Using K_D and V_S from Seismic Dilatometer (SDMT) for evaluating soil liquefaction

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ABSTRACT: The Authors have collected in the recent years a large amount of data from site investigations in the city of Catania, which was struck in the past by severe earthquakes. At San Giuseppe La Rena, measurements of SPT, CPT and K_D and *Vs* using SDMT have been made in a saturated sandy soil. This paper presents K_D and *Vs* recommended relationships for sandy soils for potential liquefaction evaluation. When using semi-empirical procedures for evaluating liquefaction potential during earthquakes, it is important to use redundant correlations. The SDMT has the advantage, in comparison with CPT and SPT tests, by measuring independent parameters, K_D and *Vs*. CPT and SPT based correlations are supported by large databases, while SDMT correlations are based on a limited database. Based on the San Giuseppe La Rena SDMT measurements recent data, a re-evaluation of K_D and *Vs* correlations have been made.
The results show that *Vs* is less sensitive to potential liquefaction behaviour than K_D, which is, in contrast, very sensitive. The plotted correlations with critical values of K_D and *Vs* are suitable and very simple to use for detecting liquefaction potential.

1 INTRODUCTION

The coastal plain of the city of Catania (Sicily, Italy), which is recognized as a typical Mediterranean city at high seismic risk, was investigated by SDMT. Seismic liquefaction phenomena were reported by historical sources following the 1693 (M_s = 7.0-7.3, I_o = X-XI MCS) and 1818 (M_s = 6.2, I_o = IX MCS) Sicilian strong earthquakes. The most significant liquefaction features seem to have occurred in the Catania area, situated in the meisoseismal region of both events. These effects are significant for the implications on hazard assessment mainly for the alluvial flood plain just south of the city, where most industry and facilities are located.

For a new commercial building, deep site investigations have been performed, which included borings, SPT and CPT. More recently, at the same site, SDMT has been performed. The locations of the SPT, CPT and SDMT are reported in Fig. 1. SPT and CPT were located in the area where the commercial building has been built. The SDMT was performed after the construction of the building, and was located outside the construction area.

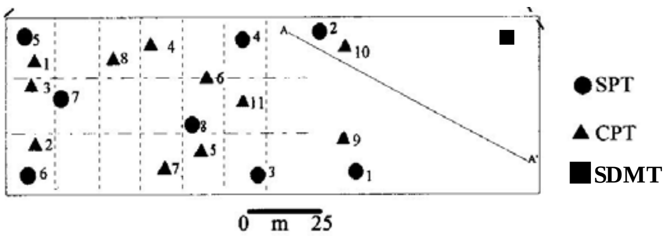

Fig. 1. Location of SPT, CPT and SDMT tests.

When using semi-empirical procedures for evaluation liquefaction potential during earthquakes, it is important to use redundant correlations. The SDMT has the advantage, in comparison with CPT and SPT, to measure independent parameters, such as K_D and V_S. Hence "matched" independent evaluations of liquefaction resistance can be obtained from K_D and from V_S according to recommended CRR-K_D and CRR-V_S correlations. CPT- and SPT-based correlations are supported by large databases, while SDMT correlations are based on a smaller database.

The liquefaction potential has been evaluated using empirical correlations with SPT and CPT, as well as by *Vs* and K_D measured by SDMT. From the comparison of the results, re-evaluations of K_D correlations have been made.

2 CURRENT METHODS FOR EVALUATING LIQUEFACTION POTENTIAL USING SPT AND CPT MEASUREMENTS

The traditional procedure, introduced by Seed & Idriss (1971), has been applied for evaluating the liquefaction resistance of San Giuseppe La Rena sandy soil. This method requires the calculation of the cyclic stress ratio CSR, and 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):

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

where τ_{av} = average cyclic shear stress, a_{max} = peak horizontal acceleration at the 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 depending on depth. The r_d has been evaluated according to Liao and Whitman (1986).

The procedures used herein for the computation of the cyclic resistance ratio CRR are from Iwasaki et al.(1978) for SPT data and from Robertson and Wride (1997) for SPT and CPT.

The results of the SPT are reported in Fig. 2. $(N_1)_{60cs}$ according to Skempton (1986) assuming Ks= 1.5 according to Robertson and Wride (1997) are reported in Fig. 3.

