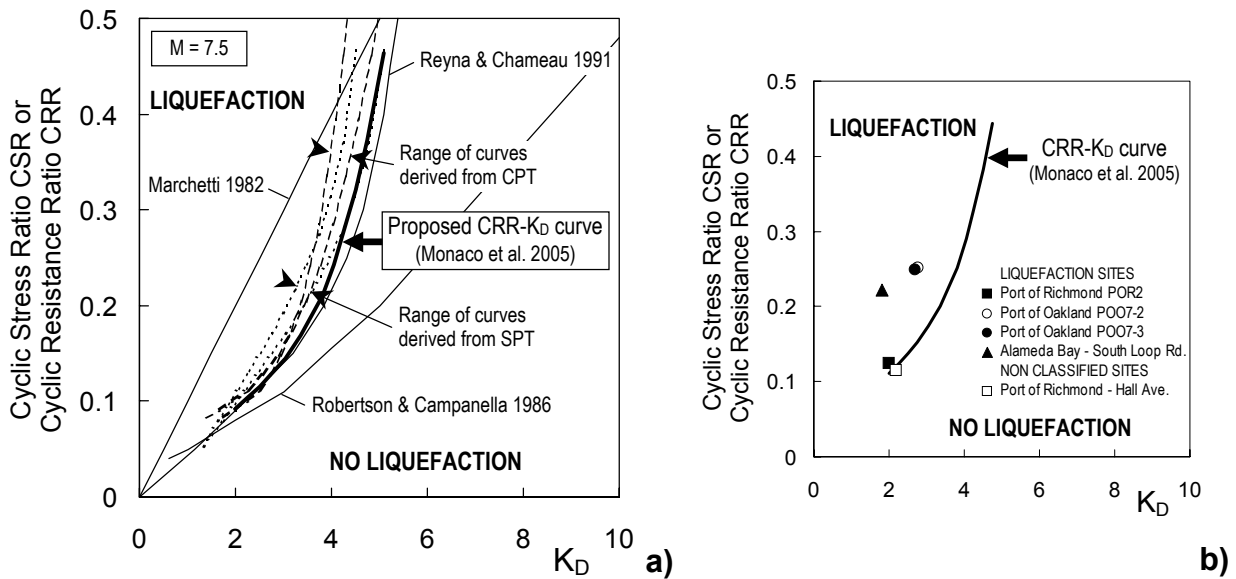
Figure 5. (a) CRR-K_D curves for evaluating liquefaction resistance from DMT (Monaco et al. 2005). (b) Comparison of CRR-K_D curve by Monaco et al. (2005) and Loma Prieta 1989 earthquake liquefaction datapoints (after Mitchell et al. 1994)

Figure 5b shows that datapoints obtained at sites where liquefaction had occurred (mostly in hydraulic sandfills) are correctly located in the "liquefaction" side. One datapoint relevant to a non classified site, with uncertain liquefaction evidence, plots very close to the CRR-K_D boundary curve (scaled for $M_w = 7$). The convergence in a narrow band of the more recent CRR-K_D curves, compared to earlier curves, in Figure 5a encourages the use of K_D to estimate CRR. However, since the CRR-K_D correlation is based on a limited real liquefaction case history database, considerable additional verification is needed.

INFLUENCE OF AGING/STRESS HISTORY ON LIQUEFACTION RESISTANCE

Several investigators have noted that the liquefaction resistance increases markedly with age. Aging in sands is generally attributed to chemical factors (formation of post-sedimentation cementing bonds at particle contacts) and mechanical factors (slippage of grains during secondary consolidation). The '96-'98 NCEER workshops (Youd and Idriss 2001) noted however that, though qualitative time-dependent increases have been documented, few quantitative data have been collected. Hence, in absence of verified correction factors for age, "engineering judgment is required to estimate the liquefaction resistance of sediments more than a few thousand years old".

Pyke (2003) observed that "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".

