29 Mar 2001, 7:30 pm - 9:30 pm

Soil Liquefaction and Risk Analysis From in Situ Tests for the City of Trapani (Italy)

Francesco Castelli
University of Catania, Italy

Antonio Cavallaro
University of Catania, Italy

Salvatore Grasso
University of Catania, Italy

Michele Maugeri
University of Catania, Italy

SOIL LIQUEFACTION AND RISK ANALYSIS FROM IN SITU TESTS FOR THE CITY OF TRAPANI (ITALY)

Francesco Castelli
University of Catania
Viale A. Doria, 6
95125 Catania

Antonio Cavallaro
University of Catania
Viale A. Doria, 6
95125 Catania

Salvatore Grasso
University of Catania
Viale A. Doria, 6
95125 Catania

Michele Maugeri
University of Catania
Viale A. Doria, 6
95125 Catania

ABSTRACT

The paper deals with a microzoning criterion based on CPT data to define liquefaction risk of the city of Trapani, Sicily (Italy). Zonation for liquefaction is a fundamental issue to prevent from seismic disasters since, as lessons of past earthquakes teach, liquefaction of sandy soils has been a major cause of damage to buildings. For the evaluation of the seismic risk of the municipal area of Trapani it has been chosen a scenario earthquake which may represent a possible repetition of the 1968 event. For this earthquake a Richter magnitude M= 6.0 and a maximum ground acceleration a_{max}= 0.30g have been estimated. While new tools and refinements continue to be developed on the subjects of pore pressure build-up due to earthquake shaking and of liquefaction triggering, reliable evaluation methods already exist for liquefaction microzonation purposes. This study focuses on the application of a method for the evaluation of the liquefaction potential to several sites of the city of Trapani, by means of relationships between liquefaction resistance and corrected cone penetration tests (CPT) resistance.

INTRODUCTION

During the last ten years several microzoning techniques have become available in relation to different purposes to be achieved. According to this, the Manual for Zonation on Seismic Geotechnical Hazards of the Technical Committee for Geotechnical Earthquake Engineering (TC4, 1999) includes methods for assessing local ground response, slope instability and soil liquefaction. Zoning for ground motions in the city of Trapani already exists (Carrubba and Maugeri, 1986), while the site does not present slope instability.
For zonation of the liquefaction risk of the municipal area of Trapani a scenario earthquake has been chosen, which may represent a possible repetition of the Belice earthquake (Fig. 1) of January 16^{th} 1968 with a Richter Magnitude M = 6.0 (CNR, 1985). Values of PGA varying in the range 0.10 ÷ 0.30g have been obtained, for this earthquake, using the Sabetta and Pugliese attenuation relation (Sabetta and Pugliese, 1987).
Because of difficulties in modelling all of the factors that affect the liquefaction resistance of a soil, in-situ penetration testing is the preferred method to estimate liquefaction resistance. In-situ penetration testing includes the cone penetration test (CPT) and the standard penetration test (SPT). The cone penetration test offers several advantages over the standard penetration test including better standardization, precision and accuracy, improved cost-effectiveness, and it provides a nearly continuous record of penetration resistance throughout a soil deposit. For these reasons, the cone penetration test has seen increasing popularity and use for liquefaction assessment (Maugeri and Vannucchi, 1999). However, the SPT is world wide used and allows verification of liquefaction resistance using existing correlations (Cascone et al., 1999). Site investigations for the city of Trapani within on area of approximately 10 Km^2, consist mainly of 82 cone penetration tests, 82 boreholes and many laboratory tests including shear strength tests performed in a static condition (Maugeri and Puglisi, 1986).

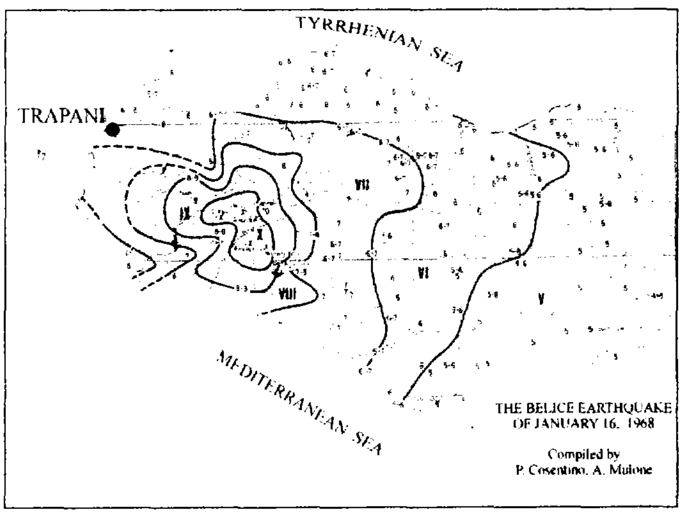

Fig.1. Isoseismal map for Belice 1968 Earthquake (after CNR, 1985)