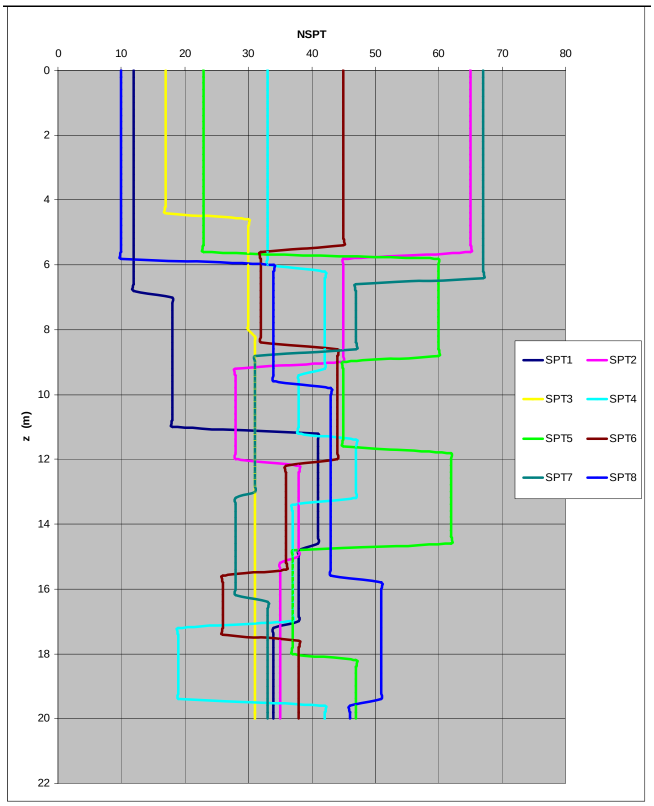

Fig. 2. N_{SPT} test results versus depth (8 profiles).

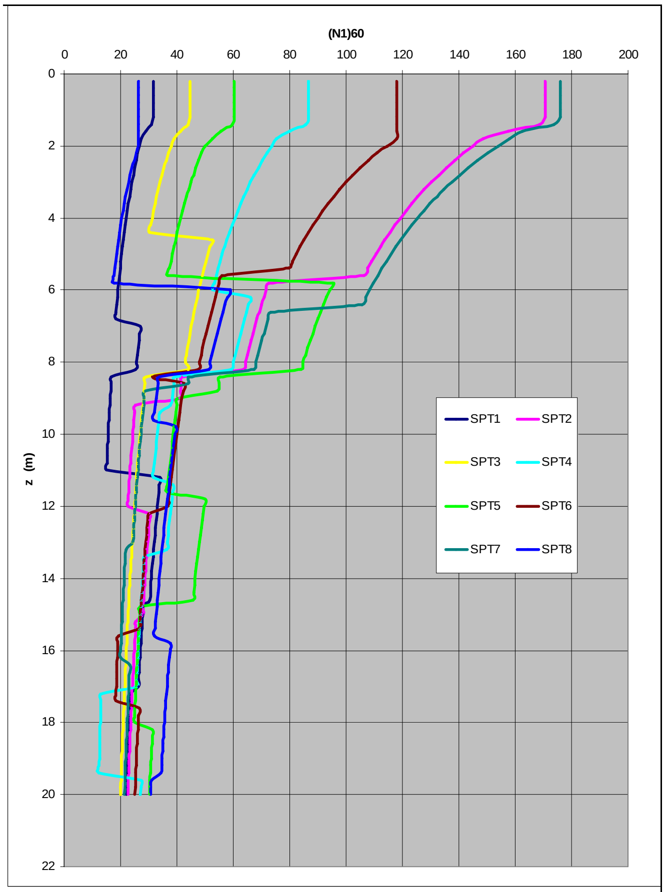

Fig. 3. $(N_1)_{60cs}$ test results versus depth assuming Ks= 1.5.

The results of CPT tests are reported in Fig. 4, and. $(qc_{1N})_{cs}$ according to Robertson and Wride (1997) are reported in Fig. 5.

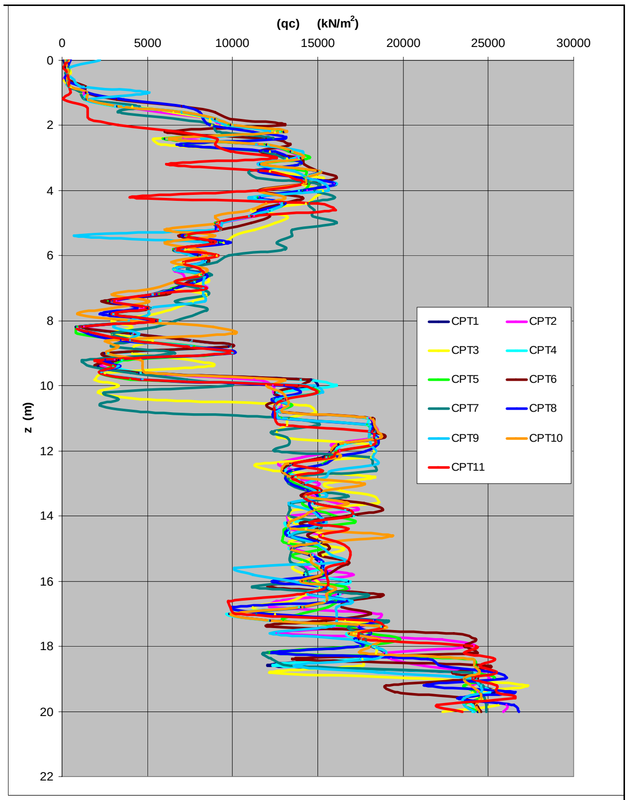

Fig. 4. q_c test results versus depth (11 profiles).