Leon et al. (2006) explicitly highlighted the importance of aging when assessing liquefaction potential. Similarly to Pyke (2003), they pointed out that commonly used correlations for estimating CRR (from SPT, CPT, V_S) were derived mostly for young or freshly deposited sands – where the aging effect is negligible or small, 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. The inability of SPT and CPT to capture the effects of aging may lead to excessively conservative estimates of liquefaction resistance. In the sand deposits 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 % (a huge underestimation, even in geotechnical engineering). Similarly, Lewis et al. (1999) remarked that the use of empirical correlations developed for young soil deposits – which do not account for increased resistance with increased age – in older sands will, at best, result in very conservative and uneconomical design, at worst in very costly remedial measures or cancellation of a project.
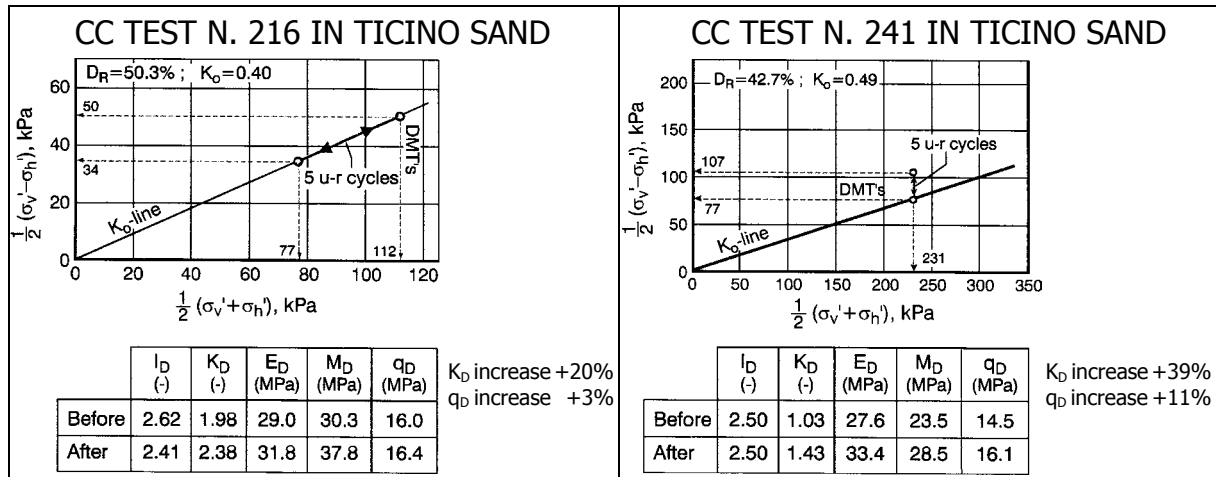
As observed by Monaco and Schmertmann (2007), giving insufficient weight to aging, or disregarding aging, is equivalent to omitting a primary parameter in a CRR correlation. No wonder, then, that such an omission leads to possibly overconservative CRR values. Also, the omission of the parameter *aging* may be an important contributor of 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 and Idriss 2001).

A way out to take into account the effects of aging, proposed by various Authors (including e.g. Andrus et al. 2004 for CRR-V_S), is to correct current CRR correlations, developed for young soils, by means of correction factors depending on the age of the deposit. The method proposed by Leon et al. (2006), using correction factors based on sand sites in South Carolina, rightly yields less conservative CRR predictions in these soils. However, for other deposits, specific factors should in general be developed, because the CRR gain due to aging can depend on many ambient factors and thus can vary widely from site to site. A desirable alternative would be using a testing tool appreciably more sensitive to aging – besides being sensitive to the various factors that are known to increase CRR. It is of interest to note that Jamiolkowski et al. (1985) had already pointed out, many years ago, that "reliable predictions of liquefaction resistance of sand deposits having complex stress-strain history would require the development of some new in situ device [other than CPT or SPT], more sensitive to the effects of past stress-strain histories".

SENSITIVITY OF K_D TO AGING

The higher sensitivity of the DMT to aging (see Monaco and Schmertmann 2007) was demonstrated by the large calibration chamber research work by Jamiolkowski and Lo Presti (1998). They showed (Figure 6) that K_D is much more sensitive to cyclic prestraining than the penetration resistance q_D of the DMT blade, and presumably also of the CPT cone. The increase in K_D caused by prestraining was found $\approx$ 3 to 7 times the increase in q_D. Two calibration chamber experiments involved stage testing and an extrapolation: (a) Filling and K_0 pressurization of the chamber. (b) Blade penetration and measuring q_D and K_D every 100 mm penetration to mid-chamber depth. (c) Five cycles of prestressing/prestraining the sand in the chamber. (d) Repeating (b) for the remaining depth of the chamber. (e) Down and up extrapolation for the q_D and K_D values at mid depth. (f) Comparing the values before and after the prestraining. The prestraining consisted of increasing both the vertical and horizontal stress according to the stress paths in Figure 6, then removing both increases and thereby returning to the same initial stress state before the DMT testing.