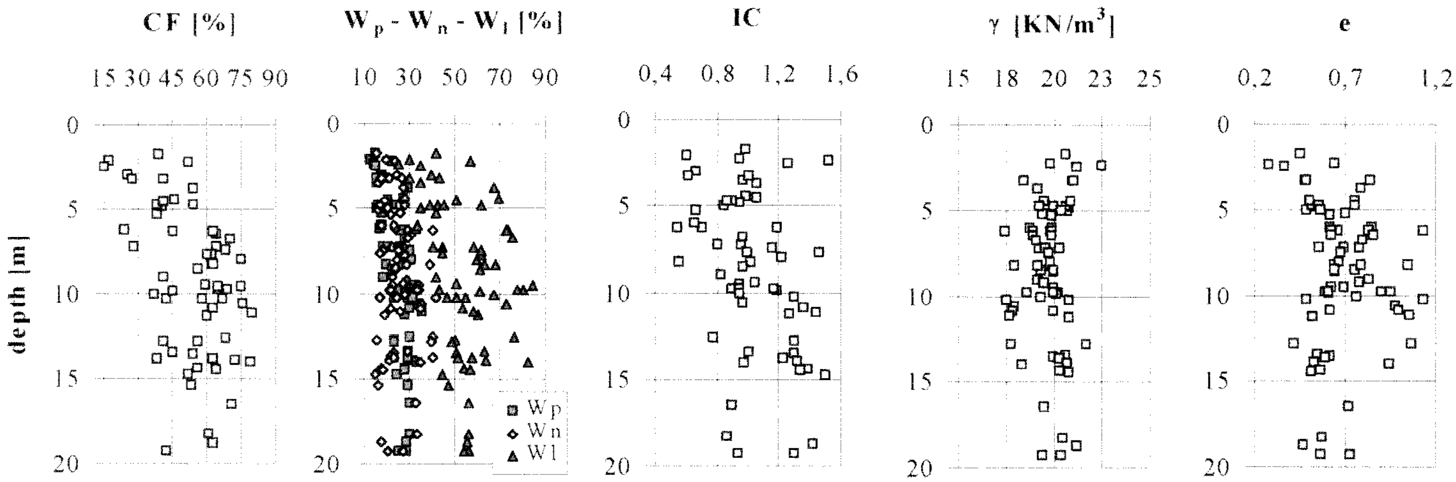

Fig. 2. Index properties of Trapani soil

GEOTECHNICAL SOIL CHARACTERIZATION

Boreholes driven to a depth of 20m were performed and undisturbed samples were retrieved for laboratory tests including shear strength tests performed into static conditions. The soil nature was calcarenite and silty clay or silty sand deposits which were highly variable in the first few meters.
The calcarenitic layers of a few meters thick are in some part of the city at ground surface, in other parts they were found at a certain depth.
The silty clay or silty sand deposits layers occasionally include calcareous detritus which is a product of alteration of Pleistocene calcarenitic rock.
The general characteristics and index properties of the Trapani soil are shown, as a function of depth, in figure 2. The values of the natural moisture content w_n prevalently range between 16 and 41 %. Characteristics values for the Atterberg limits are: w_l = 25 - 85 % and w_p = 15 - 35 %, with a plasticity index of PI = 19 - 53 %.
The data shown in figure 2 clearly indicate a low degree of homogeneity of the deposit. This indication is also confirmed by comparing the penetration resistance q_c from mechanical cone penetration tests (CPT) performed at different locations over the investigated area.
The variation of q_c with depth clearly shows the existence of layers with very different mechanical characteristics (Fig. 3).