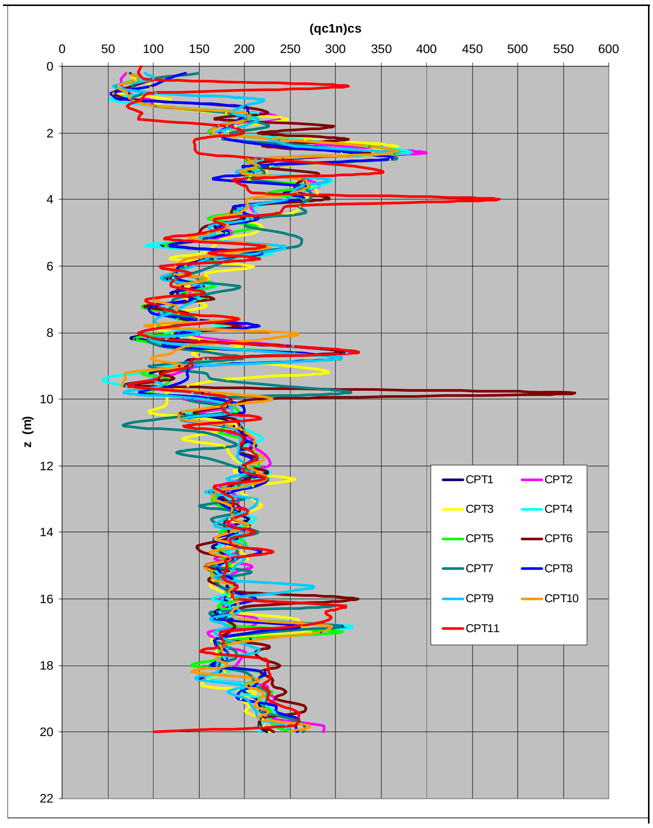

Fig. 5. $(qc_{1N})_{cs}$ test results versus depth.

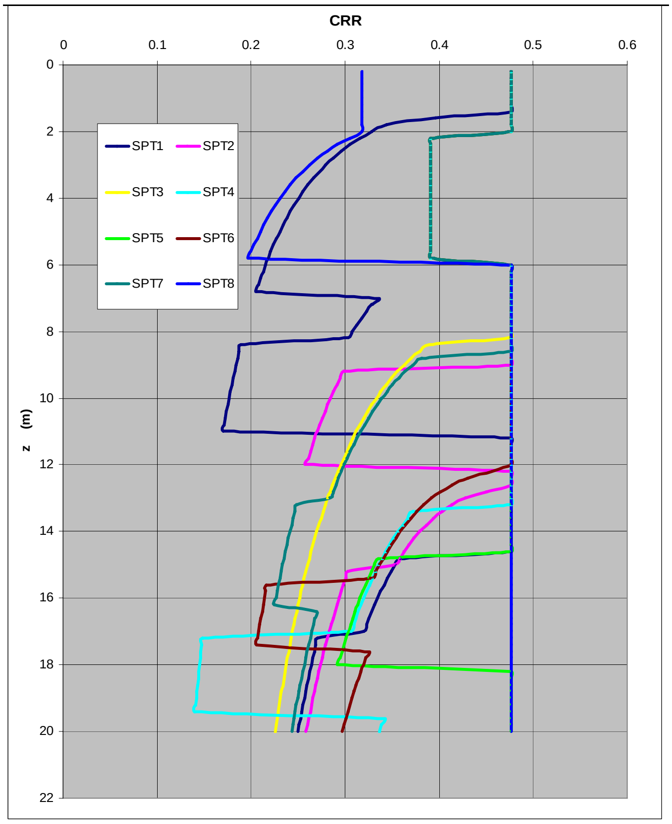

Fig. 6. $CRR_{7.3}$ for SPT data versus depth (8 profiles).

CRR for SPT data of Fig. 3 has been evaluated according to Robertson and Wride (1997) by the expression:

$$CRR_{7.5}=[a+cx+ex^2+gx^3]/[1+bx+dx^2+fx^3+hx^4] \qquad (2)$$

CRR for CPT data of Fig. 5 has been evaluated according to Robertson and Wride (1997) by the expression:

$$CRR_{7.5} = 93\,[(qc_{1N})_{cs}/1000]3 + 0.08 \qquad (3)$$

for $50 \leq (qc_{1N})_{cs} < 160$.

The values of $CRR_{7.5}$ for SPT data and CPT data have been scaled to a magnitude of M= 7.3 according to Idriss (1985) by the following expression:

$$MSF = 10^{2.24}/M^{2.56} \qquad (4)$$

The values of $CRR_{7.3}$ for SPT data, are reported in Fig. 6, and the values of $CRR_{7.3}$ for CPT data are reported in Fig. 7. CSR has been evaluated assuming in equation (1) $a_{max} = 0.50g$. The ratio CSR to CRR is called the liquefaction resistance factor (F_{SL}). Then is possible to evaluate the liquefaction potential index P_L (Iwasaki et al., 1978), given by the following expression:

$$P_L = \int_0^{20} F(z)w(z)dz \qquad (5)$$

where w(z)= 10 – 0.5z and F(z) is a function of the liquefaction resistance factor (F_{SL}) and its values are: F(z)= 0 for $F_{SL} \geq 1$ and F(z)= 1 - F_{SL} for $F_{SL} < 1$. The liquefaction potential index, P_L, for the SPT test No. 1 is reported in Fig. 8.

