2. GEOTECHNICAL ZONATION OF THE CATANIA SOILS AND EVALUATION OF THE LIQUEFACTION HAZARD

2.1 Introduction

(M. Maugeri and E. Faccioli)

It is well known that local geological and topographic conditions play a major role on earthquake ground motions and distribution of damage. This aspect becomes even more critical in areas with sharp transitions between stiff surface formations and softer soil materials, typically found in a volcanic zone like Catania which lies at the foot of the Mt. Etna volcano and was affected by many eruptions in historical and pre-historic times. Hence, a substantial effort was devoted to the zonation and seismic characterisation of soils in the Catania area. This task was carried out both by exploiting the existing data and by performing special investigations at some selected sites.

The creation of a database of about 860 boreholes provided the basis for a geotechnical zonation of the Catania municipal area; based on existing in situ tests (SPT, CPT, cross-hole and down-hole measurements) the mapping of the shear wave velocity for earthquake engineering purposes was carried out. All the borehole and in situ test data were stored in the database and the investigation sites located via GIS system (see 2.2).

To integrate the previous data, investigations were carried out for measuring the shear wave velocity by surface wave methods (see 2.3), in particular SASW investigations have been performed at beach sites south of the city (La Plaja), where saturated sand deposits exhibit a marked susceptibility to liquefaction.

Laboratory cyclic tests were performed to characterise the non linear soil behaviour, which may occur during strong earthquakes, such as the 1693 scenario earthquake (see 1). Two boreholes were made, in which down-hole velocity measurements have been executed, and undisturbed samples were retrieved. Resonant column tests and cyclic loading torsional shear tests were performed to investigate the initial shear modulus G_o and shear modulus degradation with shear strain, as well as damping ratio degradation (2.4).

Land vulnerability to earthquake-triggered phenomena was also investigated, mainly from the viewpoint of landslide and liquefaction hazard. For the landslide problem, one significant case was considered (Monte Po slide), but the data available are insufficient and it will not be treated in the following. On the other hand, soil liquefaction effects were reported by historical sources following the 1693 and 1818 earthquakes (see 2.5).

The susceptibility of a site to seismic-induced liquefaction may be assessed comparing the cyclic soil resistance to the cyclic shear stresses induced by the ground motion. The latter is of course a function of the earthquake parameters, while the former depends on the soil shear strength and can be computed using results from in situ tests.

A preliminary map of liquefaction risk was constructed; eleven potentially liquefiable sites have been identified, where the liquefaction potential has been evaluated based on SPT and CPT data, and also on *Vs* data. In particular, all these different data were available at one specific site (San Giuseppe La Rena), where the three previous methods were employed and the results compared for a better assessment of liquefaction potential (2.6).

2.2 Geotechnical zoning of the urban area of Catania for earthquake engineering porposes

(V. Pastore and R. Turello)

2.2.1 *Introduction*

Since the beginning of the Catania Project, in 1996, it has been recognised that the construction of realistic earthquake damage scenarios for the city of Catania would require a reasonably detailed model of the surface geology and geotechnical characteristics of the area.

To achieve this goal, data from geotechnical borings, water wells, geophysical investigations and geotechnical laboratory test have been collected, reprocessed and organised in a digital database. Subsequently, using the processed data, a number of geotechnical cross-sections, representative of ground conditions of different zones in the Catania urban area were prepared.

Based on the cross-sections and on an existing local geological map, a map of geotechnical units has been created; this was verified in the field and integrated with new data for the specific purpose of the Catania Project.

Each geotechnical unit in the map has been described through the values of selected parameters measured in the borings and on the recovered soil samples, or through geophysical investigations. The choice of the parameters has been strongly oriented towards the seismic characterisation of the different soil materials. As a by-product of the basic geotechnical map, a map of the distribution of near surface S-wave velocity (V_S) values in the area of interest was prepared.

Based on the data provided by some 860 borehole investigations, a depth contour map of the top of the clays constituting the base formation of the reference sequence has also been drawn, as well as a map of the water table.

The results of this study are available by anonymous-ftp at: *esdra.stru.polimi.it*.

2.2.2 *Geological framework*

Three fundamental structural domains can be recognised in Eastern Sicily (Fig. 2.1): the Hyblean Foreland, a Triassic to Quaternary thick calcareous sequence with frequent tectonically undisturbed volcanic episodes; the Gela-Catania Foredeep, filled up with Pliocene-Quaternary deposits; the Appenninic-Maghrebian Chain (Lentini, 1982).

Only the most recent deposits of the Foredeep dominion outcrop in the area of Catania, , representing a time interval that spreads from Miocene to Quaternary, locally covered by recent and present deposits, both marine and continental.

North of Catania, the effusive materials from the Etna volcano predominate. Slightly to the South of the urban area, in the zone called the “Terreforti” hills, a sedimentary series of Pleistocene age outcrops (South-Etnean series). At the base of the series there are grey-bluish marly clays (Kieffer, 1971) interbedded with quartziferous sandy silts (Francaviglia, 1940). The observed thickness ranges between 10 and 100 m; the maximum thickness can however be considered of hundreds of meters, as found in the deep borings in the Catania plain.

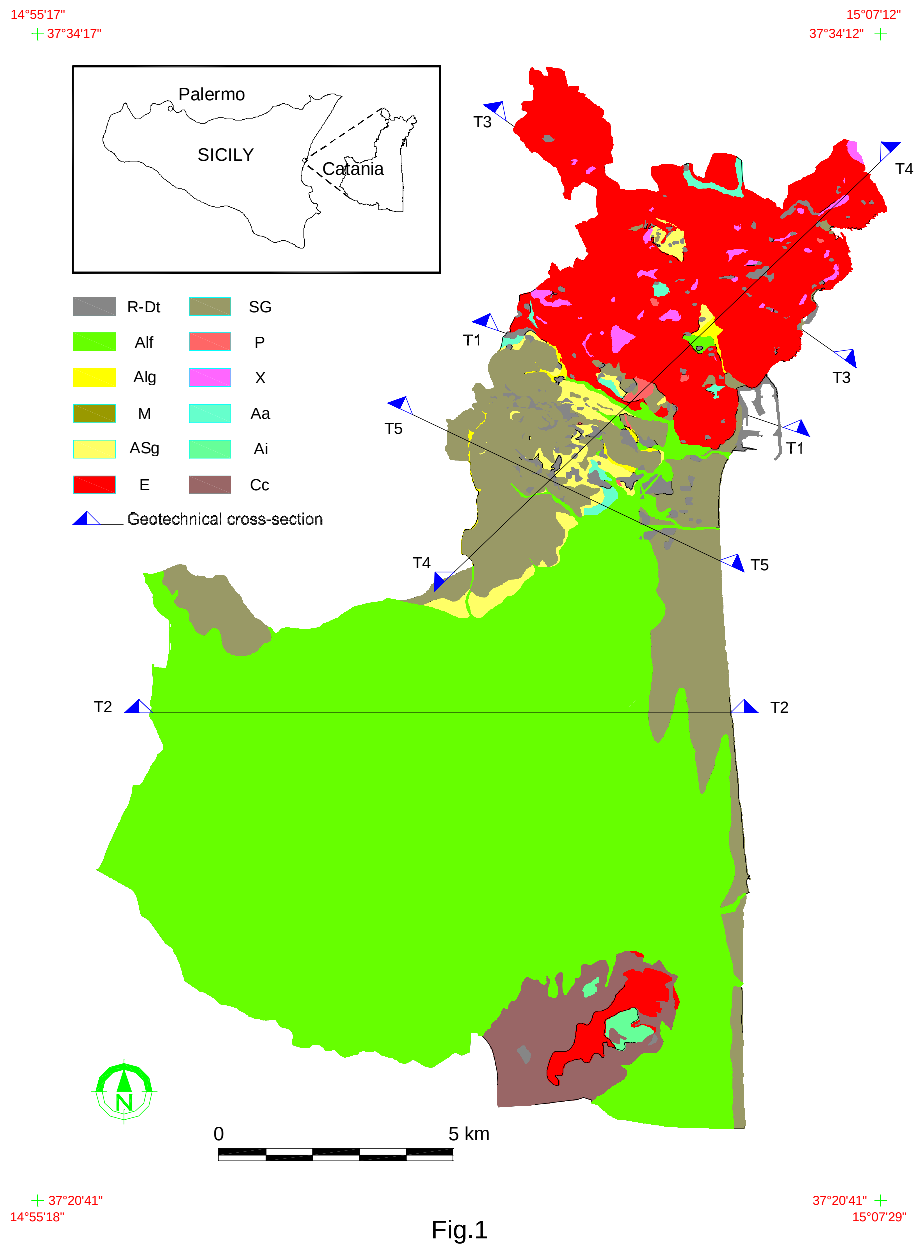

Figure 2.1 - Map of geotechnical units of the municipal area of Catania (see Table 1 for definition).