Cycles of prestrain 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). Prestrain just speeds the slippage of particles vs. that which would otherwise take place over long periods of time. It is also well known that cyclic prestrain, just as aging, increases the liquefaction resistance, due to the similarity of the mechanism (e.g. Triantafyllidis et al. 2004). Arguably K_D is much more sensitive to *aging* than penetration resistance. It is possible that current CRR correlations based on K_D, or future refined versions, will not need the introduction of "age correction factors", because part of the aging effects are already "incorporated" in K_D. On the other hand K_D is, at the same time, sensitive to factors such as stress history and cementation, long recognized as important to liquefaction behaviour.

CC TEST N. 216 IN TICINO SAND

$D_R=50.3\%$; $K_o=0.40$

(graph: $\frac{1}{2}(\sigma_v'-\sigma_h')$, kPa vs $\frac{1}{2}(\sigma_v'+\sigma_h')$, kPa; K_o-line; 5 u-r cycles; DMT's; values 50, 34, 77, 112)

	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

$D_R=42.7\%$; $K_o=0.49$

(graph: $\frac{1}{2}(\sigma_v'-\sigma_h')$, kPa vs $\frac{1}{2}(\sigma_v'+\sigma_h')$, kPa; K_o-line; 5 u-r cycles; DMT's; values 107, 77, 231)

	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%

Figure 6. Calibration chamber test results (prestraining cycles) showing the higher sensitivity of K_D to prestraining than penetration resistance q_D (Jamiolkowski and Lo Presti 1998)

COMPARISONS OF CRR-K_D AND CRR-V_S OBTAINED BY SDMT AT VARIOUS SITES

Maugeri and Monaco (2006) presented a comparison of CRR-K_D and CRR-V_S correlations based on a large amount of parallel measurements of K_D and V_S obtained by SDMT at several sandy sites. They found that current methods for evaluating CRR from V_S and K_D would provide, in general, substantially different predictions (generally CRR from V_S was found less conservative or "more optimistic" than CRR from K_D). They also showed that no evident correlation, not even site specific, exists between V_S and K_D in sands (as one could expect, considering the intended use of both for predicting CRR). Hence V_S and K_D seem to reflect, besides possibly CRR, other properties and are not interchangeable for predicting CRR, likely resulting in different CRR estimates. The above opens the question "which CRR should be given greater weight" when parallel analyses by K_D and V_S produce contradictory results. The considerations which follow are intended to provide a contribution to a possible discussion on this topic.