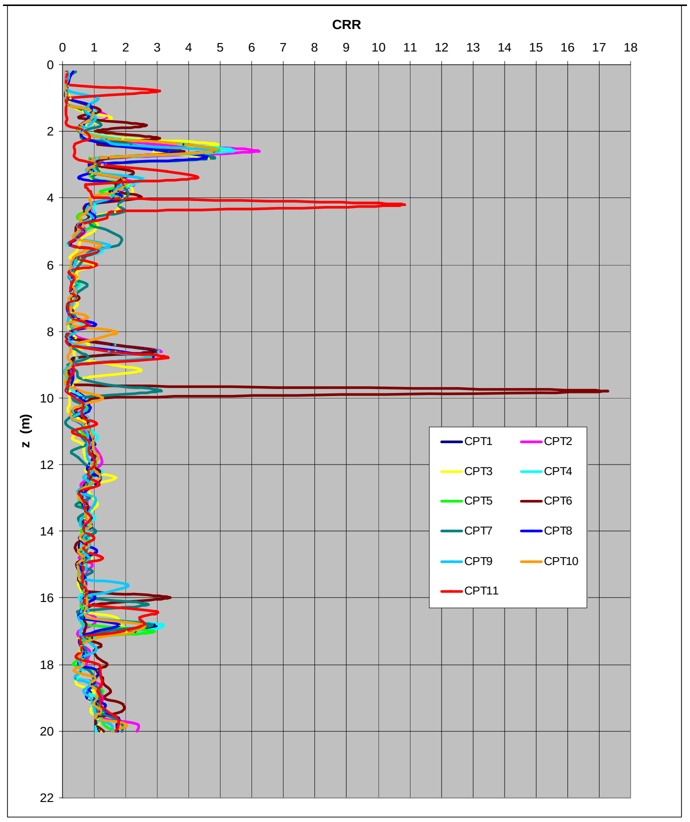

Fig. 7. $CRR_{7.3}$ for CPT data versus depth (11 profiles).

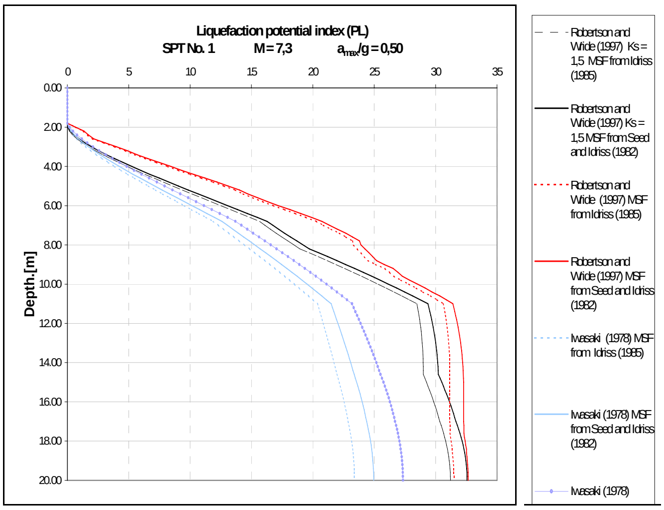

Fig. 8. P_L evaluation from SPT versus depth, for test No. 1.

From this figure the evaluation according to Robertson and Wride (1997), according to MSF given by Seed and Idriss (1982), is more conservative. In Fig. 9 is reported the evaluation of P_L for all the SPT tests assuming this most conservative evaluation criterion.

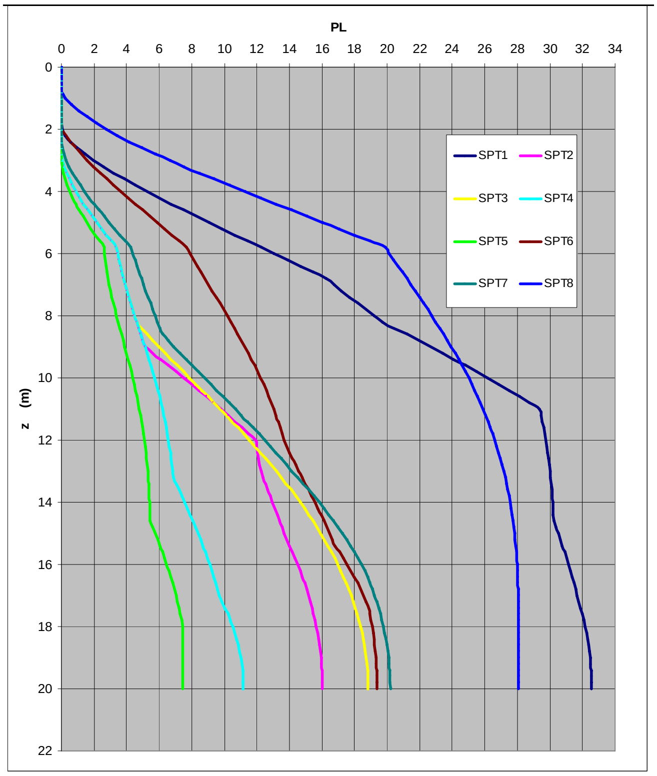

Fig. 9. The conservative P_L evaluation from SPT versus depth (8 profiles).