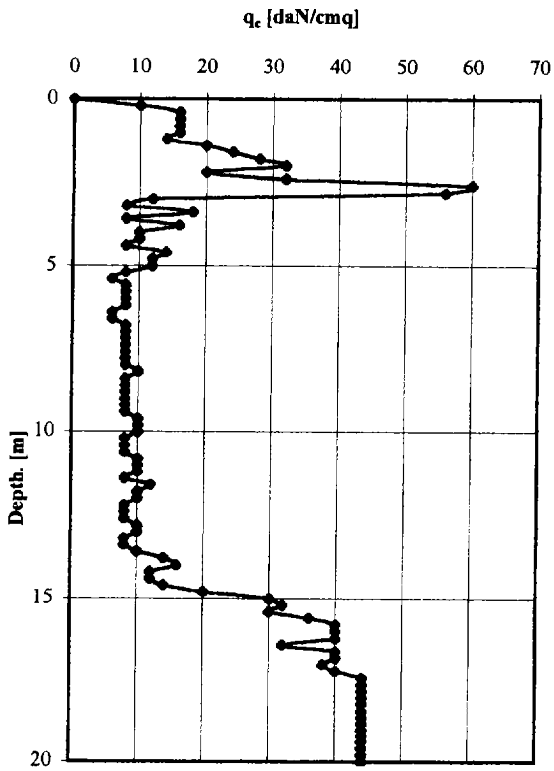

Fig. 3. Profile of the cone resistance q_c for CPT No. 16

CPT - BASED EVALUATION OF LIQUEFACTION POTENTIAL

During cyclic undrained loading, like those imposed by earthquake shaking, almost all saturated cohesionless soils are subjected to significant pore pressure build-up due to the contractive response of the soil at low strain levels. If there is shear stress reversal, the effective stress state can drop rapidly to zero.

When a soil element reaches the condition of essentially zero effective stress, the soil has very little stiffness and large deformations can develop during cyclic loading. This phenomenon is generally referred as liquefaction.
The susceptibility of a site to seismic-induced liquefaction may be assessed comparing the cyclic soil resistance to the cyclic shear stresses due to the ground motion. The latter is of course a function of the design earthquake parameters, while

the former depends on the soil shear strength and can be computed using results from in situ tests.
At present, the CPT can be considered the most important in situ test for evaluating liquefaction potential. Because it is more accurate and more repeatable than SPT. It is not expensive and it provides continuous resistance profiles. For these reasons, methods to assess soil resistance to liquefaction based on cone penetration test (CPT) data have been developed (Robertson and Campanella, 1985; Seed and De Alba, 1986; Olsen and Koester, 1995; Robertson and Fear, 1995; Suzuki et al., 1997).
In addition, in recent years, the growth of the statistical basis of CPT data have made it feasible to develop methods for liquefaction risk analysis directly from CPT results, which are very reliable. Some of these procedures not only do not need a previous knowledge of the size grain composition, but they also consider the other factors deriving from the presence of a fine fraction. The most credited among these procedures at present is the Robertson and Wride (1997) method, herein employed for the computation of the liquefaction potential of sandy soils of the city of Trapani.
This procedure consists of the following steps:
1) evaluation of the cyclic resistance ratio profile (CRR) determined for magnitude 7.5 earthquakes in function of the CPT data, by the following simplified equation:

$$\text{if } (q_{c1N})_{cs} < 50 \quad CRR_{7.5} = 0.833[(q_{c1N})_{cs} / 1000] + 0.05 \qquad (1)$$

$$\text{if } 50 \leq (q_{c1N})_{cs} < 160 \quad CRR_{7.5} = 93[(q_{c1N})_{cs} / 1000]^3 + 0.08 \qquad (2)$$

where $(q_{c1N})_{cs}$ is the clean sand cone penetration resistance normalized to 100 KPa.
2) evaluation of the cyclic stress ratio (CSR) profile in function of the seismic parameters of the scenario earthquake, by the following equation:

$$CSR = (0.65/MSF)[\, a_{max} (\sigma_{vo}/\sigma'_{vo})\, r_d] \qquad (3)$$

σ_{vo} and σ'_{vo} being the total and the effective vertical overburden stresses at the considered depth and r_d a stress reduction coefficient, given by the following expression:

$$r_d = 1 - 0.00765z \quad \text{for } z \leq 9.15\text{m} \qquad (4)$$
$$r_d = 1.174 - 0.0267z \quad \text{for } 9.15 < z \leq 23\text{m} \qquad (5)$$

