Evaluation of the Shear Stress Reduction Factor for the Liquefaction Potential in the Catania Area (Italy)

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ABSTRACT: In this paper a study concerning the soil liquefaction of some test sites in the city of Catania has been presented. In situ investigations of sandy saturated soils were carried out in order to determine the soil profiles and the geotechnical parameters for potential liquefaction under cyclic loading. The stress-based liquefaction analysis framework for cohesionless soil includes a function that describes fundamental aspects of dynamic site response, i.e. the shear stress reduction coefficient, r_d, which is depending of several factors (depth; earthquake and ground motion characteristics; dynamic soil properties).

Among the various relationships proposed, including probabilistic, a new variation of r_d with depth has been obtained using a deterministic earthquake scenario as input motion. The relationship is based on large numbers of site response analyses for different site conditions and includes the effects of a site's average shear wave velocity over a specified depth.

Therefore, the continuous profiles i.e. for the city of Catania allow a more detailed interpretation of soil layers and soil types. 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. Seismic Dilatometer Marchetti Tests (SDMT) have been also carried out, with the aim to evaluate the soil profile of shear wave velocity (V_s) and the horizontal stress index (K_d). The available data obtained from the Seismic Dilatometer Marchetti Tests results enabled also to evaluate the potential liquefaction.

Keywords: liquefaction; site response analyses; semi-empirical procedures; shear stress reduction factor.

1. Introduction

Soil liquefaction is a major cause of damage during earthquake [1]. Liquefaction is defined as the transformation of a granular material from solid to a liquefied state as a consequence of increase pore-pressure and reduced effective stress [2]. Thus, the evaluation of the susceptibility of a site to seismic-induced liquefaction is an important step in many geotechnical investigations. It may be assessed comparing the cyclic soil resistence (CSR) to the cyclic shear stress (CSR) [3].

Estimates of the in situ CSR can be developed directly, using dynamic response analysis, but it is common in simplified analysis methods to develop estimates of in situ CSR using empirical relationships [4]. Central to this method is the evaluation of the stress reduction coefficent r_d.

In this paper, new r_d relationships are proposed for the eastern coastal plain of Catania area (Italy). The city of Catania, in South-Eastern Sicily, was affected by several destructive earthquakes of about magnitude 7.0 in past times. Extensive liquefaction effects occurred following the 1693 and 1818 strong earthquakes. Previous studies performed in the industrial area of the city of Catania revealed a high liquefaction hazard during a possible repetition of the scenario earthquakes [3, 5, 6].

2. Shear stress reduction factor: state of art review

The stress-based simplified procedure for evaluating soil liquefaction potential, originally developed by Seed and Idriss [7], compares the seismic demand on a soil layer (CSR) with the capacity of the soil to resist liquefaction (CRR). If CSR is greater than CRR, liquefaction can occur. The cyclic stress ratio CSR can be calculated by the following equation:

$$CSR = \frac{\tau_{av}}{\sigma'_{v0}} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right) r_d \qquad (1)$$

where τ_{av}=avarage cyclic shear stress, a_{max}=peak horizontal acceleration at the ground surface generated by the earthquake, g=acceleration of gravity, σ_{v0} and σ_{v0}'= total and effective overburden stresses, r_d=stress reduction coefficient depending on depth.

The stress reduction coefficient r_d is added to adjust for the flexibility of the soil profile because the soil does not respond as a rigid body.

For routine practice the values of r_d are estimated from the chart by Seed and Idriss [7] shown in Fig. 1. This chart was determined using a limited number of input strong motion and soil profiles having sand in the upper ±15 m. The dashed line labeled "Avarage values" represents the recommended values of r_d from the surface to a depth of 12 m (~40 ft) [4].

The value of r_d decreases from a value of 1 at the ground surface to lower value at large depths.

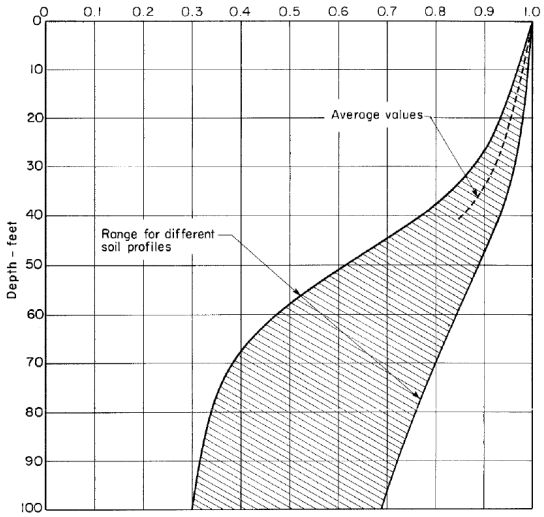

Figure 1. Range of values of r_d for different soil profiles (from Idriss [7]).

The following equations can be used to estimate the average r_d value given in the chart from the surface to a depth 30 m (~100 ft):

$$r_d = 1.0 - 0.00765z \quad for\ z \leq 9.15m \quad (2.1)$$

$$r_d = 1.174 - 0.0267z \quad for\ 9.15m < z \leq 23m \quad (2.2)$$

$$r_d = 0.744 - 0.008z \quad for\ 23m < z \leq 30m \quad (2.3)$$

where z=depth below ground surface in meters.

The equations (2.1) and (2.2) were proposed by Liao and Whitman [8] and the Eq. (2.3) was added by Robertson and Wride [9]. Youd et al. [10] suggest the Eq. (2.1) and (2.2) for noncritical projects and did not recommend values of r_d below a depth of 23 m. Indeed, the uncertainty of r_d increases with depth and the simplified procedure is not well verified for depths greater than 15 m [9]. Moreover, the r_d proposal of Seed and Idriss understates the variance and provides biased (generally high) estimated of r_d between 3 to 15 m. Unfortunately, it is the critical soil strata for evaluating soil liquefaction potential [1].

