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SPT-BASED EVALUATION OF SOIL LIQUEFACTION RISK

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ABSTRACT

The city of Catania in Sicily (Italy) been destroyed in the past by the 1169 earthquake with XI MCS intensity, the 1693 earthquake with X MCS intensity and the 1818 earthquake with VIII MCS intensity. The standard approach for the evaluation of the liquefaction susceptibility is based on the estimation of a safety factor between the cyclic shear resistance to liquefaction and the earthquake induced shear stress. The liquefaction potential index has been evaluated in the area of the Catania port, near Saint Giuseppe La Rena, that experienced liquefaction because of the 1693 and 1818 earthquake. The site under study has been characterized by means of boreholes, in situ and laboratory tests. Liquefaction susceptibility has been evaluated by means of a procedure prescribed by the new Italian Code.

INTRODUCTION

Liquefaction of sandy soils under cyclic loading conditions is considered to be one of the major causes of failure of earth structures and foundations.

The coastal plain of the city of Catania (Sicily, Italy) is recognized as a typical Mediterranean city at high seismic risk (Figure 1). Seismic liquefaction phenomena were reported by historical sources following the 1693 (M = 7.0 to 7.3, Io = X to XI MCS) and 1818 (M = 6.2, Io = IX MCS) Sicilian strong earthquakes (Figure 2).

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.

The paper deals with a microzoning criterion based on SPT data to define liquefaction risk.

The susceptibility of a site to seismic-induced liquefaction may be assessed comparing the cyclic soil resistance (CRR) to the cyclic shear stresses (CSR) 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 SPT data. In fact, one of the most common parameter for estimating soil resistance to liquefaction is the number of blows N_{SPT} obtained from Standard Penetration Test (SPT).

The N_{SPT} value, not only reflects the soil relative density and the soil fabric, but also allows to estimate soil shear strength in undrained conditions, while most of the other in situ measurements are performed in drained conditions.

To define a seismic scenario, the seismic event occurred on January 1693, having a return period of about 300 years, has been chosen as scenario earthquake. For this earthquake a Richter magnitude M = 7.3 has been estimated.

A method for the evaluation of the liquefaction potential index has been applied and the results presented in the paper show that the liquefaction risk particularly in the Saint Giuseppe La Rena site is high.

A parametric analysis to verify the effect of the seismic design data on the liquefaction potential index was carried out, showing that the value of the maximum acceleration affects dramatically the liquefaction potential index.

EVALUATION OF LIQUEFACTION SUSCEPTIBILTY

During cyclic undrained loading, like those imposed by earthquake shaking, almost all saturated cohesionless soils are subjected to significant pore pressure build-up. 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. This phenomenon is generally referred to as liquefaction.

Semi-empirical procedures for evaluating liquefaction potential of cohesionless soils during earthquakes basically consist of analytical approaches to explain experimental findings of past case histories, and the development of a suitable in-situ index to represent soil liquefaction characteristics.

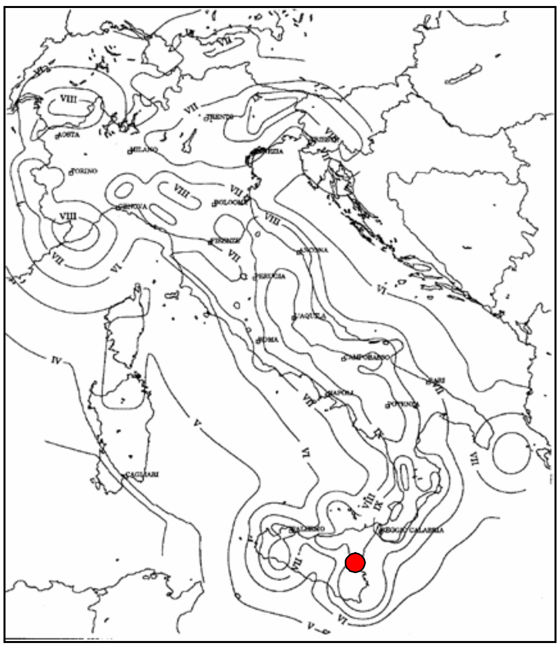

Fig. 1. Site location on the seismic hazard map of Italy.

