1st IMEKO TC-4 International Workshop on
Metrology for Geotechnics
Benevento, Italy, March 17-18, 2016

In situ measurements for evaluating liquefaction potential under cyclic loading

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***Abstract* – In this paper some information concerning the geotechnical characterisation of several sites of the city of Catania have been presented. In situ investigations of sandy harbour soils were therefore carried out in order to determine the soil profiles and the geotechnical characteristics for potential liquefaction evaluation under cyclic loading. The CPT results are generally more consistent and repeatable than results from other penetration tests. The continuous profiles i.e. for the city of Catania also allow a more detailed interpretation of soil layers and soil types. Thus the CPT can be used to develop preliminary soil and liquefaction resistance profiles for site investigations. Semi-empirical procedures for liquefaction evaluations originally have been also developed using the Standard Penetration Test (SPT) to differentiate between liquefiable and non-liquefiable sites. Criteria for evaluation of liquefaction resistance based on standard penetration test (SPT) blowcounts have been rather robust over the years. Seismic Dilatometer Marchetti Tests (SDMT) have been also carried out, with the aim to evaluate the soil profile of shear wave velocity (Vs) and the horizontal stress index (Kd). The available data obtained from the Seismic Dilatometer Marchetti Tests results enabled also to evaluate the potential liquefaction. The Seismic Dilatometer Marchetti Test (SDMT) has the advantage, in comparison with CPT and SPT tests, to measure independent parameters, such as the Horizontal Stress Index (Kd) and the shear wave velocity (Vs). The use of the shear wave velocity, V_S, as an index of liquefaction resistance, illustrated by several authors, has been also compared with the other approaches based on CPT, SPT or SDMT test results on sandy soils for potential liquefaction evaluation.**

I. INTRODUCTION

The east coast area of Sicily is considered as one of the zones of Italy with greater high seismic risk, basing on the past and current seismic history and on the typology of civil buildings and industrial activities [1]. In situ investigations of sandy soils were carried out in order to determine the soil profile and the geotechnical characteristics for the site under consideration, with special attention for the variation of shear modulus and damping with depth. 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 Seismic Dilatometer Marchetti Test (SDMT). Seismic liquefaction phenomena were reported by historical sources following the 1693 (Ms = 7.0-7.3, Io = X-XI MCS) and 1818 (Ms = 6.2, Io = IX MCS) Sicilian strong earthquakes. The most significant liquefaction features seem to have occurred in the Catania area, near Saint Giuseppe La Rena site, 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. Other SDMT tests have been also carried out near the Harbour zone of the city of Catania.

II. GEOTECHNICAL SOIL PROPERTIES

To evaluate the geotechnical characteristics of the soil, the following in situ and laboratory tests were performed in the Catania harbour area:
N°. 11 Cone Penetration Tests (CPT);
N°. 8 Standard Penetration Tests (SPT);

ISBN: 978-92-990075-0-1

N°. 5 Seismic Dilatometer Tests (SDMT);
N°. 3 Direct Shear Tests;
N°. 3 Triaxial CD Tests;
N°. 6 Resonant Column Tests (RCT);
The investigation programme was performed in the zone of *"Acquicella Porto"* in the Catania harbour.
The results of 11 CPT tests executed at the site are reported in Figure 1. An example of SPT profile is also reported in Figure 2.

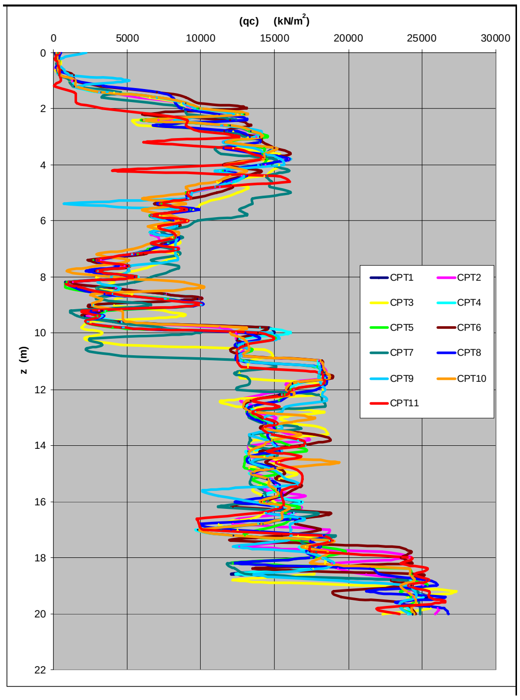

Figure 1. (qc1N)cs test results versus depth (11 profiles).