OCR and K_D crusts in sand
The K_D profile generally shows some ability to reflect OCR in sands, often resulting from a complex history of preloading, desiccation and/or other effects. "Crust-like" K_D profiles (see example in Figure 7), 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 investigated sand deposits. In many cases the K_D values in the shallow crusts were found much higher than $K_D \approx 6\text{-}7$, corresponding to $D_R = 100\%$ according to the K_D -D_R correlation by Reyna and Chameau (1991) for NC uncemented sands (Figure 4a). These values confirm that part of K_D is due to overconsolidation or cementation or aging, rather than to D_R. Note in Figure 7 that, while the existence of a shallow crust is well highlighted by the K_D profile, the profile of V_S is much more uniform and does not appear to reflect the shallow crust at all. Such capability of K_D to reflect stress history is important for liquefaction. The fact that OCR crusts – 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
The data in Figure 8 (Cassino, Italy) are somehow anomalous, in that relatively high V_S coexist with very low values of K_D and soil moduli M. Many volcanic sands in that area (pozzolana) are known to be active in developing interparticle bonding. A possible explanation could be the following. The shear wave travels fast in those sands thanks to the interparticle bonding, that is preserved at small strains. By contrast K_D is "low" because it reflects a different material, where the interparticle bonding has been at least partly destroyed by the blade penetration. As noted by Andrus and Stokoe (2000), one concern when using V_S to evaluate liquefaction resistance is that V_S measurements are made at
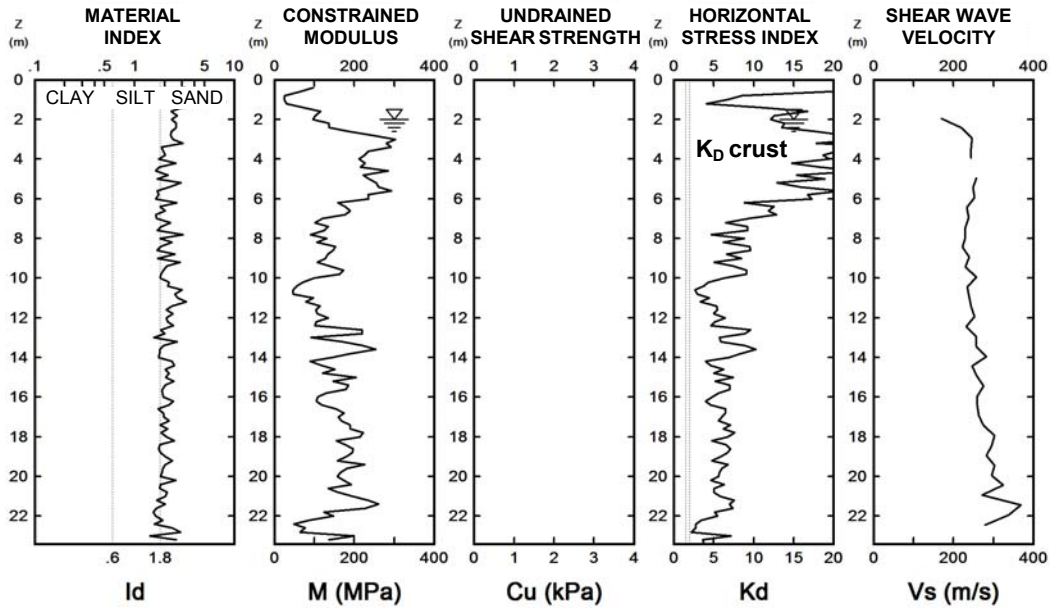
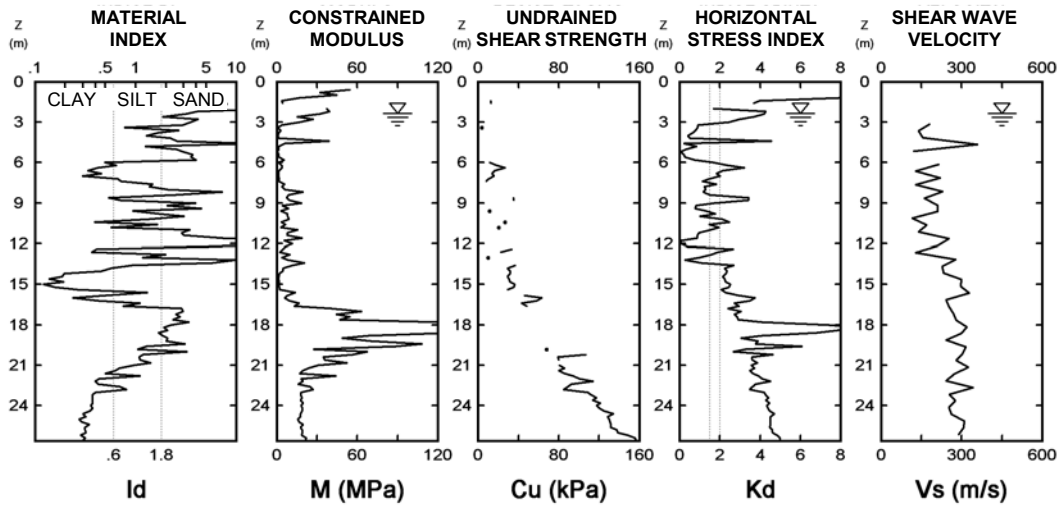**Figure 7. SDMT results at the site of Catania (San Giuseppe La Rena), Italy**