MSF is a magnitude scaling factor, to evaluate cyclic resistance ratio profile (CRR) for magnitude other than 7.5, and it is calculated as follows:

$$\text{if } M < 7.5 \quad MSF = 0.5[10^{2.24}/M^{2.56} + (7.5/M)^{3.3}] \qquad (6)$$
$$\text{if } M = 7.5 \quad MSF = 1 \qquad (7)$$
$$\text{if } M > 7.5 \quad MSF = 10^{2.24}/M^{2.56} \qquad (8)$$

3) computation of the liquefaction safety factor (LSF) profile given by the ratio of CRR (z) divided by CSR (z) where z is the depth of the deposit.
4) Computation of the liquefaction potential index P_L (Iwasaki et al., 1978), given by the following expression:

$$P_L = \int_0^{20} F(z) w(z) dz \qquad (9)$$

where:
$$F(z) = 0 \text{ for } LSF \geq 1 \qquad (10)$$
$$F(z) = 1 - LSF \text{ for } LSF < 1 \qquad (11)$$
and
$$w(z) = 10 - 0.5z \qquad (12)$$

is a function, decreasing with depth, used to give a higher weight to the shallower part of the deposit in the evaluation of the risk of liquefaction occurrence. The risk levels associated to the values of the liquefaction potential index are shown in table 1.

P_L	RISK LEVEL
0	very low
$0 < P_L \leq 5$	low
$5 < P_L \leq 15$	high
$P_L > 15$	very high

Table 1. Liquefaction Potential Index and associated risk level.

ANALYSIS OF THE CPT TESTS RESULTS AND APPLICATION OF THE PROCEDURE

The penetrometric data of the 82 CPT were processed using Robertson and Wride method; by way of example, figure 3 shows the profile of the cone resistance q_c of the CPT test n.16. These data have been treated statistically (Maugeri and Puglisi, 1986) and have been grouped into 13 groups of similar CPT point resistance profiles (see for example q_c profile of group No. 2 in figure 4). The location of CPT test belonging to each group is reported in figure 5.