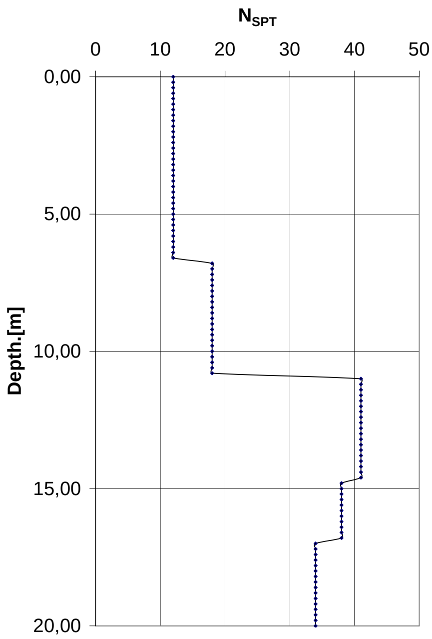

Figure 2. NSPT test results versus depth.

The 5 Seismic Dilatometer Tests (SDMT1-5) have an effective depth of 30.50 m, 32.00 m, 31.00 m, 30.00 m, 32.00 m. Figure 3 shows the location of the SDMTs in the Catania harbour. The SDMT [2-5] provides a simple means for determining the initial elastic stiffness at very small strains and in situ shear strength parameters at high strains in natural soil deposits.

Figure 3. Location of the 5 SDMTs in the Catania harbour.

SDMT obtained parameters by the equipment shown in figure 4 at the site are: I_d: Material Index; gives information on soil type (sand, silt, clay); M: Vertical Drained Constrained Modulus; Phi: Angle of Shear Resistance, figure 5; K_D: Horizontal Stress Index, figure 6 (the profile of K_D is similar in shape to the profile of the overconsolidation ratio OCR. K_D = 2 indicates in clays OCR = 1, K_D > 2 indicates overconsolidation.

Figure 4. SDMT equipment at the Acquicella Porto site.

The *"Acquicella"* site along the southern coast line of Catania is characterized by fine sands (fine particles less then 30%) with thin limestones.

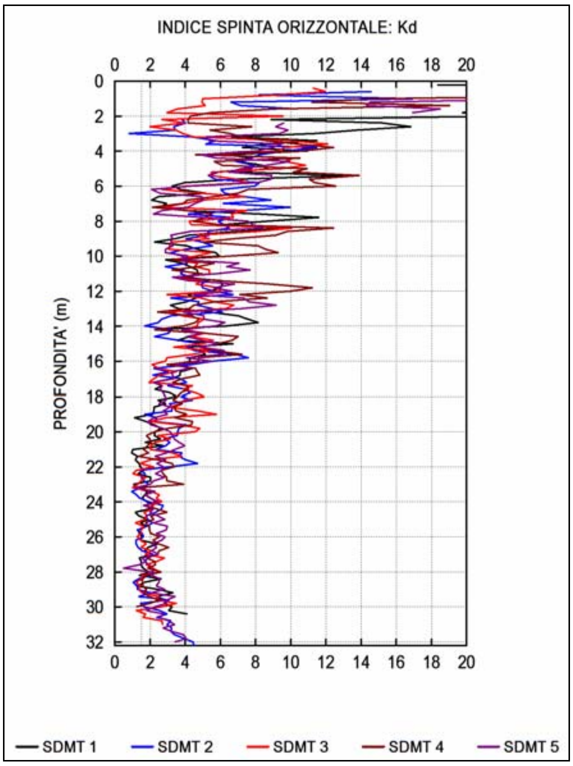

Figure 5. K_D: Horizontal Stress Index of the 5 SDMTs in the Catania "Acquicella" harbour.