The liquefaction potential index, P_L, for the CPT test No. 1 is reported in Fig. 10. From this figure the evaluation according to Robertson and Wride (1997) and according to MSF given by Seed and Idriss (1982) is more conservative. In Fig. 11 is reported the evaluation of P_L for all the CPT tests assuming this most conservative evaluation criterion. From comparison of Fig. 9 with Fig. 11 the liquefaction potential index, P_L, is more conservative for SPT data. which reaches the average value of 30 than the CPT data, which reaches the average value of 15. From these values the liquefaction potential is very high for SPT data and high for CPT data (Maugeri and Vannucchi, 1999).

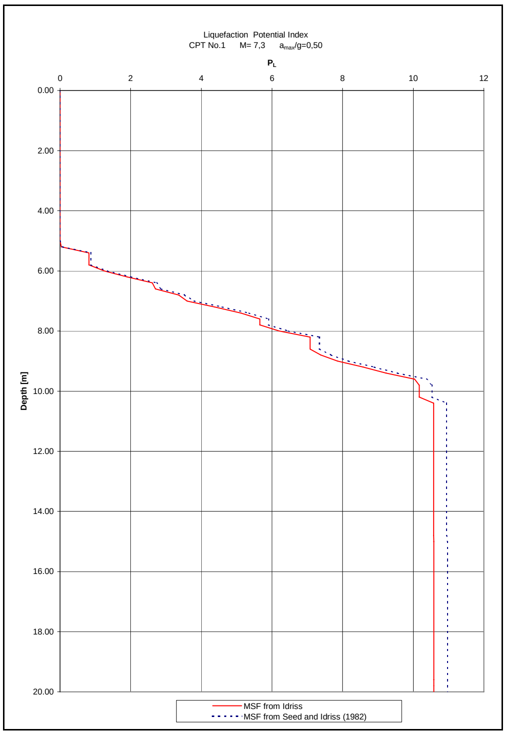

Fig. 10. P_L evaluation from CPT versus depth, for test No. 1.

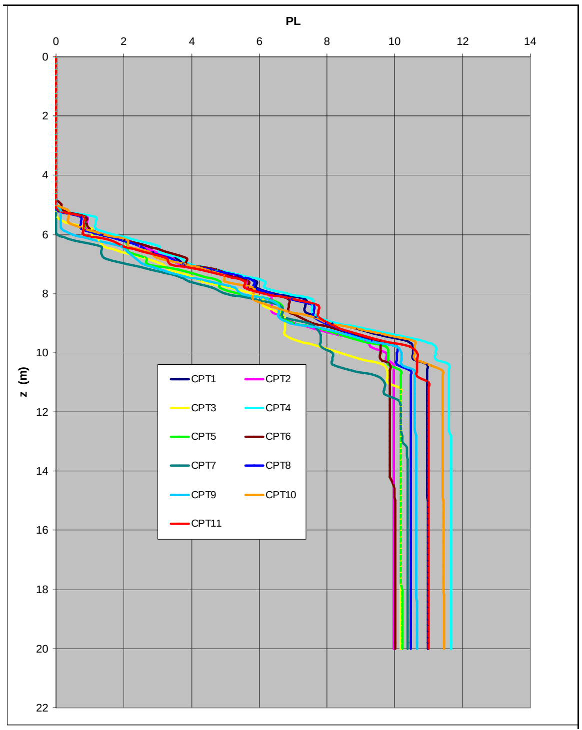

Fig. 11. The conservative P_L evaluation from CPT versus depth (11 profiles).

3 EVALUATION OF CRR FROM SHEAR WAVES VELOCITY V_S MEASURED BY SDMT

The use of the shear wave velocity, V_S, as an index of liquefaction resistance has been illustrated by several authors (Tokimatsu and Uchida, 1990; Kayen et al., 1992, Robertson et al., 1992, Lodge, 1994, Andrus and Stokoe, 1997, 2000; Robertson & Wride 1997; Andrus et al., 1999). The V_S based procedure for evaluating CRR has advanced significantly in recent years, 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. A comparison of some relationships between liquefaction resistance and overburden stress-corrected shear wave velocity for granular soils is reported in Fig. 12.

The correlation between V_S and CRR given by Andrus & Stokoe (1997, 2000) is:

$$\mathrm{CRR} = a\left(\frac{V_{S1}}{100}\right)^2 + b\left(\frac{1}{(V^*_{S1} - V_{S1})} - \frac{1}{V^*_{S1}}\right) \qquad (6)$$

Where: V^*_{s1} = limiting upper value of V_{s1} for liquefaction occurrence; $V_{S1} = V_S\,(p_a/\sigma'_{vo})^{0.25}$ is corrected shear wave velocity for overburden-stress; a and b are curve fitting parameters.