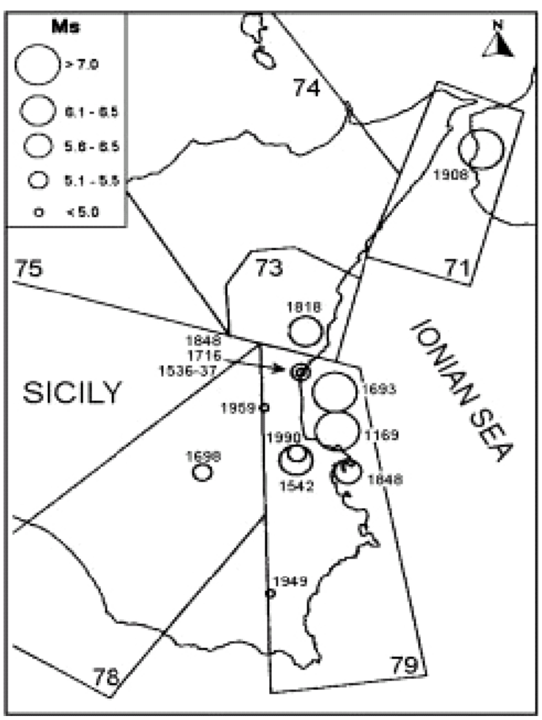

Fig. 2. Historical Sicilian strong earthquakes.

There are two approaches mainly available for quantitative evaluation of the soil's resistance to liquefaction. These are: (1) correlation and analyses based on in-situ Standard Penetration Test (SPT) data, and (2) correlation and analyses based on in-situ Cone Penetration Test (CPT) data. SPT and CPT results are generally preferred because of the more extensive databases and past experience.

The original simplified procedure for predicting liquefaction resistance of soils (Seed & Idriss, 1971) was developed by using the Standard Penetration Test (SPT) blow counts correlated with a parameter representing the seismic loading on the soil, called cyclic stress ratio (CSR).

Seed et al. (1985) provide also guidelines for performing "standardized" SPT, and provide correlations for conversion of penetration resistance obtained using most of the common alternate combinations of equipment and procedures in order to develop equivalent - "standardized" penetration resistance values - $(N_1)_{60}$. These "standardized" penetration resistance can then be used as a basis for evaluating liquefaction resistance (Figure 3).

The traditional procedure introduced by Seed & Idriss (1971) has been applied for evaluating the liquefaction resistance of 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):

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

where τ_{av} is the average equivalent uniform cyclic shear stress caused by the earthquake, a_{max} is peak horizontal acceleration at the ground surface generated by the earthquake, g is the acceleration of gravity, σ'_{vo} is the effective vertical stress, σ_{vo} the total overburden stress at the same depth, and r_d is a shear stress reduction factor which takes into account the reduction of shear stress with depth z.

The variation of r_d from the ground surface may be calculated analytically using site-specific layer thickness and stiffness, or, alternatively, by the following equations (Liao & Whitman, 1986):

$r_d = 1.0 - 0.00765\ z$ $\quad z \leq 9.15$ m

$r_d = 1.174 - 0.0267\ z$ $\quad 9.15 < z \leq 23$ m

$r_d = 0.774 - 0.008\ z$ $\quad 23 < z \leq 30$ m

$r_d = 0.5$ $\quad z > 30$ m

Liquefaction susceptibility has been evaluated by means of the procedure prescribed by the Italian Code (N.T.C., 2008), that considers a simplified and conservative approach to exclude the occurrence of liquefaction.

This approach is based on the expected peak ground acceleration (PGA), on soil composition and on soil state. For the expected PGA, the Italian Code assume that liquefaction hazard analysis can be omitted if PGA < 0.10 g.

In addition the considered sandy soils should met, at least one of the following conditions:

- Richter magnitude M less than 5;
- $(N_1)_{60}$ greater than 30.
- groundwater level deeper than 15 m.