Overlying the grey-bluish marly clays there is a sequence, about 50 m thick, of greenish and yellow clays interbedded with layers of fine sands, with rare sandstone horizons with calcareous cement; horizons of pyroclastic material are also present.

Coarser deposits follow upward, consisting of sands, gravels and pebbles locally showing some stiffness due to cementation (sandstones and conglomerates), with maximum thickness of the order of 40 m.

Interbedded tuffs occur in every stratigraphic term of Pleistocenic age (tuff are already reported in the upper portions of the grey-bluish clays), but mostly at the top and inside of the sand and -gravel layers.

South of the Terreforti Hills lies the Catania flood plain, a lowland characterised by recent and present alluvium deposits grading to coastal deposits (Giovannino *et al.*, 1960). The depth of these deposits is between 40 and 80 m.

The flood plain is limited to the South by hilly relief, where ancient terrains are present, ranging from Miocene to infra-Pleistocene age (North-Hyblean series), made up by limestones, marls and calcarenites with clayey layers. All these rocks are crossed at different levels by alkaline lava flows.

2.2.3 *Data collection and elaboration*

The data largely consist of the stratigraphic log of borings (geotechnical boreholes, water wells, etc.), characterised by variable degrees of accuracy; some are accompanied by in situ and/or laboratory tests. In total, the database assembled for the project includes 860 boring locations, with a density distribution of the investigation points highly varying from site to site. Processing of this information has resulted in the mentioned map of geotechnical units, shown in Fig. 2.1, linked to a digital boring database via the GIS Arc-Info.

Because of their relevance on the estimation of local ground shaking and site effects, data from in-hole geophysical surveys (down- and cross-hole measurements) and Seismic Analysis of Surface Waves (SASW technique) have been examined with special attention, particularly for S wave velocity measurements. Down-hole data were available from previous investigations at six different sites, in the urban area and in the industrial zone (located South of the urban agglomeration) of the plain. They include measurements in different lava flows, tuffs, sandy and marly clays and alluvial fine-grained deposits.

For the specific purpose of the Catania Project, two new borings were executed in 1997 to the depth of 40 m in the central city area (via Stellata and Piazza Palestro), with down-hole tests and sample recovery (see sub-sect. 2.4 below for the test results obtained from the samples). Specifically performed for the Project in 1997 were also three investigations using surface wave techniques for determining the *Vs* profiles, described in sub-sect. 2.3 below. Such investigations concerned the playa sand of coastal deposits, some conglomerates, and a lava flow.

2.2.4 *Adopted procedure*

First, the boring data have been summarised according to a simple lithological description, through the choice of few fundamental classes. Next, a number of cross-sections have been drawn through the area of study (see Fig. 2.1), describing the borehole logs according to the fundamental classes. Based on these cross-sections, and making reference to the geological model of the area, the geotechnical units given in Table 2.1 have been defined and characterised.

The denominations of the fundamental classes are consistent with the definitions of the Italian Geotechnical Association (AGI, 1977), considering grain size fractions and their percentage relationship: peats, clays, silts, sands, gravels and pebbles are defined with the first letter of the name (in Italian T, A, L, S, G, C), while their percentages are expressed with simple notations (conjunction, comma or parenthesis).

Table 2.1: geotechnical units.

R - Dt	Top soil and fill (R); debris and landslides (Dt)
M	Marine deposits
Alf	Fine alluvial deposits (silts and clays with subordinated sand lenses)
Alg	Coarse alluvial deposits (sands, gravels and pebbles)
X	Scoriaceous lavas, lavas in blocks, "rifusa" and volcanoclastic rocks
E	Fractured to slightly fractured lavas, with subordinated horizons of scoriaceous lavas, lavas in blocks, "rifusa" and volcanoclastic rocks
P	Pyroclastic rocks
SG	Yellow or brown quartzose sands and sandstone, gravels and conglomerates with pyroclastic alternations
ASg	Yellowish or brown clays ans sandy silts, with sandy interbeddings and pyroclastic alternations
Aa	Silty clays and grey-bluish marly clays
Ai	Clayey interlayers in Cc unit
Cc	Calcarenites and block-calcarenites; limestone, marly limestones and alternations of marls and limestones

2.2.5 *Geotechnical characterisation*

In a second, detailed phase of the geotechnical characterisation of the various units identified, we evaluated characteristic (average) values of some representative geotechnical parameters, as shown in Table 2.2.

The following soil parameters were considered:

- Physical characteristics (unit weight, moisture content, grain size, Atterberg's limits)
- Shear strength (in drained and undrained conditions)
- Shear wave propagation velocity *Vs*.

It must be noted that the previous parameters were selected on the basis of both direct measurements and empirical correlations with in situ or laboratory tests: a typical example is the angle of effective shearing resistance ϕ' and the relative density D_r of the granular materials M-A1g-P-SG, which have been estimated from well known correlations with the measured N_{SPT} values).

For the Cc and Ai formations outcropping in the South–western portion of the Catania municipal area, very few geotechnical data was available, given the small number of borings made in this zone. Therefore, geotechnical parameters were established from existing geological literature and from the corresponding description and estimated age of the materials.

The artificial fill materials (R) at the surface and the debris deposits (Dt), are extremely heterogeneous. It has been assumed that a unique characterisation of such materials was not feasible, due to the extreme local variability of composition and degree of compaction.

2.2.6 *Thematic maps*

2.2.6.1 *Geotechnical units*

The map of geotechnical units (Fig. 2.1) including the cross-sections, together with the borehole digital database accessible via GIS, represent the main operating tool contributed by this study for the creation of a seismic loss scenario in the town area of Catania. As shown in the following sections of this report, this tool has been used in the creation of scenario ground shaking maps via an engineering approach, as well as in more sophisticated modelling approaches to obtain acceleration synthetics.

The reliability of the geotechnical map varies from place to place, according to number and quality of available boring data. In the urban area, boreholes and density of data are rather high, and the map is believed to represent ina realistic way the geotechnical nature of the foundation soils.

For instance, the thickness of lava flows has been determined with good accuracy, as well as the depth of grey-bluish marly clays top. In the Catania plain the trend of the clay base formation and thickness of alluvial deposits have been quite well ascertained with data of some deep water-wells.

2.2.6.2 *Shear wave velocity*

Contours representing the estimated average values of Vs in the uppermost 30 m, or $V_{s(30)}$, were drawn, starting from the available data from in situ cross-hole, down-hole and surface wave tests. Areas with overall lava flow thickness exceeding 10 m (within the uppermost 30 m) have been excluded from the contour line database, since their extremely high values could substantially bias the numerical interpolation, leading to misleading interpretation. The final shear-wave velocity map is shown in Fig. 2.2.