Several others relationship have been proposed due to the importance of assessment of CSR. Ishihara [11] performed a series of analysis using uniform soil profile and sinusoidal input motions and concluded that the parameter r_d can be expressed as:

$$r_d = \frac{V_S}{wz}\sin\left(\frac{wz}{V_S}\right) \quad (3)$$

where V_S=uniform soil shear wave velocity, w=frequency of excitation, z=depth. This relationship is plotted in Fig. 2.

Another simple and widely used relationship is the one proposed by Iwasaki [12] in which the parameter r_d is expressed through a linearly decreasing function with depth as

$$r_d = 1 - 0.015z \quad (4)$$

This function was obtained applying six earthquake motions to two alluvial deposits.

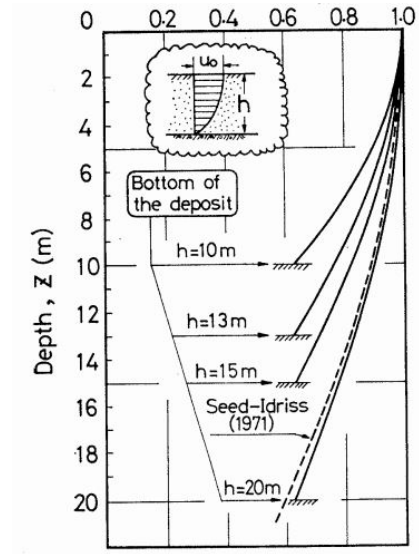

Figure 2. Stress reduction coefficient versus depth (from Ishihara [11])

In 1999, Idriss [13], based on studies carried out by Golesorkhi [14], performed several hundred parametric site response analysis and proposed a r_d relationship that takes into account the effects of earthquake magnitude and depth in the evaluation of r_d.

For z≤34 m the following equation was obtained:

$$\ln(r_d) = \alpha(z) + \beta(z)M \quad (5)$$

where

$$\alpha(z) = -1.012 - 1.126\sin\left(\frac{z}{11.73} + 5.133\right) \quad (5.1)$$

$$\beta(z) = 0.106 + 0.118\sin\left(\frac{z}{11.28} + 5.142\right) \quad (5.2)$$

For z>34 m the following expression is more appropriate:

$$r_d = 0.12\exp(0.22M) \quad (6)$$

in which z=depth in meters and M= moment magnitude. Plots of r_d calculated using previous equation for M=5½, 6½, 7½ and 8 are presented in Fig 3. Also shown, is the avarage of the range published by Seed and Idriss in 1971.

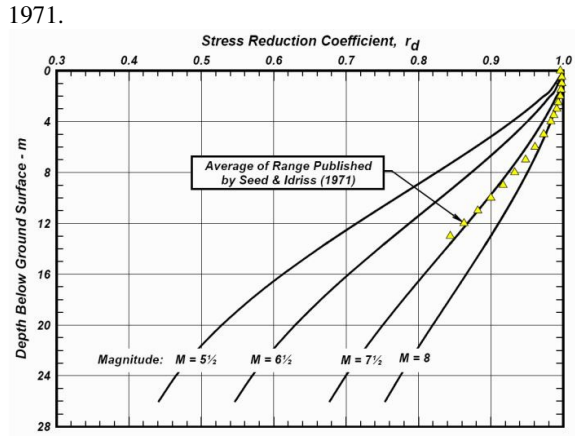

Figure 3. Variation of stress reduction coefficient with depth and earthquake magnitude (from Idriss [13]).

Cetin and Seed [4], using the Bayesian updating method, suggested new r_d correlations as a function of depth, earthquake magnitude, intensity of shaking and site stiffness. They performed a total of 2153 site response analyses by the equivalent linear method. The r_d recommendation proposed by Seed and Idriss [7] are conservatively biased compared to over 80,000 point estimations of r_d from 2153 cases as shown in Fig. 4.

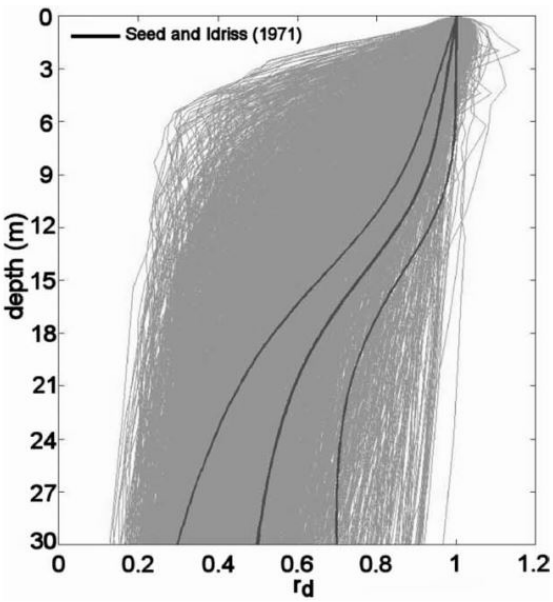

Figure 4. r_d results for all sites and motions superimposed with Seed and Idriss recommendations (from Cetin and Seed [4]) .

Another probabilistic relationship was developed by Kishida et al. [15, 16] using Monte Carlo simulations. The relationship was based on about 23,000 analyses. The input parameters were PGA, the average shear wave velocity and the spectral ratio parameter.

A recent study was realized by Lasley et al. [17]. They suggested a new r_d relationship from equivalent-linear site response analyses. Several forms for r_d were examined and the following form was selected for its simplicity and shape:

$$r_d = (1-\alpha)exp\left(\frac{-z}{\beta}\right) + \alpha \quad (7)$$

where α= limiting value of r_d at large depths, β= variable that controls the curvature of the function at shallow depths, z=depth in meters, $(1-\alpha)$=term that scales the exponential.

Two different sets of expression for α and β were proposed, one being a function of magnitude (Mw) and average shear-wave velocity in the upper 12 m of the profile (V_{S12}) and the other solely being a function of M_W. The first set of expressions for α and β is

$$\alpha_1 = \exp(b_1 + b_2 M_w + b_3 V_{S12}) \quad (7.1)$$

$$\beta_1 = exp(b_4 + b_5 M_w + b_6 V_{S12}) \quad (7.2)$$

and the second set is

$$\alpha_2 = \exp(b_1 + b_2 M_w) \quad (8.1)$$

$$\beta_2 = b_3 + b_4 M_w \quad (8.2)$$

where b_1-b_6 are regression coefficients.