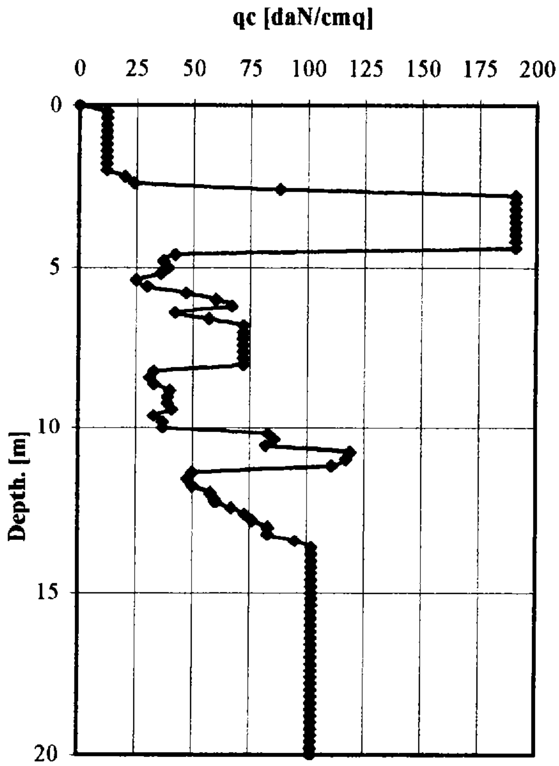

Fig. 4. Profile of the cone resistance q_c for group No. 3

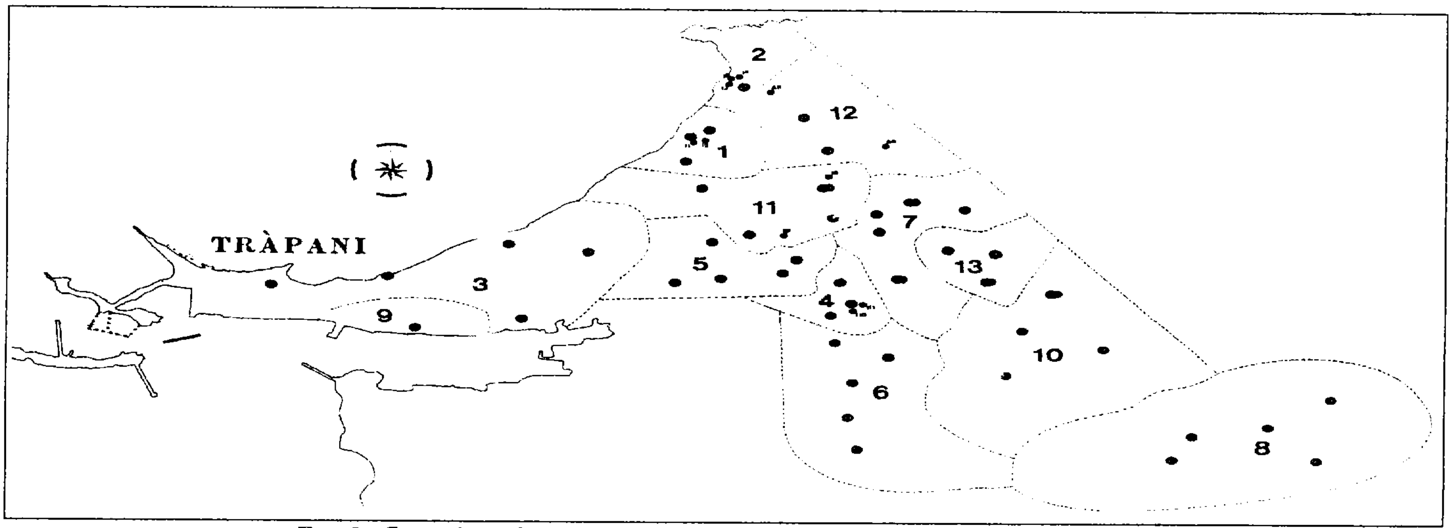

Fig. 5. Geotechnical mapping of homogeneous CPT data for the city of Trapani

The Robertson and Wride (1997) procedure defines a soil behaviour type index, I_c, which can be defined as follows:

$$I_c = [(3.47\text{-}\log Q)^2 + (\log F + 1.22)^2]^{0.5} \quad (13)$$

$$\text{where } F = [f_s/(q_c\text{-}\sigma_{vo})]100 \quad (14)$$

is the normalized friction ratio, in percent, and:

$$Q = (q_c\text{-}\sigma_{vo}) / \sigma'_{vo} \quad (15)$$

is the normalized CPT penetration resistance.
In addition, the apparent fine content FC (%) can be estimated from the penetrometric data as follows:

$$\text{if } I_c < 1.26 \quad FC(\%) = 0 \quad (16)$$

$$\text{if } 1.26 \leq I_c \leq 3.5 \quad FC(\%) = 1.75\, I_c^{3.35} - 3.7 \quad (17)$$

$$\text{if } I_c > 3.5 \quad FC(\%) = 100 \quad (18)$$

the FC (%) explains not only the actual fine content of the soil, but also the effect of the plasticity of the fine fraction. The FC (%) value of sandy soils of the Trapani site is, in general, in the range between 10 % and 20 %.
In figures 6 and 7 the profile of the cyclic stress ratio (CSR) and the profile of the cyclic resistance ratio (CRR) for CPT test No. I6, belonging to group No. 2 are shown.
In this case, the seismic design data employed are: a_{max} = 0.30 g and M = 6.0. Figure 8 provides a graph of the liquefaction potential index P_L for CPT test No. I6.
The liquefaction potential index computed according to Iwasaki et al. (1978) and to Robertson and Wride (1997) gives values of P_L greater than 5; therefore, for the design seismic action, the liquefaction risk must be considered to be high, because the threshold of $P_L = 5$ is exceeded.
Finally a parametric analysis has been performed to investigate the influence of the seismic maximum acceleration on the liquefaction potential index (computed according to Robertson and Wride).
In Figure 9, for CPT test No. 6, it is plotted the variation of P_L with depth for a_{max} ranging from 0.10 g to 0.30 g. Such results clearly demonstrate that the ground acceleration is a crucial parameter, in fact a 0,1g increase of a_{max} produce a dramatic doubling of the liquefaction potential index P_L.

ZONATION OF SEISMIC LIQUEFACTION RISK

In order to apply the procedure, by means of a statistical method, the total number of 82 tests have been grouped into 13 groups, determining the similarities between the various tests and obtaining for each group a resulting penetrometric profile representative of all tests of the group (Maugeri and Puglisi, 1986). Then, with the scenario earthquake of M=6.0 and a_{max}=0.30g, the liquefaction potential index was computed for the 13 homogeneous groups according to Iwasaki et al. (1978) and to Robertson and Wride (1997). The results of the applied procedure are shown in table 2.