Figure 2.2 - Map of average shear wave velocity (m/s) in 0÷30 m depth interval. The studied area correspond to the municipal area of Catania (see key map). Co-ordinates are written in latitude and longitude format. ***(1)*** *Sectors with lava thicker than 10 m in 0÷30 m interval (shaded); external limit of sectors with lava thinner than 10 m in 0÷30 m interval (bold lines).* ***(2)*** *Seismic survey sites (down-hole, cross-hole, SASW).*

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Tab. 2.2: Characteristic values of some representative geotechnical parameteers

Unit	Values of soil parameters	
Cc	$\gamma = 21.0 \div 23.5\ kN/m^3$	
	$v_S = 500 \div 800\ m/s$	
Ai	$\gamma = 21.0 \div 23.5\ KN/m^3$	
	$c_U = 150 \div 250$ [kPa]	for depth< 10 m from g.l.
	$c_U = 250 \div 400$ [kPa]	for depth >10 m from g.l.
	$v_S = 300 \div 450\ m/s$	for depth< 10 m from g.l.
	$v_S = 450 \div 650\ m/s$	for depth >10 m from g.l.
Aa	$\gamma = 19.5 \div 20.2\ KN/m^3$	(increasing with depth)
	$w = 24 \div 29$ %	(generally decreasing with depth - 26% on average)
	$LL \geq 55$ %	(typical values 60%)
	$IP = 30 \div 38$%	
	$Gs = 2.70 \div 2.74$	
	$c_U = 80 \div 90$ kPa	at shallow depths (weathered material)
	$c_U = 200 \div 250$ kPa	for depth >10 m from g.l. (up to 400 kPa)
	$v_S = 320 \div 450\ m/s$	for depth< 10 m from g.l.
	$v_S = 450 \div 600\ m/s$	for depth $\geq$ 10 m from g.l.
	$v_P = 1650 \div 1700\ m/s$	
ASg	***Sandy facies (cohesionless)***	
	$\gamma = 19.3 \div 20.0\ KN/m^3$	
	$\phi' = 33 \div 39°$	(estimated values from SPT correlations)
	$C' = 0$	
	$v_S = 220 \div 400\ m/s$	from down-hole tests
	$v_P = 1350 \div 1400\ m/s$	from down-hole tests
	Cohesive facies	
	$\gamma = 19.3 \div 20.0\ KN/m^3$	(increasing with depth)
	$w = 23 \div 32$ %	
	$LL \geq 55 \div 60$%	
	$IP = 28 \div 36$%	
	$c_U = 70 \div 150$ kPa	(from laboratory TX-UU and UC)
	$\phi' = 24 \div 25°$	(from direct shear tests, n 4 series)
	$C' = 10 \div 20$ kPa	
	$v_S = 220 \div 400\ m/s$	from down-hole tests
	$v_P = 1350 \div 1400\ m/s$	from down-hole tests
SG	$\gamma = 19.8 \div 20.8\ KN/m^3$	
	$Dr = 70 \div 85$%	
	$\phi' = 36 \div 40°$	(estimated values from SPT correlations)
	$C' = 0 \div 70$ kPa	(assume zero for uncemented material of the plain)
	$v_S = 350 \div 500\ m/s$	
	$v_P = 1300 \div 1600\ m/s$	

Unit	Values of soil parameters	
E	***E1 - poorly fractured to medium fractured lava***	
	$\gamma = 22.0\ KN/m^3$	
	$v_S = 750 \div 1500\ m/s$	
	E2 - very fractured lava	
	$\gamma = 24.0\ KN/m^3$	
	$v_S = 350 \div 500\ m/s$	
	$v_P = 1700 \div 3000\ m/s$	
X	$\gamma = 18.0 \div 18.5\ KN/m^3$	
	$v_S = 180 \div 300\ m/s$	
	$v_P = 700 \div 800\ m/s$	
P	$\gamma = 16.0 \div 17.0\ KN/m^3$	
	$\phi' = 33 \div 38°$	(estimated values from SPT correlations)
	$C' = 0 \div 20$ kPa	(assume zero for uncemented material of the plain)
	$v_S = 250 \div 500\ m/s$	
	$v_P = 1100 \div 1500\ m/s$	
Alf	$\gamma = 18.5 \div 19.5\ KN/m^3$	
	$w = 27 \div 32$ %	
	$LL \geq 44 \div 53$%	
	$IP = 19 \div 27$%	
	$c_U = 30 \div 50$ kPa	for depth <10 m
	$c_U = 50 \div 80$ kPa	for depth $\geq$ 10 m
	$\phi' = 25 \div 28°$	
	$C' = 0 \div 15$ kPa	
	$v_S = 130 \div 210\ m/s$	from down-hole tests
	$v_P = 350 \div 450\ m/s$	from down-hole tests
Alg	$\gamma = 18.0 \div 19.5\ KN/m^3$	
	$Dr = 50 \div 65$%	
	$\phi' = 33 \div 38°$	
	$C' = 0$	
	$v_S = 210 \div 280\ m/s$	
	$v_P = 400 \div 500\ m/s$	
M	$\gamma = 18.3 \div 19.7\ KN/m^3$	
	$Dr = 60 \div 70$%	
	$\phi' = 34 \div 38°$	(estimated values from SPT correlations)
	$C' = 0$	
	$v_S = 210 \div 280\ m/s$	
	$v_P = 500 \div 550\ m/s$	
R,Dt	$\gamma = 17.0 \div 19.0\ KN/m^3$	
	$v_S = 130 \div 220\ m/s$; $v_P = 350 \div 400\ m/s$	

2.3 Seismic characterisation of the representative soils of Catania

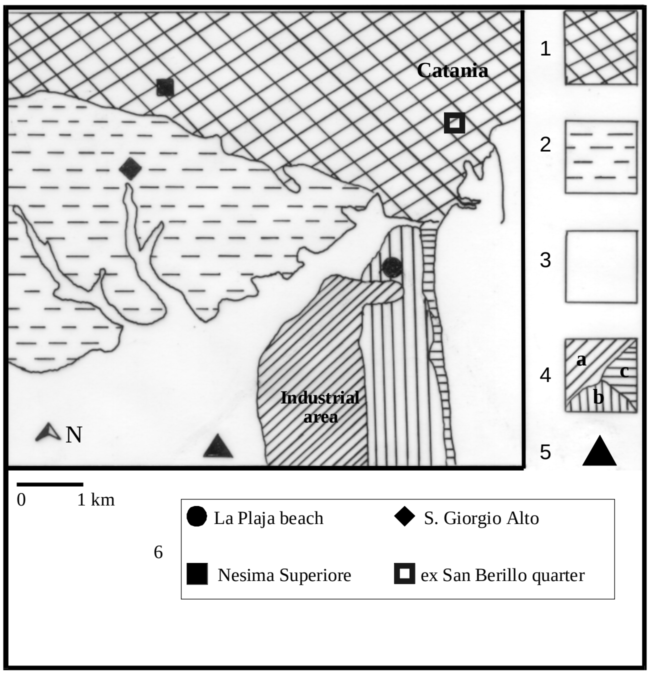
(C. Nunziata, G. Costa, M. Natale, A. Sica, R. Spagnuolo)

2.3.1 *Introduction*

We illustrate in this contribution the work performed on two topics relevant to the characterisation of the soil behaviour in the Catania area under strong earthquake shaking, such as expected for the scenario events.

Firstly, to enlarge the limited database of in-hole geophysical surveys of the shear wave velocity *Vs* (described in 2.2), independent seismic measurements of this quantity have been carried out by surface wave techniques along a few profiles. These include some of the most representative near-surface geological materials found in Catania (Fig.2.3), such as the shore sands, the conglomerates of the "Terreforti" Formation (see also sub-sect. 2.2), the lava flow of the 1669 Etna eruption (Recent Mongibello), and the Larmisi lava flow of the Prehistoric Etna eruption (Prehistoric Mongibello).

Secondly, the liquefaction potential of the shore sands at La Plaja beach has been evaluated by means of the standard approach based on the estimation of a safety factor between the cyclic shear resistance to liquefaction and the earthquake induced shear stresses. In addition, an empirical correlation between shear seismic velocities *Vs* and horizontal peak ground accelerations (Andrus and Stokoe, 1996) has been used.



Legend:
1. Etna volcanic products
2. Fluvial deposits of sand and conglomerates
3. Present & recent alluvial deposits
4. (a) Marshy deposits, (b) Shore dunes, (c) Present beach deposits
5. Catania accelerograph station
6. Location of the investigated sites.

Figure 2.3 - Geological sketch map of the Catania area.

2.3.2 *Determination of* Vs *profiles*

The *Vs* velocity profiles have been evaluated through the inversion of Rayleigh group velocities. The FTAN method (Dziewonski et al., 1969; Levshin et al., 1972) has been employed to measure group velocities, since it can be used even when higher mode contamination occurs. A sequence of frequency filters and time windows has been applied to the dispersion curve for an easy extraction of the fundamental mode. The dispersion curves obtained in such way have been inverted with the non-linear Hedgehog method developed by Valyus et al. (1968) and discussed in detail by Panza (1981). By this approach, a number of solutions (profiles) are obtained that are within an assigned error band, depending upon the quality of the measurements.

In the following we present the *Vs* profiles, Hedgehog solutions for each surveyed site.

Shore sand at the La Plaja beach

Along the southern coast line of Catania, at the La Plaja beach, seismic measurements with forward and backward spreadings of 32 and 64 m have been carried out (Fig. 2.3).