3. Seismicity of the Catania area

The city of Catania, in South-Eastern Sicily (Italy), is subjected to high seismic hazards. It was shaken by a number of strong earthquake. In particular the events of February 1169, December 1542, January 1693, February 1818 and January 1848 produced relevant damages [18]. A repetition of events with similar characteristics would provide the additional risk of a damaging tsunami, as well as liquefaction phenomena around the coast [5].

Sismic Liquefaction phenomena were reported by historical souces following the 1693 (M_S =7.0-7.3, I_o=X-XI MCS) and 1818 (M_S =6.2, I_o=IX MCS) strong earthquakes [19-21] (Fig. 5., Fig.6.).

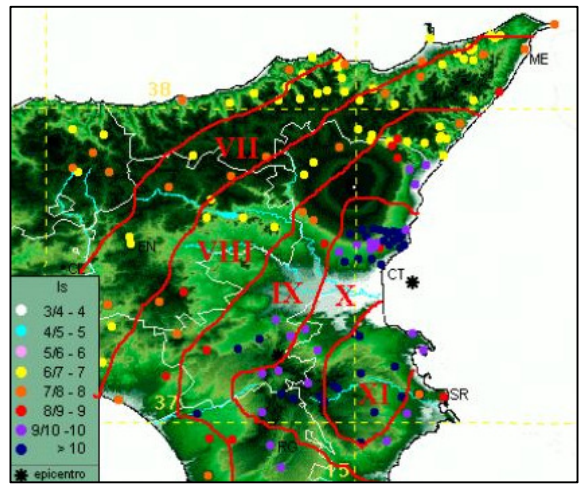

Figure 5. Isoseismal maps with shocked localities. Earthquake of January 11, 1693 After [22], modified.

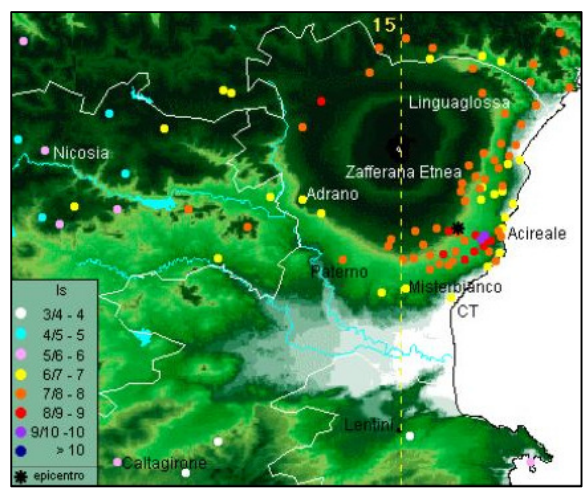

Figure 6. Isoseismal maps with shocked localities. Earthquake of February 20, 1818. After [22], modified.

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 [23].

The seismic event occurred on January 1693 has been chosen as scenario earthquake because it is the strongest remembered by Sicilians. It struck a vast territory of south-eastern Sicily and caused the partial, and in many cases total, destruction of 57 cities and 60000 casualties [24-26].

4. Site Response Analysis

Local site risponse analyses, as well as dynamic soil-structure interaction analyses, have been brought in Catania (Sicily, Italy), which is recognized as a typical Mediterranean city at high seismic risk [27-30]. To evaluate geotechnical characteristics of the soil, in situ and laboratory tests were performed [31].

In the Saint Giuseppe La Rena site eight boreholes (No. 418-425) were made. The depth of the boreholes varies from 10 to 30 meters, the water table lies around 2 m below the grond surface and, for all of them, Standard Penetration Tests (SPTs) date are available.

Near the borings eleven Cone Penetration Tests (CPTs) were also made. The subsoil exploration revealed the presence of a sand with a content of fine particles less then 30 % for a depth of about 10 meters.

More recently, at the same site, Seismic Dilatometer Marchetti Test (SDMT) has been performed. The locations of the SPTs, CPTs and SDMT are reported in Fig. 7. [3].

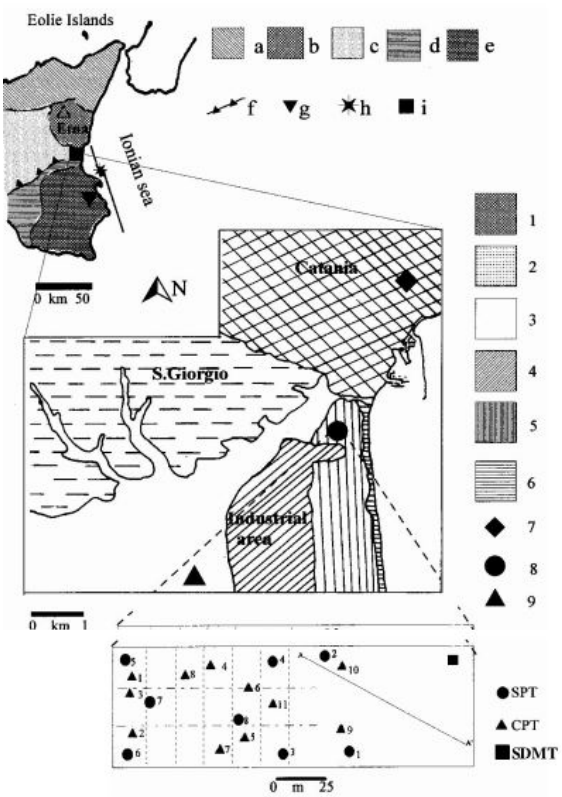

Figure 7. Location of SPT, CPT and SDMT tests (from Grasso [3]).

The SDMT has an effective depth of 23 m and has been carried out with the aim to evaluate the soil profile of shear wave velocity for the site response analysis. V_S measurements have been incorporated within a Marchetti flat dilatometer (DMT) by placing a velocity trasducer in a connectiong rod just above the blade [3].