This correlation has been improved by Andrus et al. (2004). 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} is approximated by the equation for M_w = 7.5:

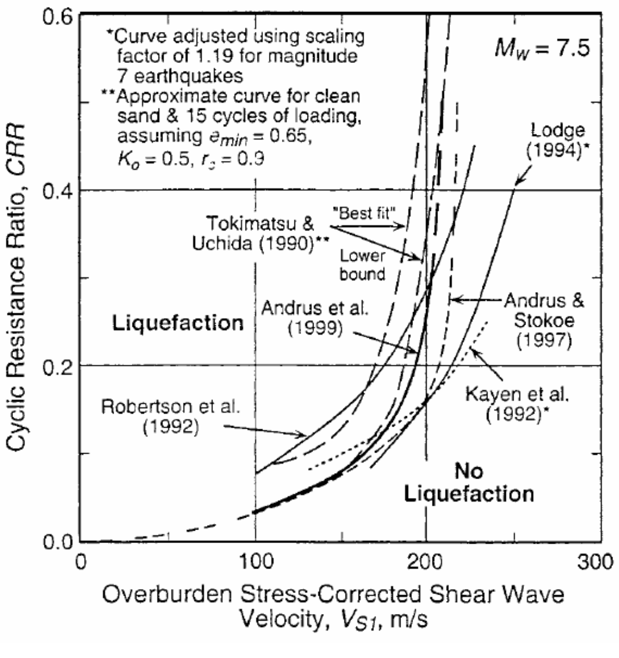

Fig. 12. Comparison of some Relationships between Liquefaction Resistance and Overburden Stress-Corrected Shear Wave Velocity for Granular Soils (Youd & Idriss 2001).

$$\mathrm{CRR}_{7.5} = \left[0.022\left(\frac{K_{a1}V_{S1}}{100}\right)^2 + 2.8\left(\frac{1}{V^*_{S1} - (K_{a1}V_{S1})} - \frac{1}{V^*_{S1}}\right)\right]K_{a2} \qquad (7)$$

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} is a factor to correct for high V_{S1} values caused by aging, K_{a2} is a factor to correct for influence of age on CRR. Both K_{a1} and K_{a2} are 1.0 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).

Shear wave velocity can be measured in-situ by down-hole, cross-hole and the new SDMT. The profile of shear wave velocity measured by SDMT at the San Giuseppe La Rena sandy site is reported in Fig. 13. The evaluation of CRR according to equation 6 (Andrus & Stokoe, 2000) and equation 7 (Andrus et al., 2004), at San Giuseppe La Rena site is reported in Fig. 14. From Fig. 14 the CRR values given by equation 7 are lower than those given by equation 6, so therefore the evaluation given by equation 7 according to Andrus et al., 2004 is more conservative. Fig. 15 shows the evaluation of liquefaction potential index, P_L, according to Iwasaki et al., 1978, which shows that the liquefaction potential index, P_L, is more conservative for Vs data than SPT and CPT data. For Vs data P_L reaches the average value of 70 according to the evaluation of CRR given by Andrus et al., 2004 and the value of 40 according to the evaluation of CRR given by Andrus & Stokoe (1997). For these values of P_L the liquefaction potential is very high. If we plot the CRR

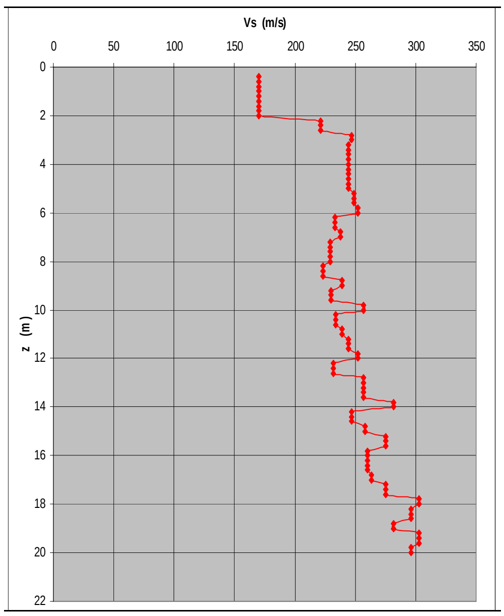

Fig. 13. V_S measurements by SDMT at San Giuseppe La Rena sandy site.

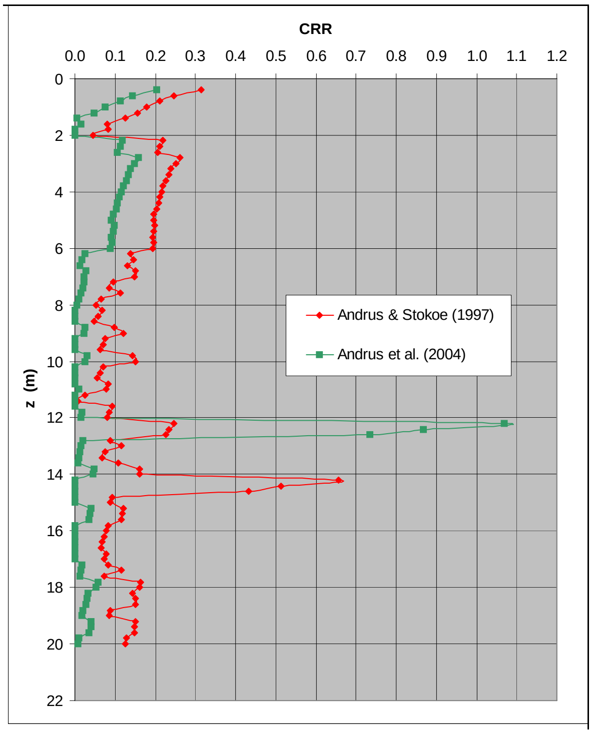

Fig. 14. Evaluation of CRR at San Giuseppe La Rena sandy site according to equation 6 and equation 7.