The parameter $(N_1)_{60}$ is strongly affected by grain size distribution. As a consequence the same value for $(N_1)_{60}$ refers to a high relative density for a fine sand, whereas refers to a very low relative density for a medium coarse sand.

Following the simplified procedure proposed by the Italian Code, the seismic action in terms of PGA is expressed as:

$$a_{max} = \frac{Sa_g}{g} \tag{2}$$

in which a_{max} is the PGA, S is a soil factor depending on stratigraphy and topography of the site and a_g/g is the PGA at the rock outcrop prescribed by the Code according to macrozonation rules. Following this procedure a value of a_{max} ranging between 0.287 and 0.348 for soil type C ($180 < Vs_{30} < 360$ m/sec) based on the measured Vs_{30}, depending on return period of 975 years and "importance" of building has been estimated.

As reported in the following, the normalized cyclic shear stress that causes liquefaction (CRR) has been evaluated by means of a procedure based on SPT results (Seed et al., 1985).

The Factor of Safety (FS) for liquefaction resistance is defined as the ratio between the cyclic resistance ratio (CRR), and the cyclic stress ratio generated by the earthquake ground motions at the site (CSR). For the purposes of evaluating the results of a quantitative assessment of liquefaction potential at a site, a factor of safety against the occurrence of liquefaction greater than 1 must be considered.

The assumption of a maximum upper value of $(N_1)_{60}$ for liquefaction occurrence is equivalent to the assumption commonly made in the penetration-based procedures dealing with clean sands, where liquefaction is considered not possible above a corrected SPT blow count of about 30 (Figure 3).

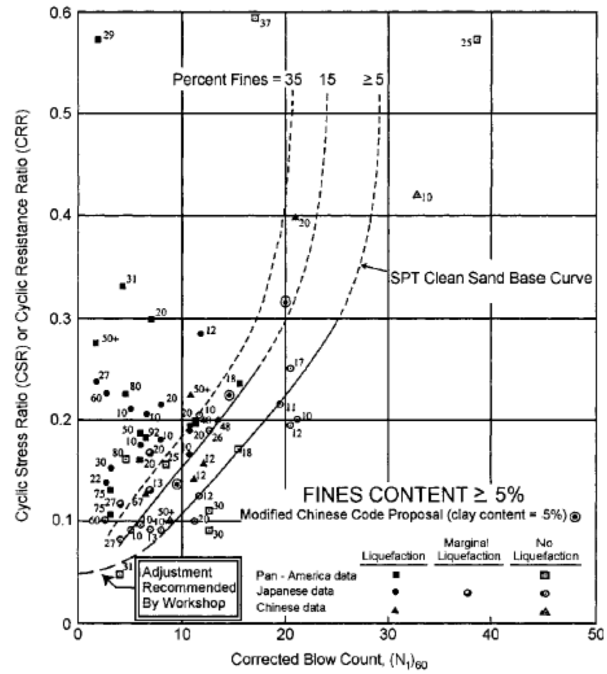

Fig. 3. Cyclic Resistance Ratio (CRR) vs corrected blow count (N1)60 for earthquake with M = 7.5 (Seed et al., 1985).

GROUND INVESTIGATION

The investigated site is located inside the port of Catania (Figure 4), in the northern corner of the Catania plain where recent sediments of fluvial and marine origin are present. Figure 5 shows the geological sketch map of the investigated site.

The ground investigations consist in: 12 boreholes up to 30 m; 120 Standard Penetration Tests; down-hole tests. Eighteen disturbed and undisturbed samples have been retrieved from boreholes. Several laboratory tests have been carried out, including the determination of grain size distribution (Table 1).

The typical stratigraphy consists of fine and coarse sands and silty sands, with bulk modulus equal to 20 kN/m^3, friction angle of 34 to 36° and mean grain size diameter of 0.01 to 0.13 mm. According to the Italian Code the soil can be classified as liquefiable (Figure 6) depending on the values of the uniformity coefficient (U_c) determined on the samples retrieved up to 16 m.