SDMT obtained parameters are: I_d : Material Index; gives information on soil type (sand, silt, clay); M: Vertical Drained Constrained Modulus; ϕ: Angle of Shear Resistance; K_D : Horizontal Stress Index; Vs: Shear Waves Velocity; $G_0 = \delta V_S^2$ Small Strain Shear Modulus.

Shear wave velocity plays a fundamental role in seismic analyses. It is widely recognized that Nspt-value and S-wave velocity of sands are variables dependent on several parameters such us combinations of effective stress, void ratio, soil fabric, etc. [32].

The possibility of using the standard penetration test blowcounts, in order to determine the V_S, is based on the presence in the literature of several empirical correlations that relate V_S and Nspt-values.

The following empirical correlations have been used to obtained the shear wave velocity profiles, as a function of depth, for each of the eight boreholes.

a) Ohta and Goto [33]:

$$V_S = 54.33(N_{SPT})^{0.173}\alpha\,\beta\left(\frac{z}{0.303}\right)^{0.193} \quad (9)$$

where V_S = shear wave velocity (m/s), N_{SPT}= number of blow from SPT, z= depth in meters, α= age factor (Holocene=1.000, Pleistocene=1.303), β=geological factor (clays=1.000, sands=1.086).

b) Yoshida and Motonori [34]:

$$V_S = \beta(N_{SPT})^{0.25}\sigma_{V0}'^{0.14} \quad (10)$$

where V_S = shear wave velocity (m/s), N_{SPT}= number of blow from SPT, β =geological factor (any soil=55, fine sand=49), σ_{v0}'= effective vertical stress.

In Fig. 8., the shear wave velocities are shown against depth for borehole 421, as an example, by Eq. (9) and (10) . Also shown, is the shear wave velocity from SDMT. It is possible to notice that the values obtained with the correlation of Yoshida and Motonori are slightly higher than values determined with the correlation of Ohta and Goto and closer than the values measured from the SDMT. Thus, it was decided to choose for the seismic response analysis, the values of V_s calculated with the Eq. (10), because they are more likely to adhere to the real values.

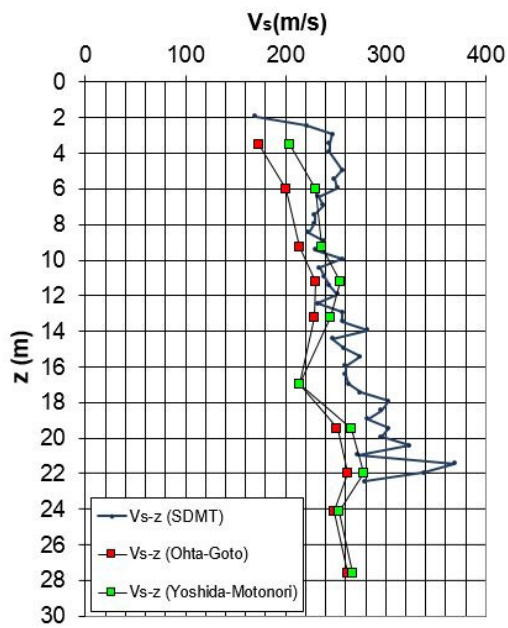

Figure 8. Comparison of V_S determined from empirical correlations and SDMT.

In addition to situ investigations, the following laboratory tests were carried out on undisturbed samples: N° 6 Resonant Column tests, N° 3 Direct shear tests and N° 3 Triaxial tests.

The experimental results of Resonant Column tests were used to determine the empirical parameters of the equation proposed by Yokota et al. [35] to describe the shear modulus decay with shear strain level:

$$\frac{G(\gamma)}{G_0} = \frac{1}{1+\alpha\gamma(\%)^{\beta}} \quad (10)$$

The values of $\alpha = 9$ and $\beta = 0.815$ were obtained.

As suggested by Yokota et al. [35], the inverse variation of damping ratio with respect to the normalized shear modulus has an exponential form:

$$D(\gamma)(\%) = \eta \exp\left[-\lambda \frac{G(\gamma)}{G_0}\right] \quad (11)$$

in which: D(γ) = strain dependent damping ratio, γ = shear strain, η, λ = soil constants. The values of η = 80 and λ = 4 were obtained [36].

Local site response analyses have been performed using 1-D linear equivalent code EERA assuming geometric and geological models of substrate as 1-D physical models.

The shear wave velocity profiles used for soil response analyses are obtained from SPTs date, available for all the eight boreholes (N°418-425), and SDMT performed in the Saint Giuseppe La Rena site. The values of the other parameters were taken from the geotechnical characterization obtained through in situ and laboratory tests performed.

The dynamic response model requires the knowledge of the depth of bedrock. The criteria of choice adopted to evaluate the depth of bedrock consists in the linear interpolation of the shear waves profiles. The depth obtained is approximately 80 m which corresponds to a Vs value of about 800 m/s.

During strong earthquakes, such as that of 1693 assumed as the scenario event in this study, the soil tend to behave as non-linear material. To take into account the soil non linearity, laws of shear modulus and damping ratio against strain have been insert in the code.

The nine 1-D colums are excited at the base using scaled seismograms of 1693, to the maximum PGA of 0.3 g and to the maximum PGA of 0.5 g. Fig. 9-10 show the results in terms of maximum accelerations with depth for SDMT and No. 418-425 boreholes.

5. Shear Stress Reduction Factor r_d in the Catania Area (Italy)

The earthquake-induced CSR can be estimated using the Eq. (1), developed as part of the Seed-Idriss Simplified Liquefaction Procedure.