The investigated site is characterised by fine sands with thin interbeddings of gravelly sands having a mean grain size between 0.24 mm (in the uppermost 10 m of soil) and 0. 13 mm. The water table lies around 2 m below the ground surface. Cone penetration tests (CPTs) show a sharp decrease of the tip resistance values q_{c1}, corrected of the overburden pressure and fine content (Robertson, 1990), which correspond to a change of relative density D_r from 75% to about 40%. This trend seems to be correlated with *Vs* profiles showing an increase of velocities at 2-3 m of depth, then a decrease of them at 5 m of depth, and again an increase at 11 m of depth (Fig. 2.4). All the profiles exhibit *Vs* values of 220 m/s at 5-11 m of depth and 280 m/s up to 20m of depth (Nunziata et al., 1999).

An estimation of the seimic quality factor *Q* was also obtained from the comparison of the synthetic fundamental mode computed for one of the Hedgehog solutions with that extracted from the measured signal. A gross *Q* value of 70 was obtained (Nunziata et al., 1999).

Conglomerates at S. Giorgio Alto

Seismic measurements have been executed in a quarry of fluvial deposits of conglomerates and sands (Terreforti formation) at S. Giorgio alto (Fig. 2.3). The signals recorded at 100, 110 and 130 m offsets in a refraction survey have been analysed. The Hedgehog solutions obtained from the inversion of the average FTAN group velocity give a detailed *Vs* profile down to 30 m depth (Fig. 2.5). The average *Vs* values increase from 320 m/s at 3 m of depth, up to 450 m/s at 30 m of depth. The high velocity in the topmost 3 m of conglomerates may be an effect of the soil compaction due to the truck traffic inside the quarry (Nunziata et al., 1999).

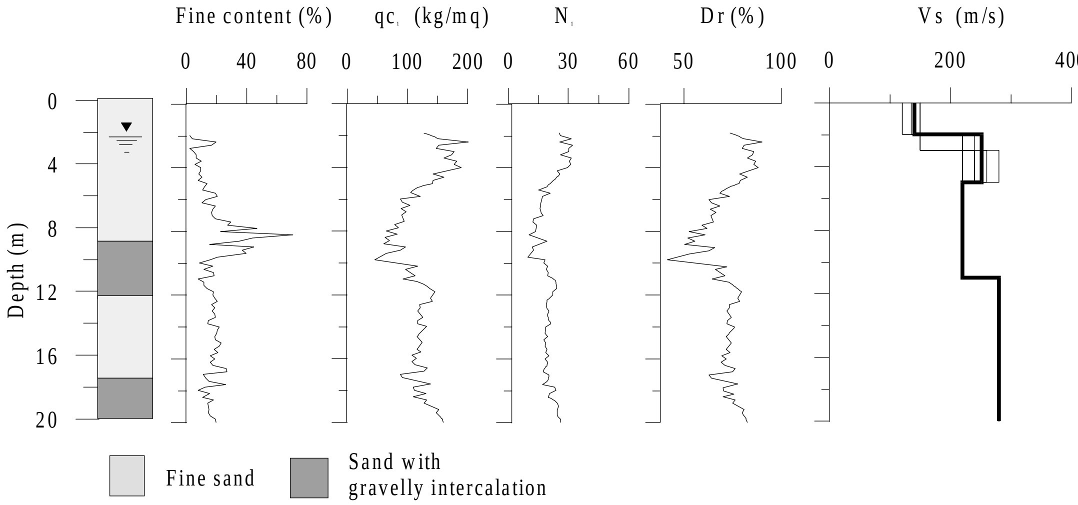


Figure 2.4 - Geotechnical and shear seismic properties of shore sands of Catania at La Plaja beach; qc1 corrected of overburden pressure and fine content; the blow count number N1, corrected of pressure, and computed from the qc1 by the empirical correlation given by Tatsuoka et al. (1990) and Meyerhof (1957). The Vs models (Hedgehog solutions) and the average model (thick line) are shown (Nunziata et al., 1999).

1669 Lava flow at Nesima Superiore

Seismic measurements with forward spreadings of 27 and 37 m have been carried out in the western part of the urban area (Fig. 2.3), close to the Civil Protection building, located in viale Lorenzo Bolano. Lava flows from Mt. Etna erupted in 1669 outcrop at the investigated site. They consist of scoriaceous and vacuous lava, highly fractured at higher depths. The Hedgehog solutions obtained from the inversion of the average FTAN group velocity have provided a *Vs* profile down to 15 m depth. The *Vs* velocities are consistent with the volcanological data, since they have average values of 110 m/s for the topmost 4.5 m and of 150 m/s down to 15 m of depth (Fig. 2.6).

2.3.3 *Liquefaction potential of the shore sands at La Plaja beach*

To evaluate the liquefaction potential of the shore sands at La Plaja beach, the standard safety factor method has been used first; see e. g. Ishihara (1993) for a detailed description. The method requires that a safety factor *F* be computed, defined as the ratio between the cyclic resistance ratio (CRR) and the cyclic stress ratio (CSR) induced by the reference earthquake. At each depth, liquefaction is said to be likely if *F* is less or equal to 1. The liquefaction potential has been evaluated both for the earthquake of December 1990 (so-called “St.Lucia earthquake”), for which a few strong motion records are avialable, and for the level I scenario earthquake, i. e. an assumed repetition of the M≅7, 1693 event. The S. Lucia earthquake (M_L=5.4) was presumably generated by a rupture along the transverse segment of the Malta escarpment fault, and was recorded in Catania at an accelerograph station lying on some 60 m of alluvium (see also 4.1 below). Using SHAKE, the recorded accelerogram has been reduced by deconvolution to the seismic bedrock (assumed *Vs*=800 m/s) represented by the blue clay formation (Aa, see sub-sect. 2.2 Table 2.2).

We have also estimated the peak acceleration of the scenario earthquake (M 7.0 to 7.5) using an attenuation law.

Moreover, we have considered the accelerogram recorded at Sortino station, on rock, at the same epicentral distance but at different azimuth.

The scenario earthquake has been simulated starting from the normal fault of the Malta escarpment. Two synthetic seismograms have been taken into account, both computed for 2D models of the local earth crust. The first one, computed by Romanelli and Vaccari (1999, see also 4.2 below), is relative to a 1D reference model (a_{max} = 0.45g) and has been associated to outcropping seismic bedrock. The same waveform has also been scaled to a_{max} = 0.35g. The second synthetic accelerogram, computed by Priolo (1999, see also 4.1 below), is relative to a receiver on the top of 75 m soil column. This waveform has been treated in two different ways: 1) by associating it to the ground surface, and computing the cyclic stress ratio (CSR) values down to 20 m depth along the soil column assumed by the author; 2) by reducing it by deconvolution to 75 m of depth, to suppress the amplification effect of the soil column, and later assuming it as input to our soil velocity profile (Fig. 2.4).

All the previous waveforms are represented in Figure 2.7 in terms of acceleration response spectra. The 1D amplification effect of the shore sands has been computed taking into account the variation of shear modulus and damping with shear strain according to Seed and Idriss (1982).

The safety factor *F* against liquefaction is found to be greater than 1 if we take as seismic input the 1990 earthquake ground motions recorded both at Catania and Sortino. The same happens if estimate the peak ground motion for a scenario of magnitude 7-7.5 by the attenuation law of Sabetta and Pugliese (1987).

On the other hand, the shore sands are found to be susceptible to liquefaction if the synthetic scenario earthquake accelerograms are used as an input. The results are practically the same for the two accelerograms previously discussed down to 10 m of depth (Fig. 2.8a). At larger depths, the *F* factor computed with the accelerograms by Romanelli and Vaccari (1999) is higher than 1, in agreement with improving geotechnical and geophysical properties at depths higher than 12 m (Fig. 2.4). Instead, the *F* values resulting from the accelerogram by Priolo (1999) are still lower than 1. This means that the shore sand would liquefy down to 12m in the case of the scenario synthetics by Romanelli and Vaccari (1999), and down to 20m in the case of the scenario synthetics by Priolo (1999). If we apply instead the procedure proposed by Andrus and Stokoe (1996), the shallowest 7 m of sand layer are not susceptible to liquefaction (Fig. 2.8b) for the 1990 earthquake. The sand layer between 5 and 11 m of depth is going to liquefy using the synthetic accelerogram by Priolo (1999), if we assume the soil profile by the author. If we reduce such accelerogram to the basement and then compute a_{max} along our soil model, these values are close enough to the boundary between liquefaction and no liquefaction. This latter result is found also if we consider the synthetic accelerogram by Romanelli and Vaccari (1999).