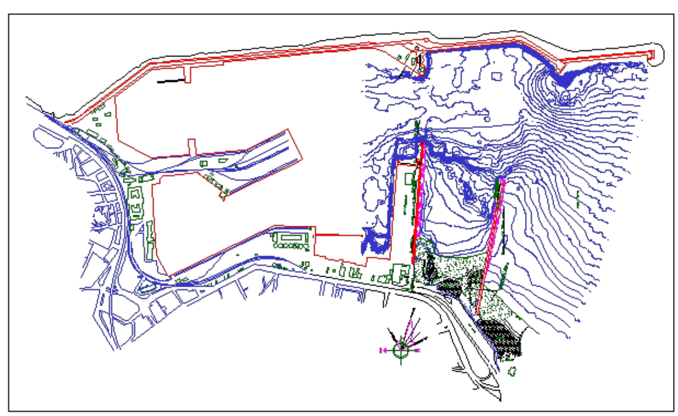

Fig. 4. Investigated location inside the Catania port.

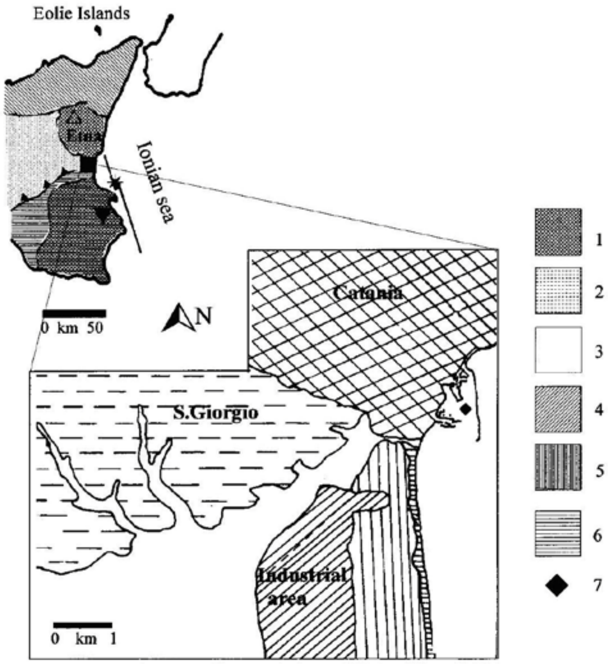

Fig. 5. Geological sketch map of the investigated site.

Table 1. Soil properties derived by laboratory tests.

Sample		Depth (m)	Sand	Silt	Clay	U_c	c' (kPa)	Φ' (°)
			(%)					
1	S1-C1	6.50 - 6.72	60.82	29.34	9.77	60.5	9.4	33
2	S1-C5	26.50 - 26.70	38.25	55.49	5.66	3.2	4.3	34
3	S2-C3	12.0 - 12.20	67.75	24.28	7.81	55	8.1	34
4	S3-C1	4.50 - 4.75	66.25	23.51	10.13	68.2	8.7	37
5	S3-C4	16.0 - 16.20	3.33	71.25	20.89	22.5	8.2	33
6	S4-C6	27.50 - 27.70	61.03	25.22	7.59	34	4	39
7	S5-C1	7.50 - 7.70	7.34	65.5	17.24	83.6	6.1	36.5
8	S6-C1	8.50 - 8.70	50.91	48.62		/	11	34
9	S6-C5	20.0 - 20.20	54.76	28.35	15.73	/	6.8	34
10	S7-C6	25.0 - 25.25	60.82	29.34	9.77	60.5	5.3	34.5
11	S8-C2	4.0 - 4.20	58.5	32	9.28	49.1	9	34
12	S8-C6	26.50 - 26.70	100	-	-	/	7	36.5
13	S9-C2	8.50 - 8.75	57.75	27.05	15.12	/	10	29
14	S10-C3	8.50 - 8.75	95.08	-	-	/	7	34
15	S10-C6	25.0 - 25.20	53.58	40.53	5.36	3.5	6	34
16	S11-C6	24.50 - 24.70	32.88	59.94	7.01	4.9	1	36
17	S12-C2	7.50 - 7.70	57.08	42.77		/	0	32
18	S12-C6	28.50 - 28.70	66.2	20.19	9.95	150.8	0	24