Central to this procedure is the evaluation of the stress reduction coefficent r_d as a parameter describing the ratio of cyclic stress for a flexible soil column to the cyclic stress for a rigid soil column [4] (Fig. 11.):

$$r_d = \frac{(\tau_{max})_{deformable\ soil}}{(\tau_{max})_{rigid\ body}} \quad (12)$$

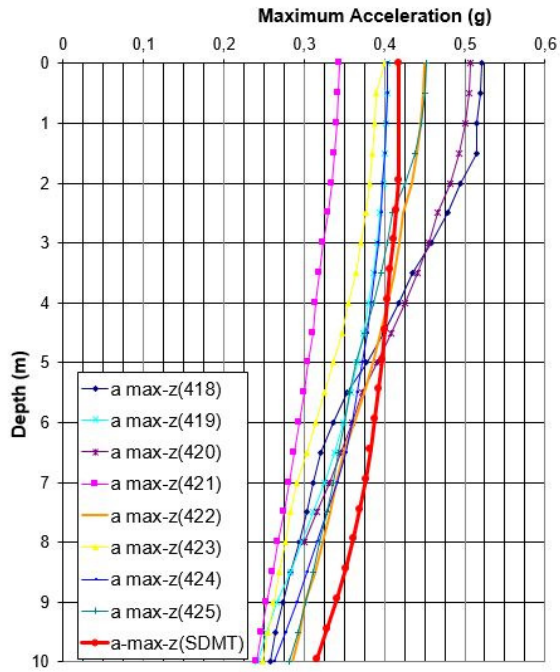

Figure 9. Maximum acceleration with depth for SDMT and for No. 418-425 boreholes using as input the 1693 scaled synthetic seismogram to the maximum PGA of 0.3 g.

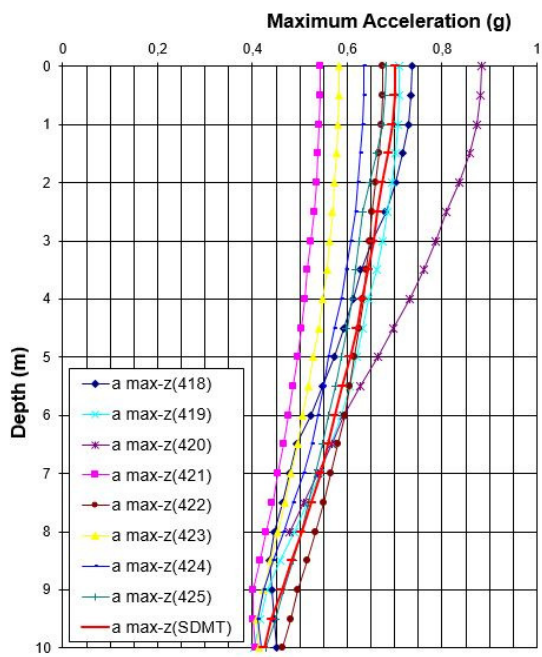

Figure 10. Maximum acceleration with depth for SDMT and for No. 418-425 boreholes using as input the 1693 scaled synthetic seismogram to the maximum PGA of 0.5 g.

Herein, new stress reduction coefficient r_d relationships are proposed for the eastern coastal plain of Catania area (Italy). They have been developed from equivalent-linear site response analyses performed on soil profiles obtained from SPTs date, available for eight boreholes (No. 418-425), and from SDMT carried out in the Saint Giuseppe La Rena site. It is an area located on the eastern coastal zone of Sicily and subjected to hight seismic hazards, as well as, the whole city of Catania.

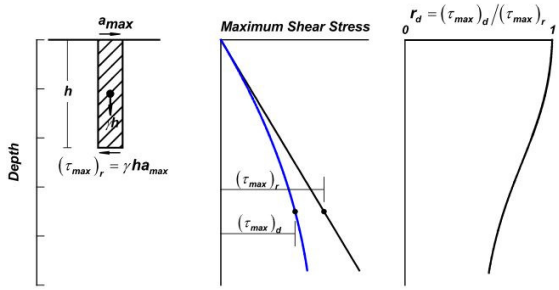

Figure 11. Schematic for determining maximum shear stress, τ_{max}, and the stress reduction coefficient, r_d tests (from Idriss [37]).

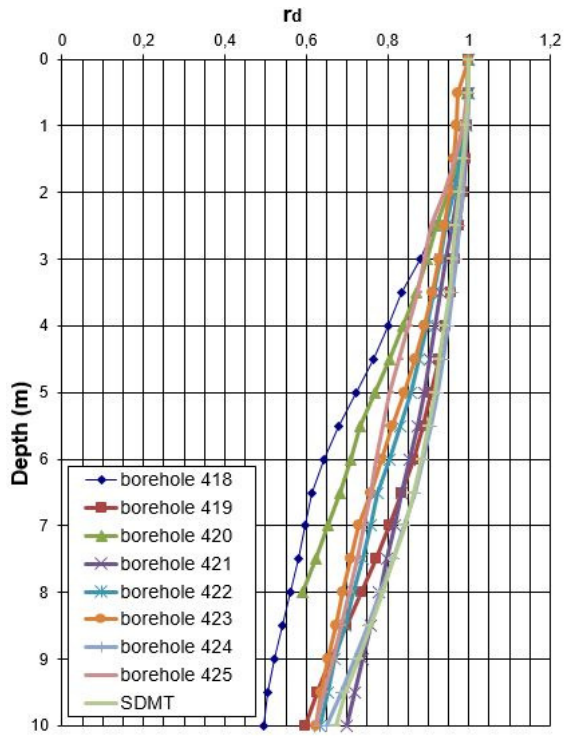

Figure 12. r_d results from Response Analyses for different soil profiles using as input the 1693 scaled synthetic seismogram to the maximum PGA of 0.3 g.

The seismic event of 1693, considered one of the biggest earthquakes which occurred in Italy, has been chosen as scenario earthquake. The nine 1-D colums are excited at the base using scaled seismograms of 1693 earthquake.

The Fig. 12. and Fig. 13 show the results of seismic site response analyses obtained from the synthetic seismograms of 1693 with a PGA of 0.3 g and 0.5 g to evaluate the variation of r_d over range of soil profiles.

According to the approach originally proposed by Seed and Idriss [7], it has been determined the ranges of values of r_d for sandy saturated soil profiles of eastern coastal Catania area. They are shown in the Fig. 14. and Fig. 15.