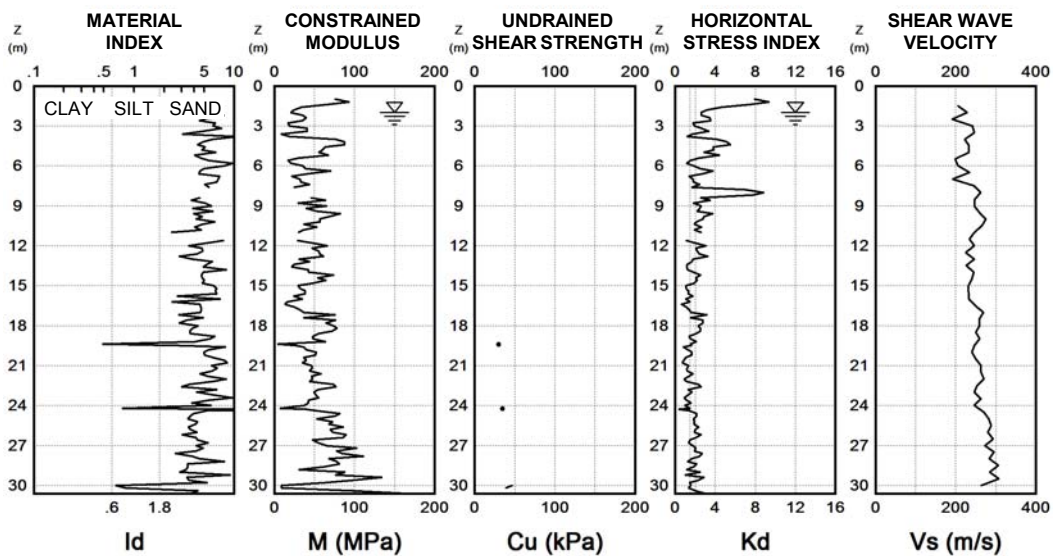**Figure 8. SDMT results at the site of Cassino, Italy**

Figure 9. SDMT results at the site of Zelazny Most tailing dam, Poland

small strains, whereas pore-pressure build up and liquefaction are medium- to high-strain phenomena. This concern is significant for cemented/bonded soils, because small-strain measurements are highly sensitive to weak interparticle bonding that is eliminated at medium-high strains (range of K_D measurement). Weak interparticle bonding can increase V_S, while not necessarily increasing CRR. Thus, for liquefiability, the K_D indications could possibly be more relevant. Very light earthquakes, however, may not destroy bonding, then CRR evaluated by V_S may be appropriate in this case.

Limiting values of V_{S1} and K_D for liquefaction occurrence
Another difference in the correlations CRR-V_S and CRR-K_D may be noted in the limiting values of V_{S1} and K_D for which liquefaction occurrence can be definitely excluded, even in case of strong earthquakes (asymptotes of the CRR-V_{S1} curve in Figure 3 and CRR-K_D curve in Figure 5a). Such values are respectively $V^*_{S1} = 215$ m/s and $K^*_D = 5.5$ (see Maugeri and Monaco 2006), for clean sands and $M_w = 7.5$. In the example shown in Figure 9 (Zelazny Most tailing dam, Poland), while V_{S1} values (mostly > 215 m/s) suggest "no liquefaction" for any earthquake, K_D values ($\approx$ 1.5-2) indicate that liquefaction may occur above a certain seismic stress level (high CSR).

CRR from V_S vs. CRR from other methods
Various Authors have discussed the accuracy of CRR evaluated from V_S compared to CRR by other methods (SPT, CPT). Seed et al. (2003) commented that V_S based correlations provide less reliable estimates of CRR than SPT-CPT, due to the smaller field case history database and to the poor correlation of the small-strain V_S measurement with the large-strain liquefaction phenomenon. Idriss and Boulanger (2004) observed that SPT, CPT and V_S are differently sensitive to the relative density of the soil, one of the major factors influencing CRR, being the SPT the most sensitive and V_S the least sensitive. (Accordingly Maugeri and Monaco 2006 showed that K_D is more sensitive to D_R than V_S). Idriss and Boulanger (2004) remarked the persisting need for an improved understanding of CRR-V_S correlations and recommended that greater weight should be given to CRR from SPT or CPT, in case of contradictory predictions by SPT, CPT and V_S. In the writers' view, a crucial aspect, when assessing the accuracy of different CRR correlations, is the sensitivity of the testing tool, besides to relative density, to factors – above all *aging* and *stress history* – which play a primary role in increasing liquefaction resistance (for a given D_R).