In conclusion, the analysis of the geotechnical data and shear seismic velocities and the assumption of different descriptions of the scenario earthquakes, indicate a high probability of liquefaction occurrence of the shore sands of La Plaja beach for an M 7 earthquake.

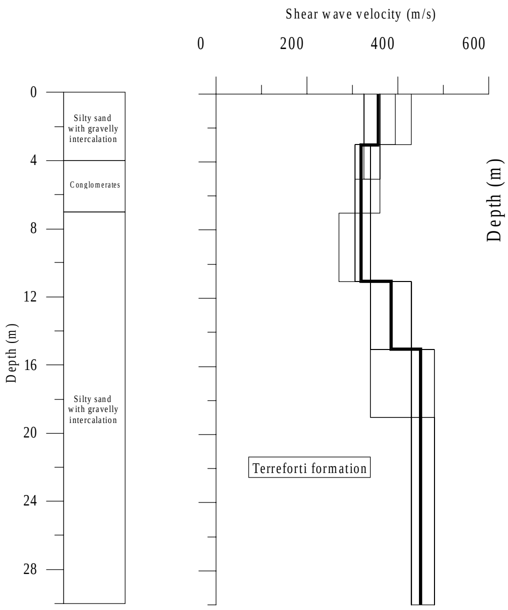


Figure 2.5 - The Vs models for the conglomerates at S. Giorgio Alto

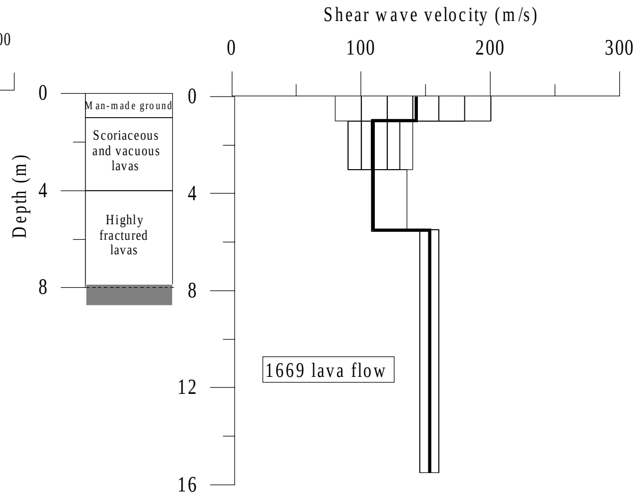


Figure 2.6 - The Vs models for the 1669 lava flow at Nesima Superiore

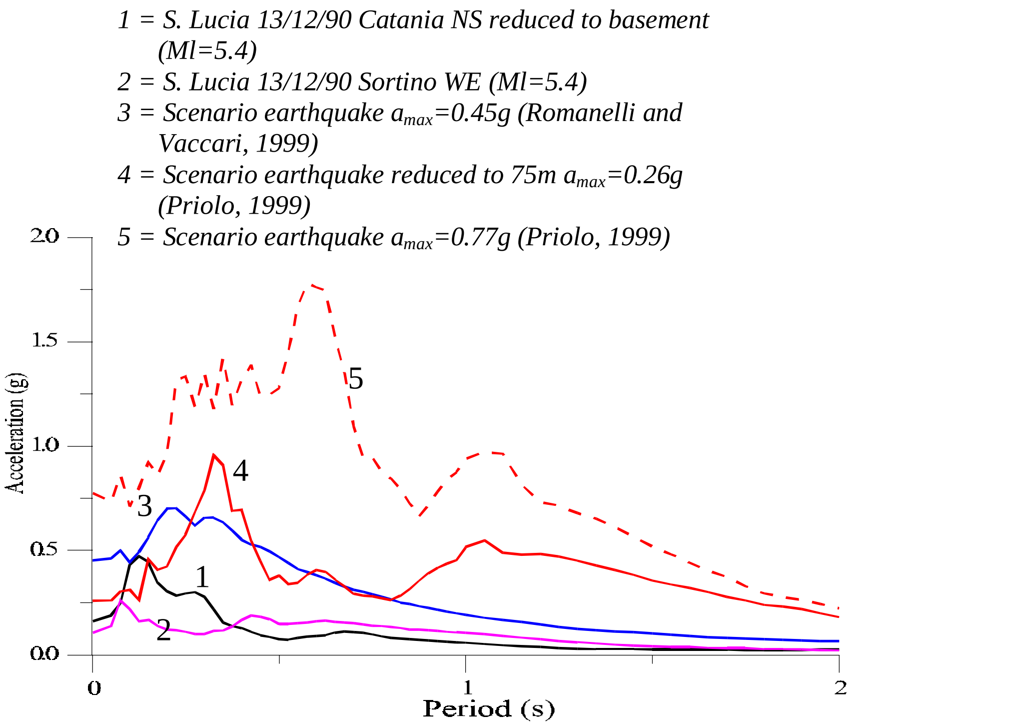


Figure 2.7 - Acceleration response spectra (damping 5%) of the studied earthquakes for the liquefaction susceptibility.

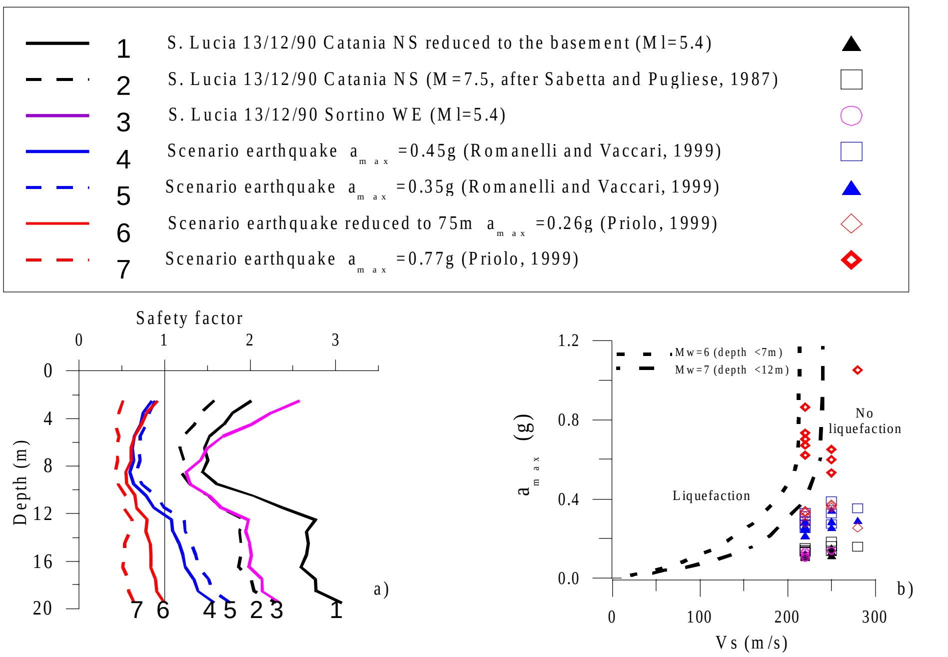


Figure 2.8 - Analysis of the liquefaction susceptibility of the shore sands at La Plaja beach (a) with the safety factor empirical method (Tatsuoka et al., 1990; Seed and Idriss, 1971) and (b) with the procedure proposed by Andrus and Stokoe (1996).

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2.4 Non linear soil behaviour of Catania clays

(M. Maugeri and A. Cavallaro)

2.4.1 *Introduction*

During strong earthquakes, such as that of 1693 assumed as the primary scenario event in this project, the soil tend to behave as non-linear material (see sub-sect.2.5 below). The non-linear behaviour had been investigated a few years ago by Carrubba and Maugeri (1988a, 1998b) and by Maugeri et al. (1988) for the clay layers found in the Catania plain (geotechnical unit Alf in Table 2.2). On the other hand, for the clay layers typically found in the central area of Catania (geotechnical unit ASg), the non-linear behavior has been investigated by Resonant Column Tests (RCT) and Cyclic Loading Torsional Shear Tests (CLTST), performed on undisturbed Shelby samples retrieved from one recent borehole (located in Via Stellata, see sub-sect. 2.2), specifically executed for the project.

2.4.2 *Shear modulus and damping ratio*

The Resonant Column/Torsional shear apparatus (Lo Presti et al. 1993) was used for evaluation of the shear modulus, *G*, and the damping ratio, *D*, of Catania clay (geotechnical unit Asg).