The dashed line labeled "Avarage values" represents the recommended values of r_d from the surface to a depth of 10 m. They can be approximated by Eq. 13 and 14.

$$r_d = 1 - 0.0389\, z \qquad z \leq 10\text{m}, \text{PGA} = 0.3\text{g} \qquad (13)$$

$$r_d = 1 - 0.0362\, z \qquad z \leq 10\text{m}, \text{PGA} = 0.5\text{g} \qquad (14)$$

Liquefaction evaluations for depths greater than about 10 m could benefit from site response analyses because the uncertainty in r_d becomes large at these depths [38].

It is possible to notice that Eq. (14) provides a slope of the straight line slightly lower than that given by Eq. (13). This is due to the fact that, during strong motion, the soil tend to behave as non-linear.

In Fig. 16, the r_d relationships obtained for soil profiles of Catania coastal area are compared to relationships previously proposed by Liao-Whitman [8] and Iwasaki [12]. As can be seen from the chart, the latter provide higher estimates of r_d.

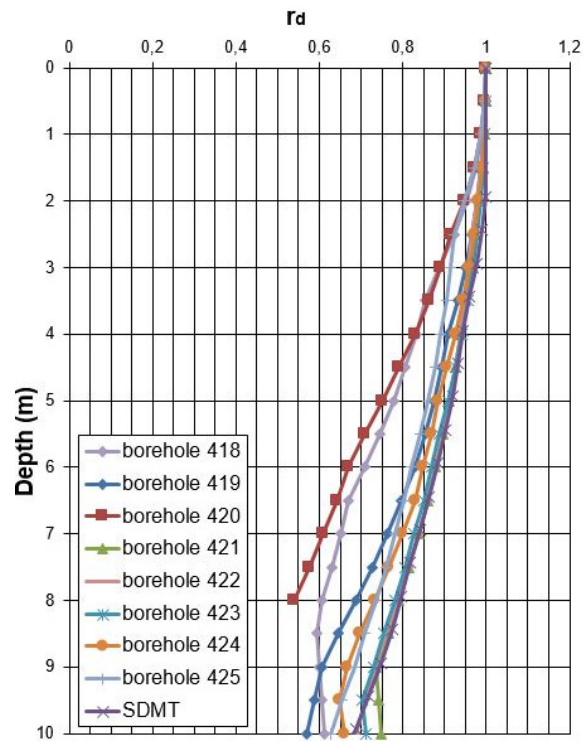

Figure 13. r_d results from Response Analyses for different soil profiles using as input the 1693 scaled synthetic seismogram to the maximum PGA of 0.5 g.

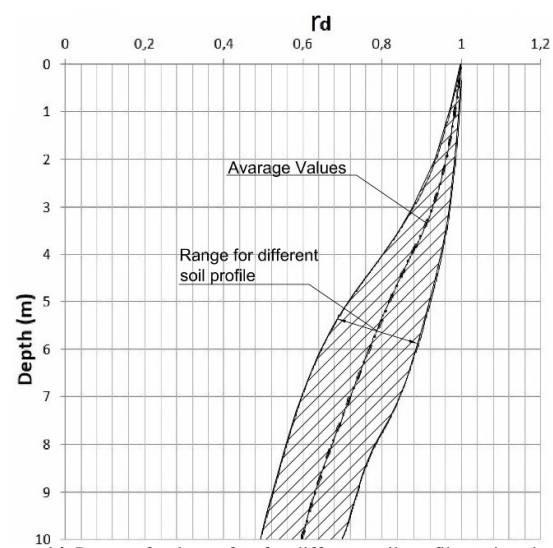

Figure 14. Range of values of r_d for different soil profiles using the 1693 scaled synthetic seismogram to the maximum PGA of 0.3g.

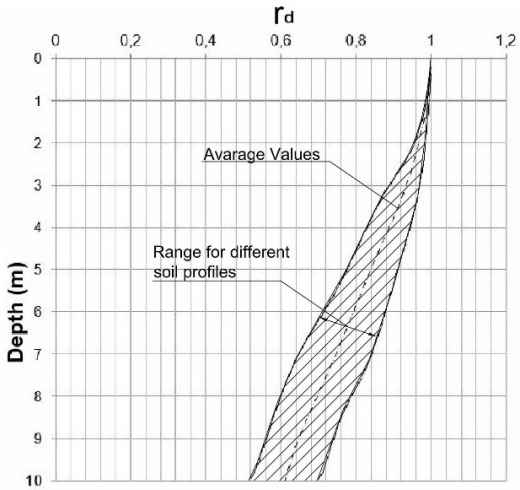

Figure 15. Range of values of r_d for different soil profiles using the 1693 scaled synthetic seismogram to the maximum PGA of 0.5g.

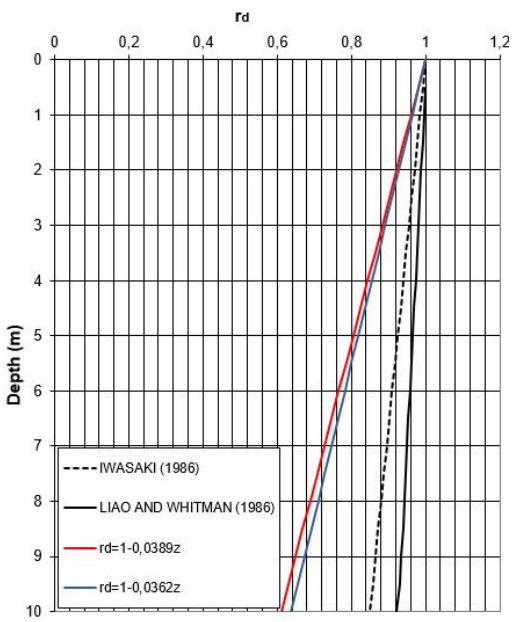

Figure 16. Comparison of r_d relationships obtained by Iwasaki [12], Liao-Whitman [8] to relationships proposed in this study.

6. Conclusions

In this paper, a new variation of r_d with depth has been obtained from equivalent-linear site response analyses performed on different profiles representative of eastern coastal plain of the Catania area.