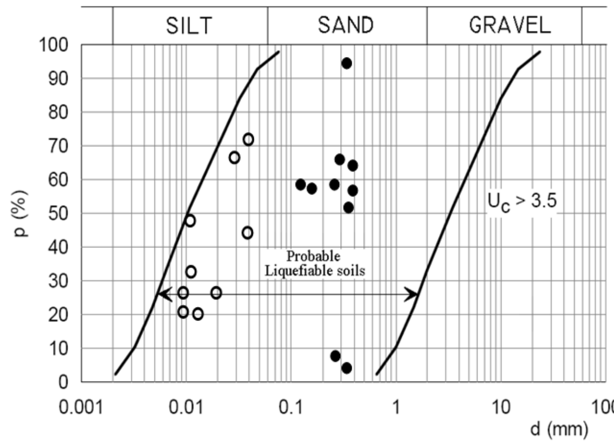

Fig. 6. Grain size distribution.

ANALYSIS OF LIQUEFACTION POTENTIAL

Information reported in historical sources confirms that the alluvial region of the Catania plain is quite susceptible to the formation of liquefaction effects not only during strong (M ≈ 7.0), but also during moderate shaking (M = 6.2).

In the case of earthquakes such as the 1693 one (first level scenario), the widespread distribution of liquefaction sites scattered over a large area within the X-XI MCS isoseismal, as far as around 20 km from the epicentre, indicates that the industrial district and facilities (airport, life-lines, etc.) south of Catania may be affected by severe damage thus losing their functionality (Cascone et al., 1999; Grasso & Maugeri, 2006).

In the case of a minor event such as the 1818 one (second level scenario), liquefaction effects may also occur at individual locations.

Detailed descriptions of liquefaction features are available for the 1818 earthquake. Longo (1818) reported evidence for liquefaction-induced features in two areas near Catania: (I) in the outskirts of Paternò, 18 km west of Catania, and (II) in the Catania plain. In this last case, features observed in the locality Paraspolo, are clearly related with earthquake-induced liquefaction. The area affected by liquefaction, apparently rather limited, is located in the littoral zone 300 m from the sea, along the transitional strip separating the sandy deposits of the shore from the silty-clayey sediments which extensively outcrop in the floodplain.

More recently, in the framework of the Catania Project supported in 1997 by the Italian Research Council CNR (Consiglio Nazionale delle Ricerche), geological, geotechnical and seismic studies were performed to define a risk scenario in the town of Catania for a destructive earthquake like that happened in 1693, which caused extensive structural damages, thousands of victims and liquefaction phenomena (Maugeri & Vannucchi, 1999).

The 1693 event, with intensity above X, represents one of the most destructive earthquakes in Sicily and its magnitude should be around 7.3. Thus, the evaluation of liquefaction susceptibility was carried out by the estimation of a safety factor for this scenario earthquake, assuming a magnitude M = 7.0 and maximum ground acceleration a_{max} = 0.35g.

The values of $CRR_{7.5}$ for SPT data (Figure 7) have been scaled to a magnitude of M = 7.0 considering the "magnitude scaling factors (MSF)" introduced by Seed & Idriss (1982), and expressed by the following expression:

$$CRR = CRR_{7,5} \cdot MSF \tag{3}$$

Consequently, an estimation of factor of safety against liquefaction has been computed by means of the following relation:

$$F_S = \left(\frac{CRR_{7,5}}{CSR} \right) MSF \tag{4}$$

In order to develop a liquefaction resistance profiles for the site investigated, in Figure 8 is shown the relation CRR - $(N_1)_{60}$ regarding to the case history points. With reference to the Standard Penetration Test data (N_{SPT}) reported in Figure 7, an average profile was considered.

The results obtained lead to the following considerations:

– dynamic penetration tests lead to locate a liquefiable stratum up to a depth of around 3 m;
– thickness of liquefiable soil is lower than thickness of non liquefiable soil.

The use of this relation provides a convenient means for evaluating the cyclic stress ratio required to cause liquefaction for the cohesionless soils.