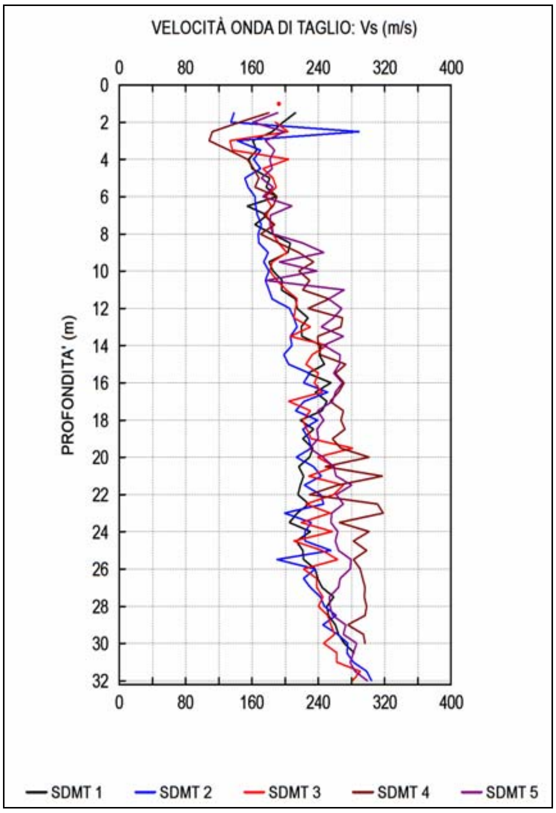

Figure 6. Vs: Shear Wave Velocity of the 5 SDMTs in the Catania "Acquicella" harbour.

III. CPT-BASED AND SPT-BASED PROCEDURE FOR EVALUATING SOIL LIQUEFACTION

The traditional procedure, introduced by [6], has been applied for evaluating the liquefaction resistance of Catania harbour 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 [6]:

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

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, r_d = stress reduction coefficient depending on depth and MSF is magnitude scaling factor. The stress reduction coefficient rd is a parameter describing the ratio of cyclic stresses for a flexible soil column to the cyclic stresses for a rigid soil column. Plots of rd calculated using previous equation for M = 5½, 6½, 7½ and 8 are presented in Figure 7.

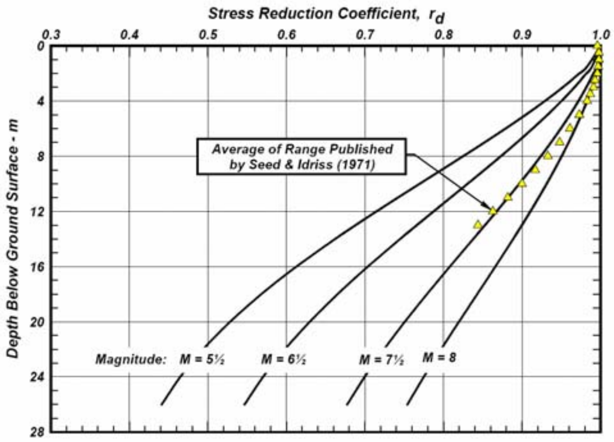

Figure.7. Variations of stress reduction coefficient with depth and earthquake magnitude.

As regards the peak horizontal acceleration, the value of 0.45 g has been chosen (see Figure 8). It is the value of the acceleration with the 5% probability of exceedance in 50 years (return period of 975 years), amplified with an amplification factor of 1.80 given by the seismic response analysis in Catania. The magnitude scaling factor, MSF, has been used to adjust the induced CSR during earthquake magnitude M (M=7.3 of the 1693 scenario earthquake) to an equivalent CSR for an earthquake magnitude, M = 7½. A primary advantage of the CPT for evaluating the cyclic resistance ratio CRR is that a nearly continuous profile of penetration resistance is developed for stratigraphic interpretation. Since considerable uncertainties inevitably exist on the values of the seismic parameters, a parametric analysis was carried out to clarify the influence of the earthquake magnitude and of the peak acceleration a_{max} on the liquefaction potential index. The results obtained are shown in Figure 9.

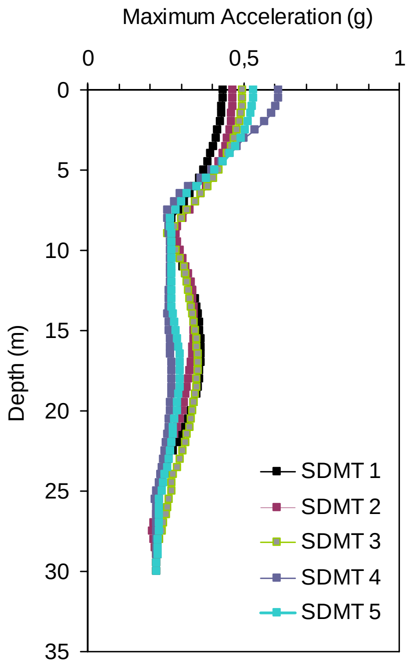

Figure 8. Maximum accelerations with depth for SDMTs No. 1-5 (475 years earthquake scenario return period).