To evaluate the soil profiles and the geotechnical characteristics the following in situ and laboratory tests were performed: N°. 11 Cone Penetration Tests (CPT), N°. 8 Standard Penetration Tests (SPT), N°. 1 Seismic Dilatometer Tests (SDMT), N°. 3 Direct Shear Tests; N°. 3 Triaxial CD Tests; N°. 6 Resonant Column Tests (RCT).

Two different charts were determined analytically using synthetic seismograms of 1693 with PGA of 0.3g and 0.5 g for imput motion. The dashed range represents the range of r_d values and the dashed line represent the recommeded values of r_d from the surface to a depth of 10 m.

Avarage values can be approximated by Eq. (13) and Eq. (14).

Comparing the relationships obtained in this study to the relationships previously proposed by Liao-Whitman and Iwasaki, it is possible to notice that the values of r_d obtained here are lower.

This work is useful for potential liquefaction evaluation in the eastern coastal plain of Catania area because it might benefit from the new r_d relationships more responsive to soil types examined. Moreover, the site response analyses have been performed using only the seismogram of the 1693 earthquake scaled to different accelerations. Thus, it could be interesting for further studies to add additional seismograms to better capture the variability of the seismic loading.

References

[1] Seed, R. B., Cetin, K. O., Moss, R. E. S., Kammerer, A. M., Wu, J., Pestana, J. M., Reimer, M. F. "Recent advances in soil liquefaction engineering and seismic siteresponse evaluation", 4th International Conference and Sym-posium on Recent Advances in Geotechnical Earthquake Engineeringand Soil Dynamics, Univ. of Missouri, Rolla, Paper SPL-2, pp. 7-8, 2001.

[2] Marcuson, W. F., III. "Definition of terms related to liquefaction", J. Geotech. Engrg. Div., ASCE, 104(9), pp. 1197–1200, 1978.

[3] Grasso, S., Maugeri, M. "The Seismic Dilatometer Marchetti Test (SDMT) for Evaluating Liquefaction Potential Under Cyclic Loading", Proc. IV Geotechnnical Earthquake Engineering and Soil Dynamics. Sacramento, USA, May 18-22, 2008. Geotechnical Earthquake Engineering and Soil Dynamic IV GSP 181 © 2008 ASCE, Geo Institute, ISBN 978-0-7844-0975-6, 15 p., 2008.

[4] Cetin, K. O., Seed, R. B. "Nonlinear shear mass participation factor (r_d) for cyclic shear stress ratio evaluation", Soil Dynamics and Earthquake Engineering, Vol. 24, pp. 103-113, 2004. https://doi.org/10.1016/j.soildyn.2003.10.008

[5] Maugeri, M., Grasso, S. "Liquefaction potential evaluation at Catania Harbour (Italy)", WIT Trans Built Environment, pp. 69-81, 2013. https://doi.org/10.2495/ERES130061

[6] Cavallaro, A., Capilleri, P.P., Grasso, S. "Site characterization by dynamic in situ and laboratory tests for liquefaction potential evaluation during emilia romagna earthquake", Geosciences (Switzerland) Open Access Volume 8, Issue 7, 29 June 2018, Article number 242.

[7] Seed, H. B., Idriss, I. M. "Simplified procedure for evaluating soil liquefaction potential", Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 97, pp. 1249–1273, 1971.

[8] Liao, S. S. C., Whitman, R. V. "Overburden Correction Factor for SPT in Sands", Journal of Geotechnical Engineering, ASCE, Vol. 112, No. 3, pp. 373–377, 1986. https://doi.org/10.1061/(ASCE)0733-9410(1986)112:3(373)

[9] Robertson, P. K., Wride, C. E. "Cyclic Liquefaction and its Evaluation Based on the SPT and CPT", NCEER Workshop on Evaluation of Liquefaction Resistance of Soils, Technical Report NCEER-97-0022, pp. 3-4, 1997.

[10] Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Finn, W.D.L., Harder, L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., & Stokoe, K.H. "Liquefaction Resistance of Soils: Summary Report from the 1996NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils", J. Geotech. Geoenviron. Eng., ASCE, 127(10), pp. 817-833, 2001.

[11] Ishihara, K. "Simple method of analysis for liquefaction of sand deposits during earthquakes", Soils and Foundations, 17(3), pp. 1 – 17, 1977. https://doi.org/10.3208/sandf1972.17.3_1

[12] Iwasaki, T. "Soil liquefaction studies in Japan: state-of-the-art", Soil Dyn Earthquake Engng, pp. 1 – 68, 1986. https://doi.org/10.1016/0267-7261(86)90024-2.

[13] Idriss, I. M. "An update to the Seed-Idriss simplified procedure for evaluating liquefaction potential", Proceedings, TRB Workshop on New Approaches to Liquefaction, Publication No. FHWARD-99-165, Federal Highway Administration, 1999.

[14] Golesorkhi, R. "Factor influencing the computational determination of earthquake-induced shear stressed in sandy soils", Ph. D. thesis, University of California, Berkeley, p. 395, 1989.

[15] Kishida, T., Boulanger, R. W., Abrahamson, N. A., Driller, M. W., and Wehling, T. M. "Site effects for the Sacramento-San Joaquin Delta", Earthquake Spectra, EERI, 25(2), pp 301-322, 2009.
https://doi.org/10.1193/1.3111087

[16] Kishida, T., Boulanger, R. W., Abrahamson, N. A., Driller, M. W., and Wehling, T. M., "Seismic response of levees in Sacramento-San Joaquin Delta" Earthquake Spectra, EERI, 25(3), pp. 557-582, 2009.
https://doi.org/10.1193/1.3157259

[17] Lasley, S.J., Green, R. A., Rodriguez-Marek, A. "New stress reduction coefficient relationship for liquefaction triggering analyses", Journal of Geotechnical and Geo-environmental Engineering, 142 (11): 06016013, pp. 1-8, 2016.
https://doi.org/10.1061/(asce)gt.1943-5606.0001530

[18] Bonaccorso, R., Grasso, S., Lo Giudice, E., Maugeri, M. "Cavities and hypogeal structures of the historical part of the City of Catania", Advances in Earthquake Engineering Volume 14, 2005, Pages 197-223.