Group No.	Liquefaction Potential Index (P_L)
1	5.54
2	11.21
3	5.41
4	1.15
5	6.63
6	2.38
7	0.43
8	0
9	8.70
10	0
11	3.49
12	1.98
13	0.25

Table 2. Liquefaction Potential Index of the 13 groups

CONCLUDING REMARKS

The results obtained applying the procedures by Robertson and Wride (1997) to the available CPT data for the city of Trapani grouped as shown in figure 5, allow to draw the following conclusions: the liquefaction risk level for groups 8 and 10 is very unlikely due to the high soil strength. The liquefaction risk level for groups 4, 6, 7, 11, 12 and 13 is low and concern unlikely depths greater than 10 meters. The liquefaction risk level for groups 1, 2, 3, 5 and 9 is high and is

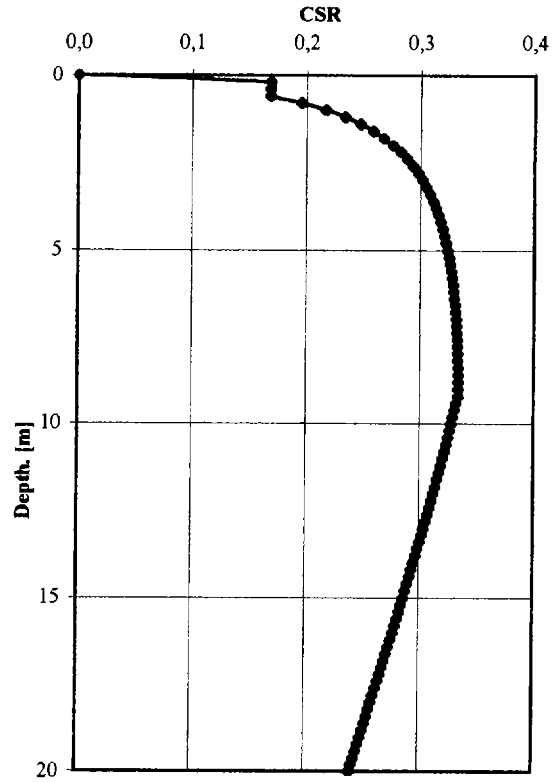

Fig. 6. Profile of the cyclic stress ratio CSR for CPT No. I6

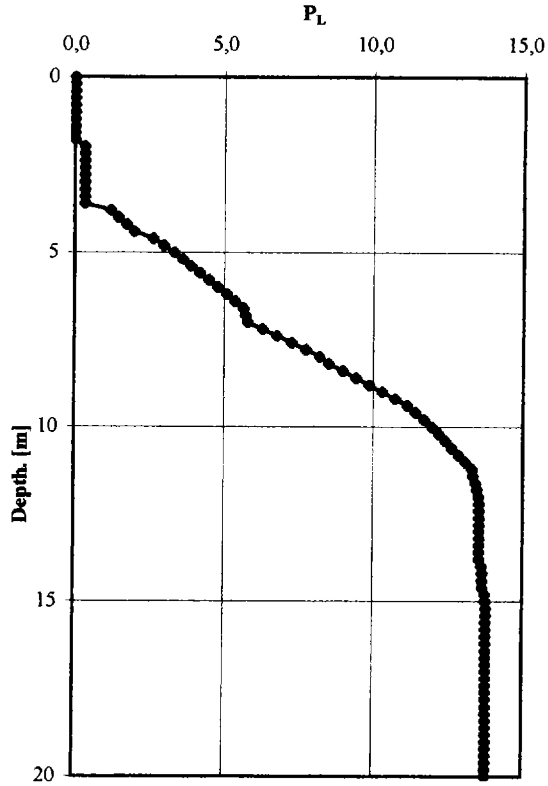

Fig. 8. Liquefaction potential index P_L for CPT No. I6

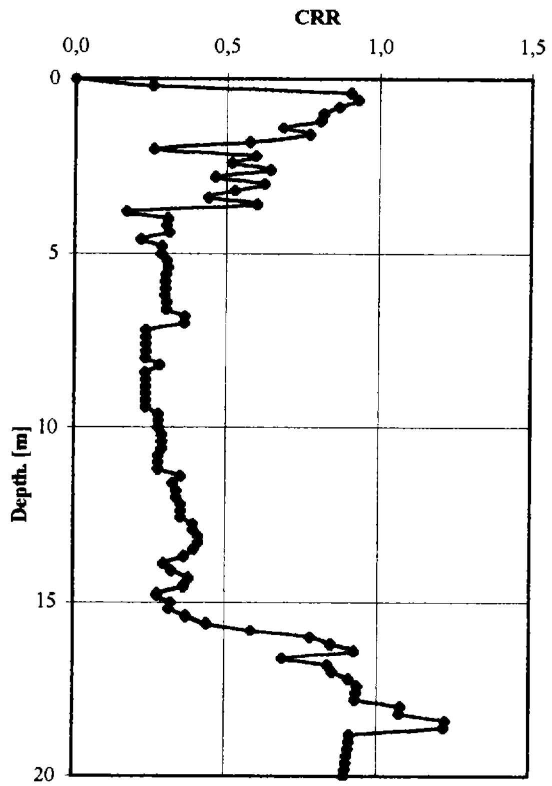

Fig. 7. Profile of the cyclic resistance ratio CRR for CPT No.I6

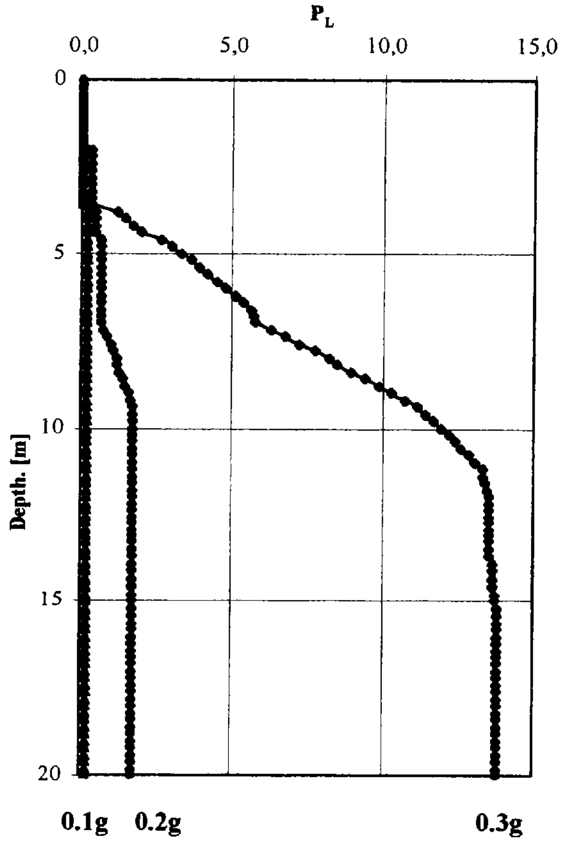

Fig. 9. Effect of the seismic design data on the P_L for CPT No. I6

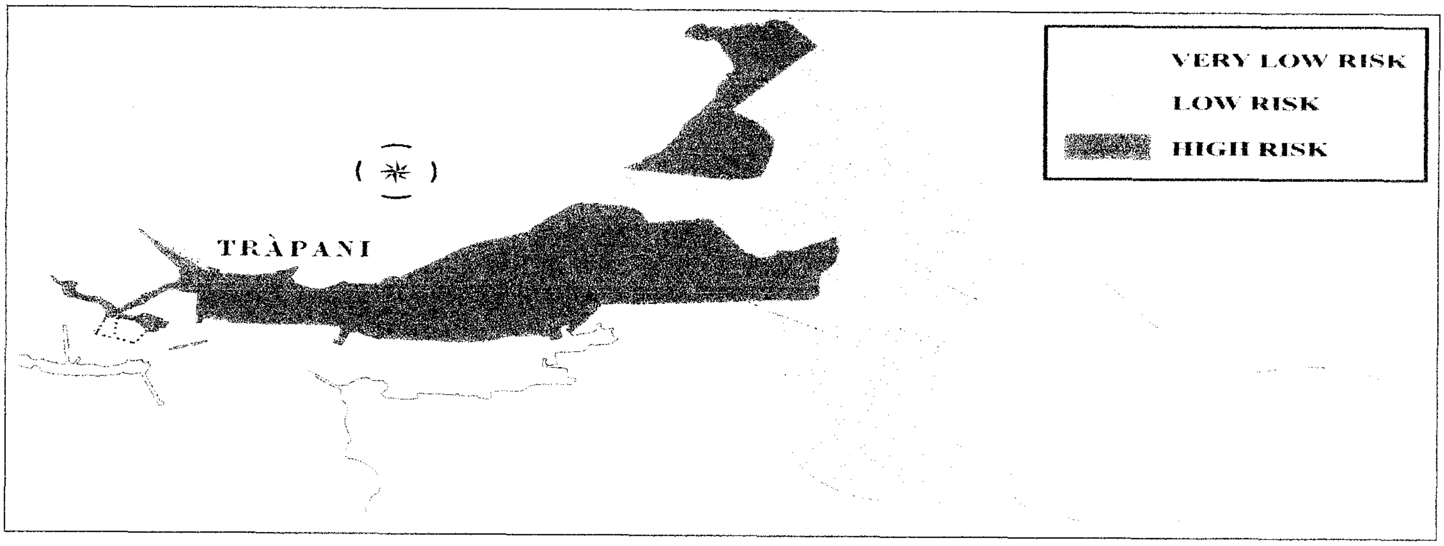

Fig. 10. Microzoning map of the liquefaction risk for the city of Trapani

relevant for the whole thickness of the sandy layer. Finally, a map of the liquefaction risk for the city of Trapani was obtained as shown in figure 10.

REFERENCES