CLOSING REMARKS

The paper deals with a microzoning criterion based on SPT data to define liquefaction risk in the area of Catania port, near Saint Giuseppe La Rena (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.

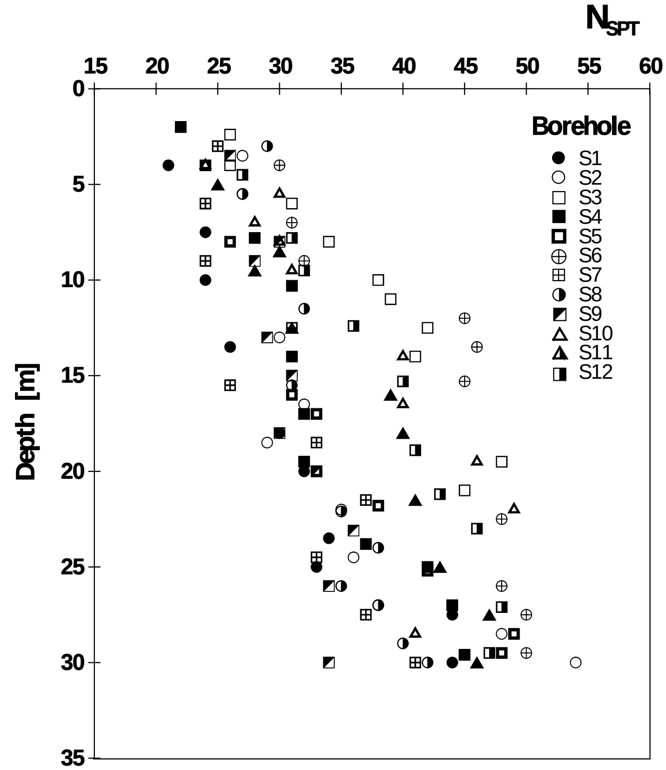

Fig. 7. Standard Penetration Test data (N_{SPT}).

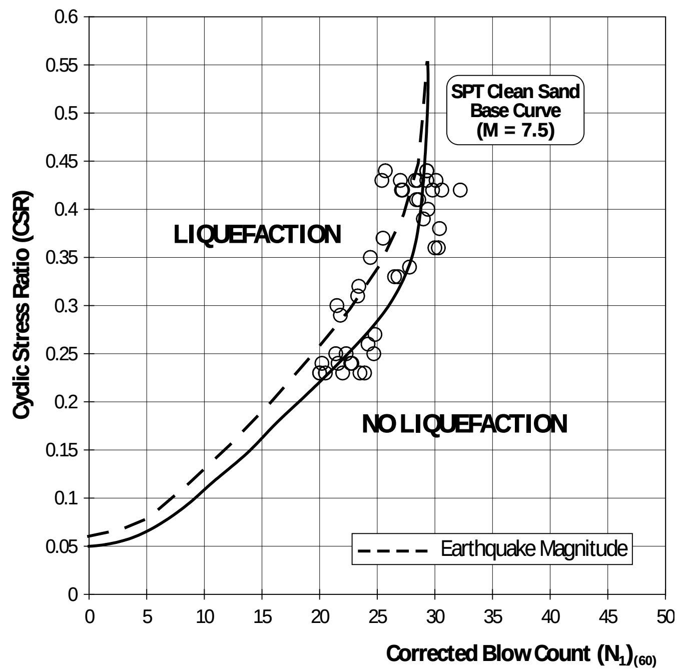

Figure 8. SPT - based case histories and recommended relation for clean sands for M = 7½.

For the evaluation of the seismic risk of the investigated area it has been chosen a scenario earthquake which may represent a possible repetition of the 1693 event. For this earthquake a Richter magnitude M = 7.0 and a maximum ground acceleration a_{max} = 0.35g have been considered.

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 procedure for the evaluation of the liquefaction potential by means of a relationship between liquefaction resistance and "standardized" penetration (SPT) resistance.

A qualitative estimation of possible damages to structures can be carried out on the basis of the results obtained.

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