[19] Grasso, S., Maugeri, M. "The Road Map for Seismic Risk Analysis in a Mediterranean City", Soil Dynamics and Earthquake Engineering, ISSN: 0267-7261. 29 (6), pp. 1034-1045, 2009.
https://doi.org/10.1016/j.soildyn.2008.12.001

[20] Grasso, S., Maugeri, M. "The Seismic Microzonation of the City of Catania (Italy) for the Maximum Expected Scenario Earthquake of January 11, 1693", Soil Dynamics and Earthquake Engineering, 29 (6), pp. 953-962, 2009.
https://doi.org/10.1016/j.soildyn.2008.11.006

[21] Grasso, S., Maugeri, M. "The Seismic Microzonation of the City of Catania (Italy) for the Etna Scenario Earthquake (M=6.2) of February 20, 1818", Earthquake Spectra, Vol. 28 (2), pp. 573-594, 2012.
https://doi.org/10.1193/1.4000013

[22] Monachesi, G., Stucchi, M. "DOM4.1: an intensity database of damaging earthquakes in the Italian area", GNDT-CNR open file report, 2 vv., Milano. Website: http://emidius.mi.ingv.it/DOM/.

[23] Castelli, F., Grasso, S., Lentini, V., Massimino, M. R. "In situ measuremnts for evaluating liquefaction potential under cyclic loading", 1st 1MEKO TC4 International Workshop on Metrology for Geotechnics, MetroGeotechnics 2016, pp. 79-84, 2016.

[24] Cavallaro, A., Massimino, M.R., Maugeri, M. "Noto Cathedral: soil and foundation investigation", Construction and Building Materials Journal, vol. 17, pp. 533-541, 2003.
https://doi.org/10.1016/S0950

[25] Grasso, S., Maugeri, M. "Seismic Microzonation Studies for the City of Ragusa (Italy)", Soil Dynamics and Earthquake Engineering. ISSN: 0267-7261. Vol. 56 (2014), pp. 86–97. doi: 10.1016/j.soildyn.2013.10.004.

[26] Castelli, F., Cavallaro, A., Grasso, S. "SDMT soil testing for the local site response analysis", 1st IMEKO TC4 International Workshop on Metrology for Geotechnics, MetroGeotechnics 2016, Pages 143-148.

[27] Abate, G., Massimino, M.R., Romano, S., "Finite Element Analysis of DSSI Effects for a Building of Strategic Importance in Catania (Italy) ", Procedia Engineering, Vol. 158, 2006, pp. 374-379. ISSN: 18777058. doi: 10.1016/j.proeng.2016.08.458. 2016.

[28] Abate, G., Corsico, S., Massimino, M.R., "FEM Modelling of the Seismic Behavior of a Tunnel-soil-Aboveground Building System: A Case History in Catania (Italy)". Procedia Engineering. Vol. 158, 2016, pp. 380-385. ISSN: 18777058. doi: 10.1016/j.proeng.2016.08.459. 2016.

[29] Caruso, S., Ferraro, A., Grasso, S., Massimino, M.R., "Site Response Analysis in eastern Sicily based on direct and indirect Vs measurements". 1st IMEKO TC4 International Workshop on Metrology for Geotechnics, MetroGeotechnics 2016, pp. 115-120. ISBN: 978-929900750-1. 2016.

[30] Massimino, M.R., Abate, G., Corsico, S., Louarn, R., "Comparison Between Two Approaches for Non-linear FEM Modelling of the Seismic Behaviour of a Coupled Soil–Structure System". Geotechnical and Geological Engineering. Vol. 37, Issue 3, 1 June 2019, pp. 1957-1975. ISSN: 09603182. doi: 10.1007/s10706-018-0737-y. 2019.

[31] Castelli, F., Cavallaro, A., Ferraro, A., Grasso, S., Lentini, V., Massimino, M.R., "Static and dynamic properties of soils in Catania (Italy)". Annals of Geophysics, Vol. 61, Issue 2, 2018, Article number SE221. ISSN: 15935213. doi: 10.4401/ag-7706. 2018.

[32] Kokusho, T., Yoshida, Y., "SPT N-value and S-wave velocity for gravely soils with different grain size distribution", Soils and Foundations, 37 (4), pp. 105–113, 1997.

[33] Ohta, Y., Goto N. "Empirical Shear Wave Velocity Equations in Terms of Characteristic Soil Indexes", Earthquake Engineering and Structural Dynamics,Vol. 6, pp. 167–187, 1978.
https://doi.org/10.1002/eqe.4290060205

[34] Yoshida Y., Motonori I. "Empirical Formulas of SPT Blow-Counts for Gravelly Soils", Proceedings of ISOPT-1, Orlando (USA), pp. 381–387, 1988.
https://doi.org/10.1007/s11069-017-2744-3

[35] Yokota, K., Imai, T., Konno, M. "Dynamic Deformation Characteristics of Soils Determined by Laboratory Tests", OYO Tec. Rep. 3, pp. 13 – 37, 1981.

[36] Ferraro, A., Grasso, S., Massimino, M., "Site Response Analysis and Liquefaction Hazard Evaluation in the Catania Harbour (Italy)", In: Proceedings of the Third International Conference on the Flat Dilatometer. S. Marchetti, P. Monaco and A.V. Da Fonseca Eds., Rome, Italy, 14-16 June 2015, pp. 317-324.

[37] Idriss, I., M., Boulanger, R., W., "Semi-empirical procedures for evaluating liquefaction potential during earthquakes", Proc. of 11thICSDEE/3rdICEGEP roceedings, Stallion Press, 1, pp. 32-56, 2004.
https://doi.org/10.1016/j.soildyn.2004.11.023

[38] Boulanger, R., W., Idriss, I., M. "CPT and SPT based liquefaction triggering procedures", Report No. UCD/CGM-14/01, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, CA, p. 9, 2014.