Carrubba, P. and Maugeri, M. [1986]. *A microzoning proposal for the city of Trapani*, Proceedings of the International Symposium on Engineering Geology problems in seismic areas, Bari, Italy, Vol. III, pp. 305-318.

Cascone, E., Castelli, F., Grasso, S. and Maugeri, M. [1999]. *Zoning for soil liquefaction at Catania city (Italy)*, Proceedings of the International Conference on Earthquake Resistant Engineering Structures '99, pp. 311-320.

CNR - Progetto Finalizzato Geodinamica, [1985]. *Atlas of isoseismal maps of Italian earthquakes*, Fratelli Treves Editori-Milano.

Iwasaki, T., Tatsuoka, F., Tokida, K. and Yasuda, S. [1978]. *A practical method for assessing soil liquefaction potential based on case studies at various sites in Japan*, Proceedings of the 2nd International Conference on Microzonation for Safer Construction, Research and Application, San Francisco, California, Vol.II, pp. 885-896.

Manual for Zonation on Seismic Geotechnical Hazards [1999]. Technical committee for Earthquake Geotechnical Engineering, TC4, ISSMGE.

Maugeri, M. and Puglisi, A. [1986]. *CPT data for geotechnical zoning of large areas*, Proceedings of the International Symposium on Engineering Geology problems in seismic areas, Bari, Italy, Vol. III, pp. 373-386.

Maugeri, M. and Vannucchi, G. [1999]. *Liquefaction risk analysis at S.G. La Rena, Catania (Italy)*. Proceedings of the International Conference on Earthquake Resistant Engineering Structures '99, pp. 301-310.