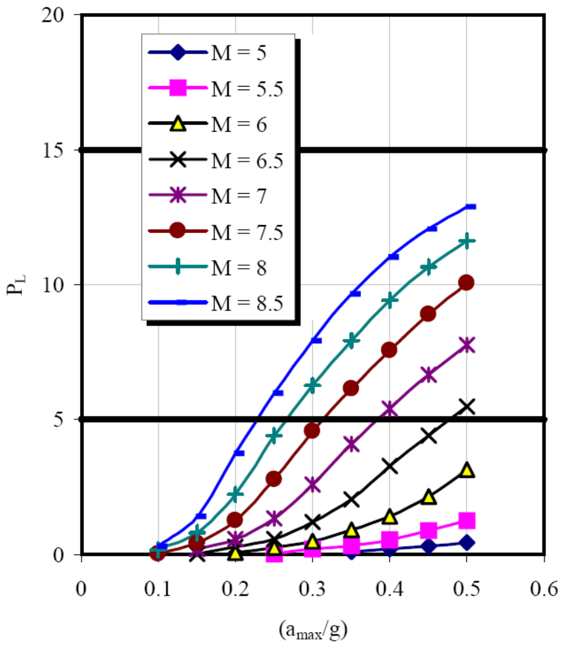

Figure 9. Effect of magnitude and of a_{max} *on the liquefaction potential index* P_L.

The CPT results are generally more consistent and repeatable than results from other penetration tests. The continuous profile also allows a more detailed interpretation of soil layers and soil types. The revised CRR $-q_{C1N}$ relation can be conveniently expressed as [7]:

$$CRR = \exp\left\{ \frac{q_{c1N}}{540} + \left(\frac{q_{c1N}}{67}\right)^2 - \left(\frac{q_{c1N}}{80}\right)^3 + \left(\frac{q_{c1N}}{114}\right)^4 - 3 \right\} \quad (2)$$

Semi-empirical procedures for liquefaction evaluations originally were developed using the Standard Penetration Test (SPT), beginning with efforts in Japan to differentiate between liquefiable and non-liquefiable sites. Criteria for evaluation of liquefaction resistance based on standard penetration test (SPT) blowcounts have been rather robust over the years. Those criteria are largely embodied in the CSR versus $(N_1)_{60}$.

The value of CRR for a magnitude M =7½ earthquake and an effective vertical stress σ'_{vo}=1atm (≅1 tsf) can be also calculated basing on $(N_1)_{60cs}$ using the following expression:

$$CRR = \exp\left\{ \frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8 \right\} \quad (3)$$

The use of these equations provides a convenient means for evaluating the cyclic stress ratio required to cause liquefaction for a cohesionless soils with any fines content.

The value of CRR can be also evaluated from SDMT. Marchetti and later studies suggested that the horizontal stress index K_D from DMT ($K_D = (po - uo) / \sigma'vo$) is a suitable parameter to evaluate the liquefaction resistance of sands. Previous CRR-K_D curves were formulated by Marchetti. The following CRR-K_D curves have been used in the present study, approximated by the equations:

$$CRR = 0.0107\,K_D^3 - 0.0741\,K_D^2 + 0.2169\,K_D - 0.1306 \quad (4)$$

$$CRR = 0.0242\,e^{(0.6534K_D)} \quad (5)$$

$$CRR = 0.0084\,K_D^{2.7032} \quad (6)$$

Equation (4) has been developed by [8]; equations (5) and (6) have been developed by [9]. Figure 10 shows CRR-K_D trends i.e. for SDMT1.

The use of the shear wave velocity, V_S, as an index of liquefaction resistance has been also illustrated by several authors [10-11]. The V_S based procedure for evaluating CRR has advanced significantly in recent years.

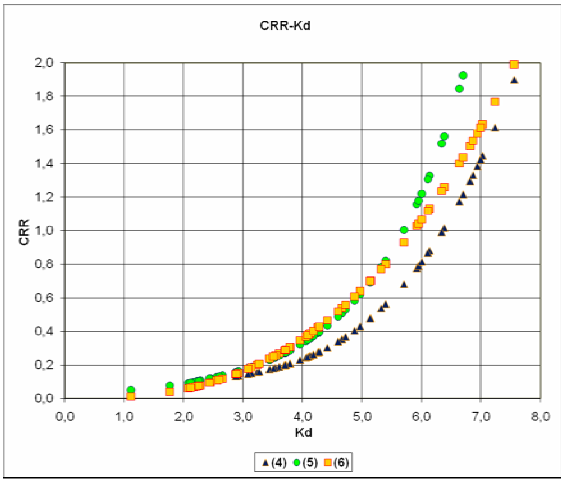

Figure 10. CRR- K_D trends obtained used K_D values from SDMT1.