G is the unload-reload shear modulus evaluated from CLTST and RCT, while G_0 is the maximum value or also "plateau" value as observed in the G-log(γ) plot, where γ is the cyclic shear strain amplitude. Generally *G* is constant until a certain strain limit is exceeded. This limit is called elastic threshold shear strain (γ_t^e) and it is believed that soils behave elastically at strains smaller than γ_t^e. The elastic stiffness at $\gamma<\gamma_t^e$ is thus the already defined G_0.

For CLTSTs the damping ratio was carried out using the definition of hysteretic damping ratio (*D*) by:

$$D = \frac{\Delta W}{4\pi W} \qquad \text{Eq. (2.1)}$$

in which ΔW is the area enclosed by the unloading-reloading loop and represents the total energy loss during the cycle and W is the elastic stored energy. For RCTs the damping ratio was determined using two different procedures: (*a*) following the steady-state method (SSM), the damping ratio was obtained during the resonance condition of the sample, and (*b*) following the amplitude decay method (ADM) *D* was obtained from the amplitude decay of free vibration.

The laboratory test conditions and the obtained small strain shear modulus G_O are listed in Table 2.3. The G_0 values, reported in Table 2.3, indicate moderate influence of strain rate even at very small strain where the soil behaviour is supposed to be elastic. To appreciate the rate effect on G_O, it is worthwhile to remember that the equivalent shear strain rate ($\dot{\gamma} = 240 \cdot f \cdot \gamma[\%/s]$) experienced by the specimens during RCT can be three orders of magnitude greater than those occurring in the CLTST (Cavallaro 1997).

Table 2.3: Test Conditions.

Test No.	H [m]	σ'_{vc} [kPa]	e	PI	CLTST RCT	G_o(1) [MPa]	G_o(2) [MPa]
1	17.00	172	0.551	26.05	U	91	-
2	22.00	246	0.582	28.60	U	45	64
3	35.70	375	0.653	20.02	U	62	77
4	39.00	411	0.695	31.40	U	77	93

where: H = depth of sample, σ'_{vc} = effective confining stress, e = void ratio, PI = plasticity index. G_O (1) from CLTST, G_O (2) from RCT.

Figure 2.9 shows the results of RCTs normalised by dividing the shear modulus *G(γ)* for the initial value G_o at very low strain. The experimental results of specimens from site C were used to determine the empirical parameters of the expression proposed by Yokota et al. (1981) to describe the shear modulus decay with shear strain level:

$$\frac{G(\gamma)}{G_o} = \frac{1}{1+\alpha\gamma(\%)^{\beta}} \qquad \text{Eq. (2)}$$

in which: *G(γ)* = strain dependent shear modulus; γ = shear strain; α, β = soil constants.

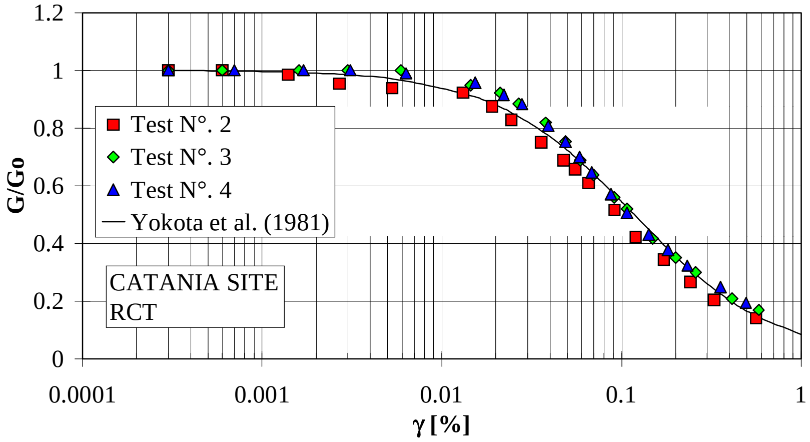

Figure 2.9 - G/G_o-γ *curves from RCT tests.*

Expression (2) allows the complete shear modulus degradation to be considered with strain level. The values α = 11 and β = 1.119 were obtained for the central Catania clay. The same equation was used by Carrubba and Maugeri (1988a). They obtained, for the clay of the Catania plain, α = 7.15 and β = 1.223.

A comparison between the damping ratio values obtained from RCT and those obtained from CLTST is shown in Figure 2.10.

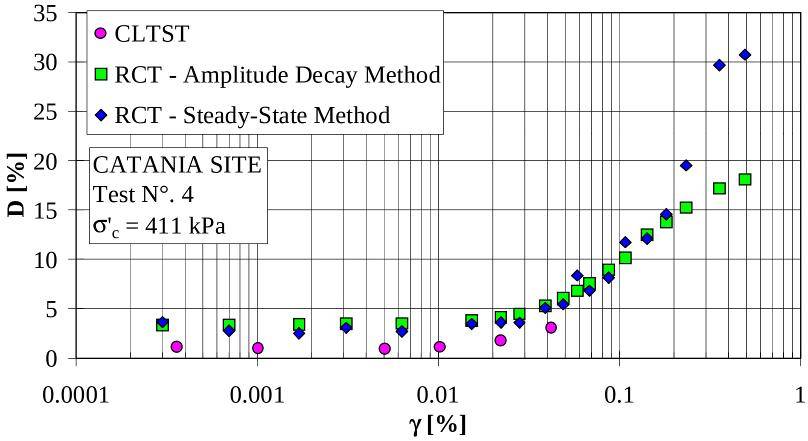

Figure 2.10 - Damping ratio from CLTST and RCT tests.

The damping ratio values obtained from RCT using two different procedures are alike, although higher values of *D* have been obtained from SSM for strains higher than 0.2 %.

We note that the damping ratio from CLTST, at very small strains, is equal to about 1 %. Greater values of *D* were obtained from RCT for the whole investigated strain interval. It is supposed, in agreement with Shibuya et al. (1995) e Tatsuoka *et al.* (1995), that resonant column tests provide larger values of D than CLTST because of the rate (frequency) effect. Moreover soil damping, at very small strains, is mainly due to the viscosity of the soil skeleton or of the pore fluid, depending on the strain rates or frequencies.

As suggested by Yokota *et al*. (1981), the inverse variation of damping ratio with respect to the normalised shear modulus has an exponential form as illustrated in Figure 2.11:

$$D(\gamma)(\%) = \eta \cdot \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_o}\right] \qquad \text{Eq. (3)}$$

in which: $D(\gamma)$ = strain dependent damping ratio; η, λ = soil constants. The values η = 31 and λ = 1.921 were obtained for the central Catania clay. Equation (3) gives a maximum value D_{max} = 31 % for $G(\gamma)/G_o$ = 0, and a minimum value D_{min} = 4.54 % for $G(\gamma)/G_o = 1$.

Therefore, equation (3) can be re-written in the following normalised form:

$$\frac{D(\gamma)}{D(\gamma)_{max}} = \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_o}\right] \qquad \text{Eq. (4)}$$

The same expression had been used in the previous study Catania plain clay (Carrubba and Maugeri 1988a), where the following values of the parameters were obtained: η = 19.87, λ = 2.16 using the damping values assessed by means of the SSM.

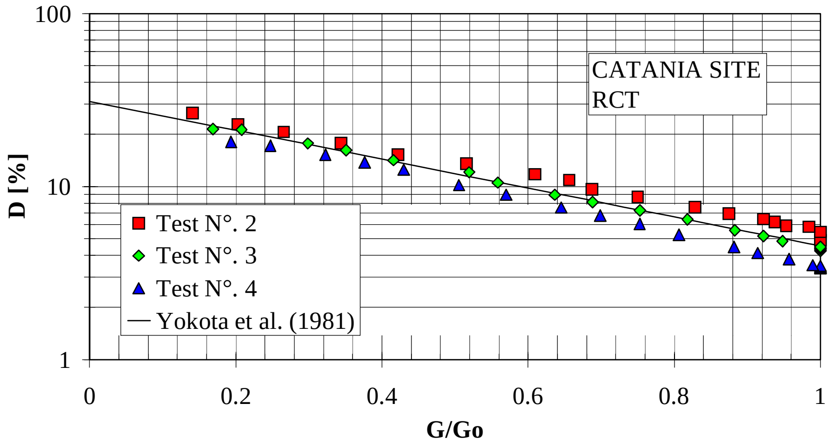

Figure 2.11 - D-G/G_o *curves from RCT tests.*

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2.5 Liquefaction-induced features for the scenario earthquakes in the Catania area

(R. Azzaro)

Seismic liquefaction phenomena were reported by historical sources following the 1693 and 1818 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.