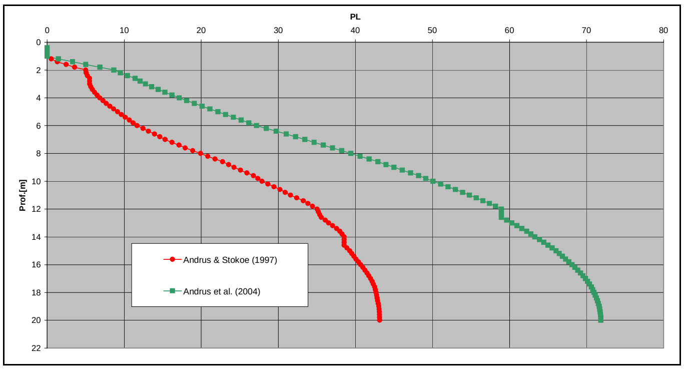

Fig. 15. Evaluation of Liquefaction potential Index P_L from V_s data at San Giuseppe La Rena sandy site.

results in the graphs of Fig. 12, the representative points lie on the border line between the liquefaction and non-liquefaction areas.

4 EVALUATION OF CRR FROM THE DMT HORIZONTAL STRESS INDEX 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.

Fig. 16 (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 data-points (Imperial Valley, South California).

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, 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).

The "equivalent" CRR-K_D curves derived in this way from CPT and SPT (dashed lines in Fig. 16) 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. 16), approximated by the equation:

$$CRR = 0.0107\,K_D^3 - 0.0741\,K_D^2 + 0.2169\,K_D - 0.1306 \quad (8)$$

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

Additional CRR-K_D curves for San Giuseppe La Rena coastal plain area were derived by translating current CRR-CPT and CRR-SPT curves 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

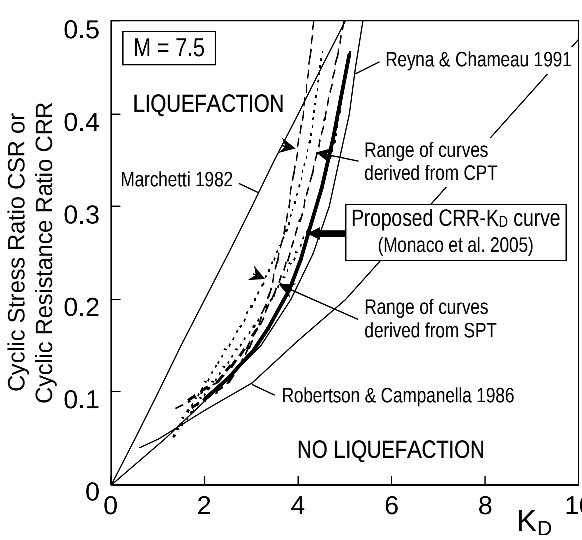

Fig. 16. CRR-K_D curves for evaluating liquefaction resistance from DMT (after Monaco et al. 2005).

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curves, evaluated using current correlations (D_R -q_c by Baldi et al. 1986 and Jamiolkowski et al. 1985, 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). Three new tentative CRR-K_D curves approximated by the equations:

$$CRR = 0.0908\,K_D^3 - 1.0174\,K_D^2 + 3.8466\,K_D - 4.5369 \qquad (9)$$

$$CRR = 0.0308\,e^{(0.6054 K_D)} \qquad (10)$$

$$CRR = 0.0111\,K_D^{2.5307} \qquad (11)$$

have been proposed by the authors as interpolation of the K_D curves derived from SPT and CPT.

Fig. 17 shows the variation with depth of K_D measured by SDMT and K_D obtained by empirical correlations for SPT and CPT data. The discrepancy of K_D results for top layers are due mainly to different location of SPT and CPT tests (located in the area before the construction of the industrial building) and SDMT located about 55 m from the constructed building. It is important to stress that the upper rigid crust (probably due to the increasing of clay content and to the presence of cemented layer) evidenced by K_D (Fig. 17) is not felt by V_s (see Fig. 13).

Fig. 18 shows the evaluation of CRR, for CPT No. 1, according to different correlations given by equations (8), (9), (10) and (11). Equation (8), given by Monaco et al. (2005) is the less conservative than the proposed equations (9), (10) and (11).

Fig. 19 shows the variation with depth of CRR given by correlation with SPT No. 1 and CPT No. 1 tests, performed at San Giuseppe La Rena test site. The CRR obtained by correlations with Vs, according to Andrus & Stokoe (1997) and to Andrus et al. (2004), show that the correlations with Vs give

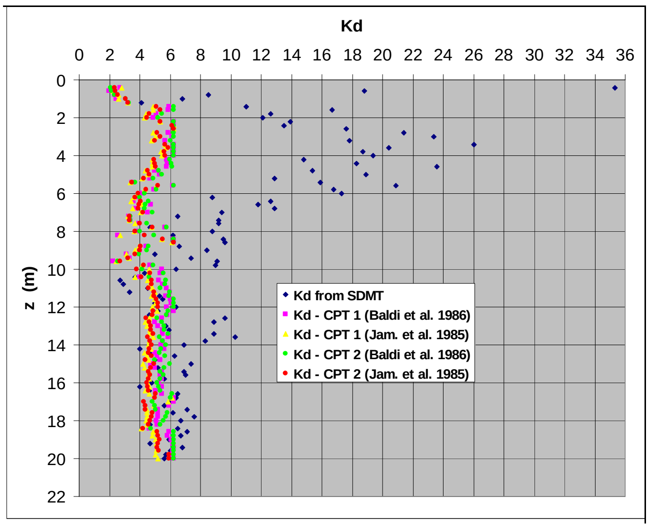

Fig. 17. K_D versus depth from SDMT and from empirical correlations for CPT test No. 1 and test No. 2 data.