Olsen, R.S. and Koester, J.P. [1995]. *Prediction of liquefaction resistance using the CPT*, Proceedings, International Symposium on Cone Penetration Testing, CPT'95. Linkoping, Sweden, Vol. II, pp. 251-256.

Robertson, P.K. and Campanella, R.G. [1985]. *Liquefaction potential of sands using the cone penetration test*, Journal of Geotechnical Division of ASCE, March 1985, 22(3), pp. 277-286.

Robertson, P.K. and Fear, C.E. [1995]. *Liquefaction of sands and its evaluation*, Proceedings, IS Tokyo '95, 1st International Conference on Earthquake Geotechnical Eng., Keynote Lecture.

Robertson, P.K. and Wride (Fear), C.E. [1997]. *Cyclic liquefaction and its evaluation based on SPT and CPT*, Final Contribution to the Proceedings of the 1996 NCEER Workshop on Evaluation of Liquefaction Resistance, Salt Lake City, Utah.

Sabetta F. and Pugliese A. [1987]. *Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records*, Bulletin of the Seismological Society of America, Vol.77, n.5, pp. 1491-1523.

Seed, H.B. and de Alba, P. [1986]. *Use of SPT and CPT tests for evaluating the liquefaction resistance of sands*, Use of in-situ Tests in Geotechnical Engineering, ASCE, Geotechnical Special Publication, Vol. VI, pp. 281-302.

Suzuki, Y., Koyamada, K. and Tokimatsu, K. [1997]. *Prediction of liquefaction resistance based on CPT tip resistance and sleeve friction*, Proceedings of XIV ICSMFE, Hambourg, Vol. I, pp. 603-606.