2.5.1 *The January 11, 1693 earthquake*

Extensive liquefaction effects occurred in the Catania area following the January 11 mainshock. Probably due to the severity of the earthquake (M_s = 7.0, I_o = X-XI MCS; see sub-sect. 1.2), contemporary sources tended essentially to describe the catastrophic consequences of damage suffered by the towns, providing only generic information on seismogeological effects among which the liquefaction-induced features. In particular Boccone (1697) reported the widespread occurence of venting of water to the surface in the Catania plain (Fig. 2.12, site 1), issuing from swales and long linear fissures:

"In the plain and the territory of Catania in more than fifty places there appeared holes, from which sprang ample sources of water, mixed with sand, but ceased to flow 12 hours after the earthquake of the 11th as if they were connected with a large well, or with the sea itself, by the newly made fissures in the Earth […] In the Catania plain it is said that from one of these very long fissures, four or more miles from the sea, salt water sprang as if the very same water from the sea".

In addition Privitera (1695) supplied a description of liquefaction for the area near the Simeto river:

"At the very time of the earthquakes, were to be seen in most parts of the Catania plain […] spouting streams of water, rising up to 10 canne high, throwing out also sulphur; forming sand hills, this occurring beyond the Simeto river".

2.5.2 *The February 20, 1818 earthquake*

More detailed descriptions of liquefaction features are available for the 1818 earthquake, both because of the greater attention devoted to the scientific investigation of natural phenomena in general and of the lesser impact of this shock on the land (M_s = 6.2, I_o = IX MCS, see sub-sect. 1.2). 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. The first site (Fig. 2.12, site 2), locality *Salinelle* (37.573 lat. N, 14.889 long. E), is not of strict interest for the project since it is located beyond Catania's commune boundaries. Here, sand blows observed during the 1818 earthquake cannot be ascribed to real liquefaction features but to well-known phenomena of secondary volcanism characterised by continuous eruptions of water and CO_2 leading to the typical mud volcanoes (Chiodini et al., 1996), with paroxysms often in connection with seismic or volcanic activity.

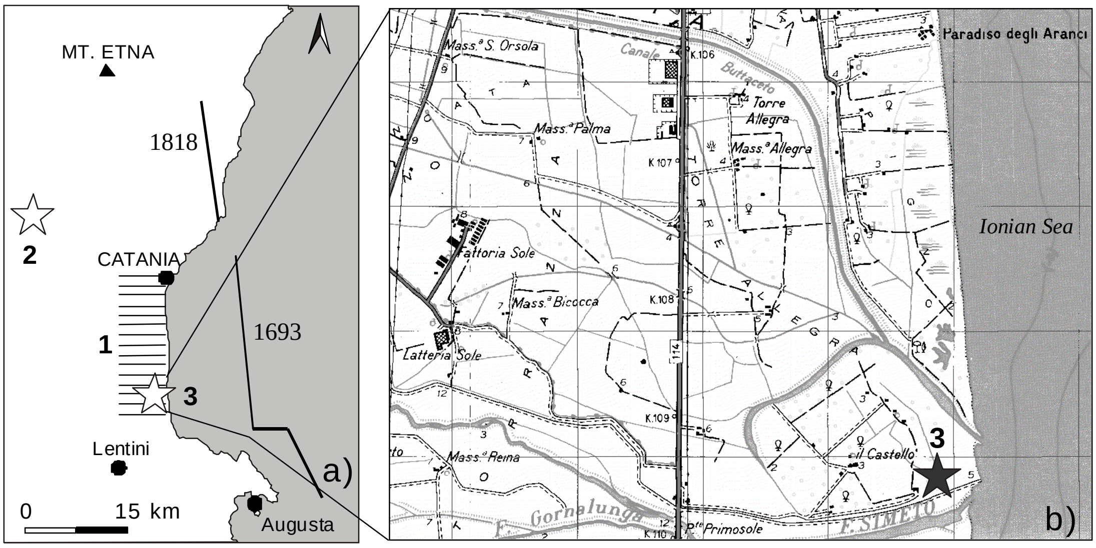

Figure 2.5.1 a): location of the 1693 (horizontal bars) and 1818 (stars) liquefaction sites and related seismic sources (solid lines). 1, approximate boundary of the Catania plain; 2, Salinelle of Paternò; 3, Paraspolo. b): topographic map showing the location of the Paraspolo site.

On the contrary, features observed in the Catania plain site (Fig. 2.12, site 3), locality *Paraspolo* (37.404 lat. N, 15.089 long. E) 1 km east of the road SS114 near the mouth of the Simeto river, 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 (see 2.2). Fissuring and venting took place in recent-Holocene terrains. Field observations by Longo (1818) also provide information on the development of liquefaction:

" Worthy of further comment however, is the phenomenon which occurred in the estate of the Duke of Misterbianco known as Paraspolo not far from the Simeto. Five or six minutes after the earthquake there suddenly sprang forth 14 jets of water, arising up to 6 palms (about 1.5 m) creating a considerable clamour. These jets encompassed an area of about 20 canes (40 m). The water emanated was salty. The jets lasted for about 20 minutes and gradually diminished until they disappeared. Around the holes of 2/3 of a palm in diameter (17 cm) remained quite covered in sand which on analysis comprised only quartz, silicate sand and calcium carbonate,

all impregnated with muriatic soda1. The limestone-clay soil there is about 20 palms (5 m) above sea level, and is 150 canne from the beach (310 m). One of these vents visited by our Professor of Botany D. Ferdinando Cosentino on Sunday 22 February was still so hot as to not allow him to suffer the heat on his naked arm which when removed was hot and damp. He was not able to measure the temperature for the lack of a thermometer; but the steam coming out well indicated that it must have been very high2. A fissure in the land was also notable not longer than 6 palms (1.5 m), and four fingers wide (32 cm), which reached as far as the above mentioned sea level, from which it is unknown what came out. Some time afterwards the peasants in the near dwellings heard a loud din like a thunder clap, and thinking that some walls had fallen they went to various houses to inspect them. The following day they found that in the storehouse the cement floor made of lime and crushed brick was completely separated from the walls and split in various directions; but they did not observe any cracks in the walls".

A similar description of the *Paraspolo* site is also reported by Spampinato (1818):

"Eight to ten minutes after the strike of the earthquake of 20 February, in the estate of the Duke of Misterbianco, where the land is limestone-clay, not far from the Simeto, one saw 14 jets of water gushing forth, according to some, to the height of about 6 palms (1.5 m), and in the space of 7 or 8 minutes, decreasing and ceasing. The water coming out was certainly sea water; it had all the properties and the sea is not far from this location. In addition, the area around the vents from which sprang the water, remained quite covered in sand which when analysed showed all the characteristics of sand which is found on the beach, having however a bitumen-like odour and a blackish colour".

2.5.3 *Conclusion*

Information reported in historical sources confirms that the alluvial region of the Catania plain is quite susceptible to the occurrence of liquefaction phenomena not only during strong ($M_s \approx 7.0$) but also during moderate shaking ($M_s = 6.2$). In the

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1 " Sand gathered from a number of holes has certain particularities which distinguish it from others. It has the following characteristics: it is notably finer and more powdery, less coarse to the touch, it is a yellowish colour, scarce in quartz, abundant in calcium carbonate, and placed on hot coals it crumbles less, and gives off an odour of a burnt animal substance. I would not know with certainty where this empyreumatic smell comes from; perhaps from a little bitumen oil".

2 " The above cited Professor of Botany observed on location that the plants, which had been watered by the salt water sprung from the vents, quickly dried up, except those near only three holes, which although of the same species were growing prosperously. This circumstance would lead to suspect that salt water did not spring from these three vents, but rather fresh river water, which from there is not further than 60 paces (50 m)".

case of a large earthquake such as that of 1693 one (level 1 scenario), the widespread distribution of liquefaction sites scattered over a large area within the X-XI MCS isoseismal, as far as ca. 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 with loss of function. This is also supported by the liquefaction risk analyses carried out in the coastal sector of the playa (see 2.3 and 2.6).