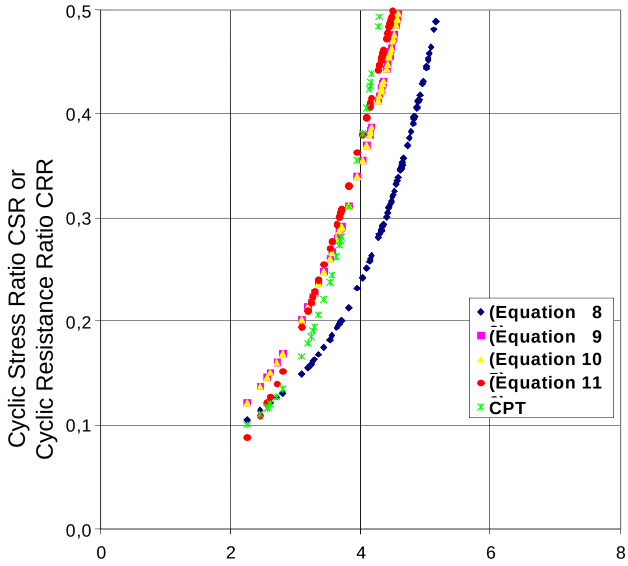

Fig. 18. CRR-K_D curves given by different correlations for CPT test No. 1.

lower and more conservative CRR values.

For the evaluation of liquefaction potential index, P_L, (Iwasaki et al., 1978), the correlations given by equations (8), (9), (10) and (11) use the K_D values measured by SDMT instead of the correlations by SPT and CPT because of the presence of the upper rigid crust was not measured by Vs or by SPT and CPT.

Fig. 20 shows that the evaluation of the liquefaction potential index, P_L, is less than 5 because this method took into consideration the presence of the rigid upper crust. Therefore, the liquefaction potential is low for K_D data, according to Fig. 16 (representative point CRR=0.4 and K_D=10), while it was high for CPT data and very high for SPT and Vs data.

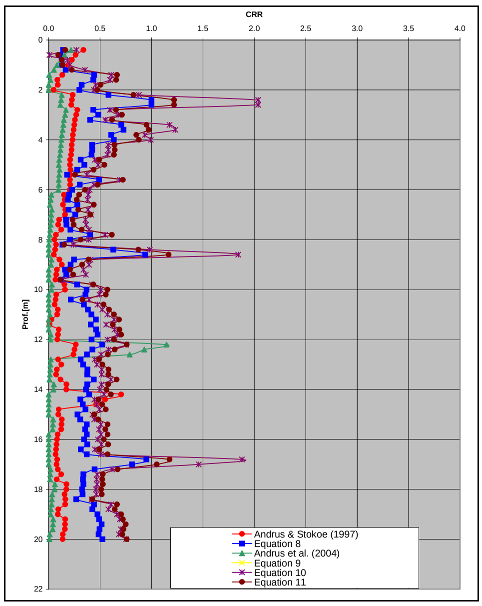

Fig. 19. CRR with depth, from CPT, K_D and V_S data from SDMT, at San Giuseppe la Rena test site.

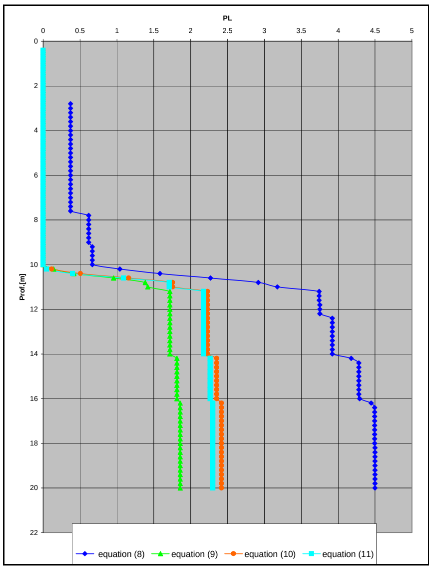

Fig. 20. Evaluation of Liquefaction potential Index P_L from K_D data at San Giuseppe La Rena sandy site.

5 CONCLUSIONS

SDMT gives the possibility to use two independent measurements V_s and K_D for evaluating soil liquefaction. The test performed at San Giuseppe La Rena, Catania, Italy, gave some contrasting results. When using the V_s or SPT data, the liquefaction potential index, P_L, is very high, and P_L is high for the CPT data. When using K_D data, however, P_L is low because K_D detected the upper rigid crust, which was overlooked by V_s, SPT and CPT measurements.

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