The correlations between V_S and CRR used in the present study are given by Andrus & Stokoe:

$$\text{CRR} = a\left(\frac{V_{S1}}{100}\right)^2 + b\left(\frac{1}{(V^*_{S1} - V_{S1})} - \frac{1}{V^*_{S1}}\right) \tag{7}$$

$$\text{CRR}=\left[0.022\left(\frac{K_{a1}V_{S1}}{100}\right)^2 + 2.8\left(\frac{1}{V^*_{S1} - (K_{a1}V_{S1})} - \frac{1}{V^*_{S1}}\right)\right]K_{a2} \tag{8}$$

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 of equation (7) are curve fitting parameters, while K_{a1} and K_{a2} are aging factors = 1.0 for uncemented soils of Holocene age. However the CRR-V_s correlations are not reliable when V_s exceeds the value of 225 m/s. In addition, the V_s measurements are made at small strains, whereas pore-pressure build up and liquefaction are medium- to high-strain phenomena.

Figure 11 show P_L values obtained by CRR-SPT correlation, while Figure 12 show P_L values obtained respectively by CRR-K_D correlations i.e. for SDMT1-2.

Other results on site effects and liquefaction analyses using also SDMT can be found in [12-20]. Similar studies have been performed for the zonation on seismic geotechnical hazards and also for soil-structure interaction [21-23] and retrofitting [24-28] in other sites of the city of Catania (Italy) and for the Abruzzo Region (Italy) during L'Aquila earthquake [29-31].

IV. CONCLUSIONS

In this paper some information concerning the geotechnical characterisation by CPT, SPT and SDMT tests for soil liquefaction evaluation of the *"Acquicella Porto"* zone in the Catania harbour (Italy) have been presented. Local site response analyses have been brought for the "Acquicella Porto" area by 1-D linear equivalent computer codes for the evaluation of the amplification factors of the maximum acceleration. Results of the site response analysis show high values of soil amplification factors especially for the 475 and for the 975 return periods of the scenario earthquake, higher than those obtained by the current Italian Seismic Code. CRR-K_D correlations obtained for the *"Acquicella Porto"* zone in the Catania harbour have been used for the evaluation of liquefaction potential index, P_L. The results obtained by the SDMT1 show that the Liquefaction Potential Index P_L is below 5 (low risk) up to a depth of about 7 meters; while the results obtained by SDMT2 show low risk up to a depth of 10 m. By the way it is unlikely to have liquefaction at a depth greater than 7-10 m.

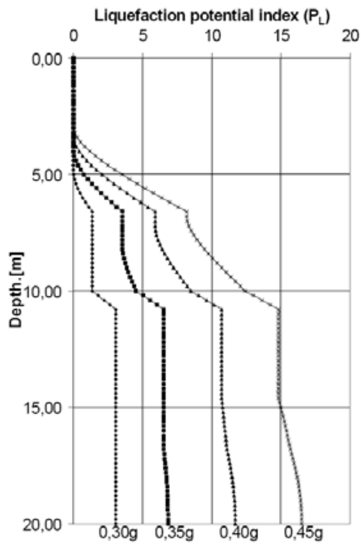

Figure 11. Liquefaction potential obtained by CRR- SPT.

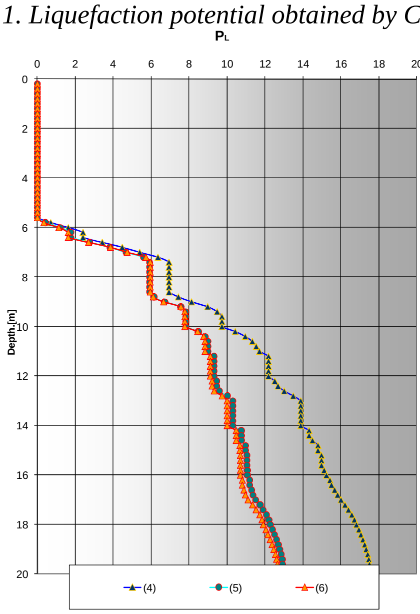

Figure 12. Liquefaction potential obtained by CRR- K_D.

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