CONCLUSIONS

The seismic dilatometer (SDMT) offers an alternative or integration to current methods for evaluating the liquefaction resistance of sands based on CPT-SPT. Two parallel independent evaluations of liquefaction resistance CRR can be obtained from the horizontal stress index K_D and from the shear wave velocity V_S, by means of the CRR-K_D and CRR-V_S correlations shown in Figure 5a and in Figure 3, to be used in the framework of the Seed and Idriss (1971) simplified procedure. This possibility appears attractive, since "redundancy" in the evaluation of CRR by more than one method is generally recommended. The use of V_S for evaluating CRR is well known. Correlations CRR-K_D have been developed in the last two decades, stimulated by the recognized sensitivity of K_D to prestraining/aging, combined with the ability of K_D to reflect a number of factors which are known to increase liquefaction resistance – stress history, cementation, structure – and the correlation of K_D to relative density and state parameter.

Recent research has definitely shown that accounting for aging is not a refinement, but a necessity for economical design, because aging has a first order of magnitude influence on liquefaction behaviour. Ignoring aging effects and using current CRR correlations, developed for young or freshly deposited sands and based on in situ tests (SPT, CPT, V_S) poorly sensitive to aging, would result in many cases in overconservative design. A desirable alternative, seemingly better than relying on an "average" from correlations missing the aging factor, would be to use a testing tool significantly more sensitive to aging.

CC research by Jamiolkowski and Lo Presti (1998) has shown that K_D is much more sensitive to cyclic prestraining – a sort of "simulated aging" – than penetration resistance. On the other hand, it is well

known that cyclic prestrain, just as aging, increases the liquefaction resistance, due to the similarity of the mechanism. Therefore the results of the above CC research suggest that K_D is much more sensitive to aging than penetration resistance. It is possible that current CRR correlations based on K_D, or future refined versions, will not need the introduction of "age correction factors", because part of the aging effects are already "incorporated" in K_D. Moreover K_D is sensitive to factors such as stress history and cementation, long recognized as important to liquefaction behaviour. Using an in situ testing tool also more sensitive to aging effects, such as the DMT/SDMT, could possibly lead to better correlations to obtain CRR.

The aptness of the K_D parameter to evaluate CRR has been reinforced by the experience gained with a large number of tests performed in the recent years with the SDMT. A clear feature emerging from many comparisons of the K_D and V_S profiles is the clarity with which "Stress History crusts" (which are not "Relative Density crusts") are evidenced by K_D, while such crusts are barely recognizable in the V_S profiles. Such capability of K_D to reflect stress history is important. In fact, in addition to the sensitivity to aging, the evaluation of any alternative method to evaluate liquefaction resistance would be incomplete without also checking its ability to account for other stress history effects.

Comparisons based on parallel measurements of K_D and V_S obtained by SDMT at several sandy sites have shown that V_S and K_D would provide, in general, substantially different estimates of CRR, leaving open the question "which CRR should be given greater weight" when parallel analyses by K_D and V_S produce contradictory predictions. In principle, the authors would propend to give greater weight to CRR by K_D for the following reasons:

– Shallow OC crusts (believed to be very unlikely to liquefy), found at the top of most sand deposits, are unequivocally depicted by high K_D values but almost "unfelt" by V_S. This suggests a lesser ability of V_S to profile liquefiability.
– V_S is measured at small strains, whereas pore-pressure build up and liquefaction are medium- to high-strain phenomena. In cemented/bonded soils V_S can be "misleadingly" high due to interparticle bonding, largely destroyed at higher strains (range of K_D measurement). Thus the K_D indications could possibly be more relevant for liquefiability. Very light earthquakes, however, may not destroy bonding, then CRR evaluated by V_S may be appropriate in this case.
– 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 more sensitive than V_S to relative density D_R and to other factors that greatly increase liquefaction resistance, such as stress history, aging, cementation, structure (which, incidentally, are felt considerably more than by penetration resistance).

The above obviously deserves considerable additional verification, supported by well documented real-life liquefaction case histories.

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