In the case of a smaller event such as the 1818 earthquake (level 2 scenario), liquefaction effects may also occur at individual locations. For the site near the Simeto river, analysis of historical reports suggests the following: (i) description of vented sediments is consistent with the local geotechnical conditions (see 2.2); (ii) expelled water is brackish (prevailing) and fresh according to the occurrence of two groundwater tables, one due to the intrusion of sea water, another to the proximity of the river (ca. 50 m); (iii) development of liquefaction, which followed shaking after 5-10 minutes with duration from 7 to 20 minutes, indicates that liquefaction originated in strata located at a some depth beneath the surface; on the other hand the occurrence of a nonliquefiable stratum due to an overlying finer grained cap is consistent with the description of the vented sediments; (iv) fractures in the house floor and in the field clearly indicate that liquefaction led the surface layer to break into blocks bounded by fissures because of densification of liquefied sediment after expulsion of water. Finally (v), the distance of the liquefaction site from the epicentre (see par. 1.2) is 25 km, equal to the value reported by Obermeier (1996) for worldwide earthquakes with $M \approx 6.2$-6.3.

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2.6 Liquefaction potential of saturated sand deposits in the urban area of Catania

(T.Crespellani, E.Cascone, F.Castelli, S.Grasso, M.Maugeri, G.Vannucchi)

2.6.1 *SPT-based evaluation of liquefaction potential*

One of the most common parameters for estimating soil resistance to liquefaction is the number of blows N obtained from standard penetration tests. In fact 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. In addition to that, a large number of case histories of earthquake-induced soil liquefaction have been interpreted using SPT data, making it possible the development of reliable empirical correlations between soil resistance to liquefaction and SPT values.

Two procedures, based on SPT data, have been applied to evaluate the liquefaction potential of five sites located in the municipal area of Catania. Actually, eleven potentially liquefiable sites have been identified within the municipal boundary, but only for five of them SPT data was available. The sites are shown by the arabic numerals in Figure 2.13, and the sites for which SPT data was available are nos. 1, 3, 4, 10 and 11. The procedures employed for the evaluation of the liquefaction potential are those due to Iwasaki *et al*. (1978), and Robertson and Wride (1997); the former authors introduce a liquefaction potential index P_L with values ranging between 0 and 100. Low risk is for $P_L < 5$, and high risk for $5 < P_L < 15$.

The results expressed in terms of risk level are given in Figure 2.13 Among the investigated sites, only site no. 11 has a liquefaction potential index greater than 5, corresponding to a high risk level.

The single boring available for site no.1 indicates that the local soil deposit consists of a silty sand layer 15 m thick. At site no. 3 three borings were available, and SPT tests were carried out in all of them; the data allow to distinguish a layer of silty sand (10-15 m thick) resting on a clayey soil. At site no. 4 two borings were available, with SPT test data. The profile obtained from the borings showed that the soil deposit consists of clayey sands, for which the development of liquefaction is unlikely; thus, the liquefaction potential P_L is close to zero for this site. At site no. 10 only one boring existed, showing a layer of sand (14 m thick) resting on a layer of clayey sand. The evaluation of the liquefaction potential index for this site resulted in $P_L \cong 0$ because of the high value of N_{SPT} (>40).

At site no.11 eight borings, that is nos. 418÷425 in the boring database the project (see 2.2 above), were available together with SPT data. Near the borings, eleven CPT tests had also been carried out. The subsoil exploration revealed the presence of a sand layer with a fine content FC < 30% down to a depth of about 10 m. The SPT profiles for borings 418 and 425 are shown in Figure.2.14a and 2.15a respectively. The liquefaction potential index P_L, is greater than 5 (Figure 2.14b and 2.15b).

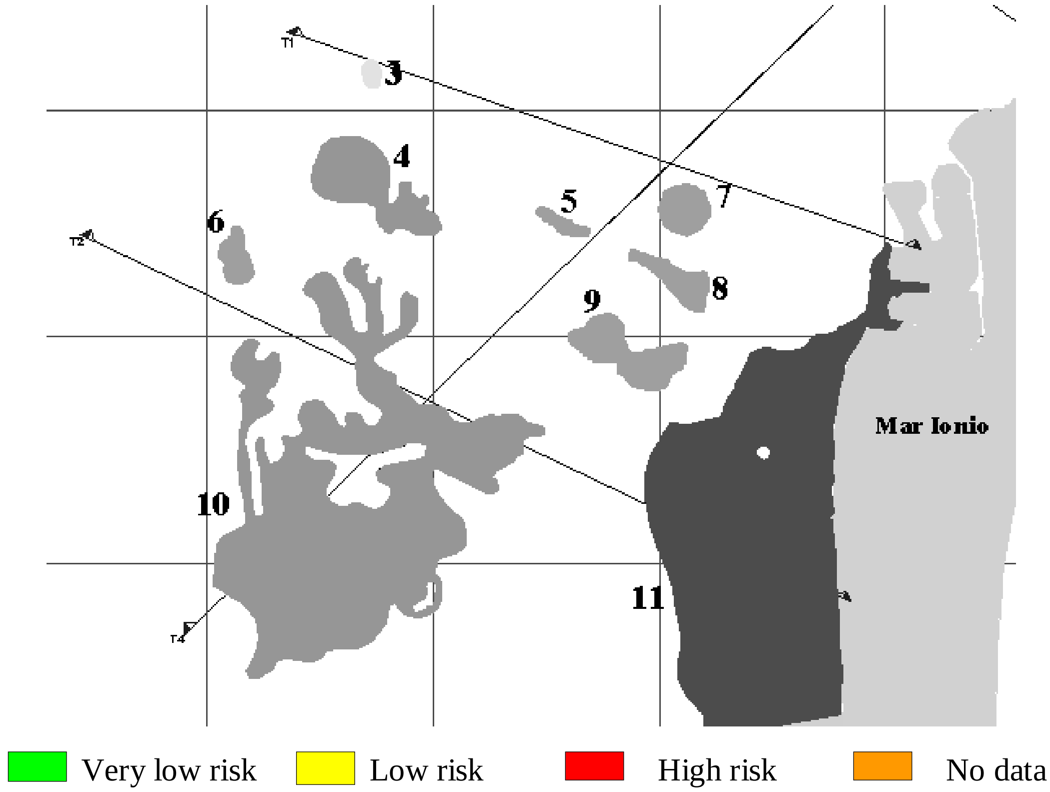

Figure 2.13 – Map of the risk of liquefaction within the Catania municipality. Arabic numerals denotes sites with SPT data.

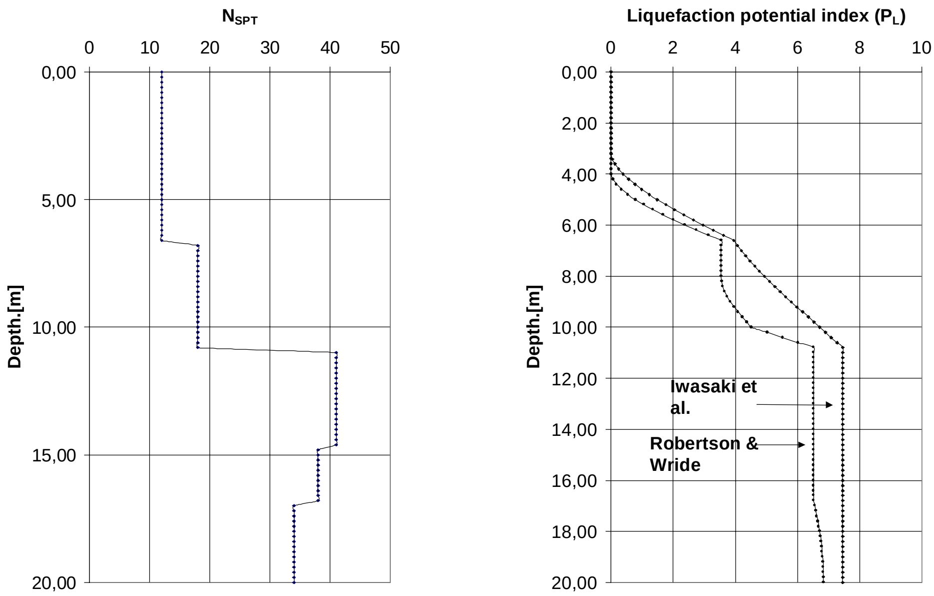

Figure 2.14 - Site 11, boring n.418: a) N_{SPT} profile; b) liquefaction potential index.

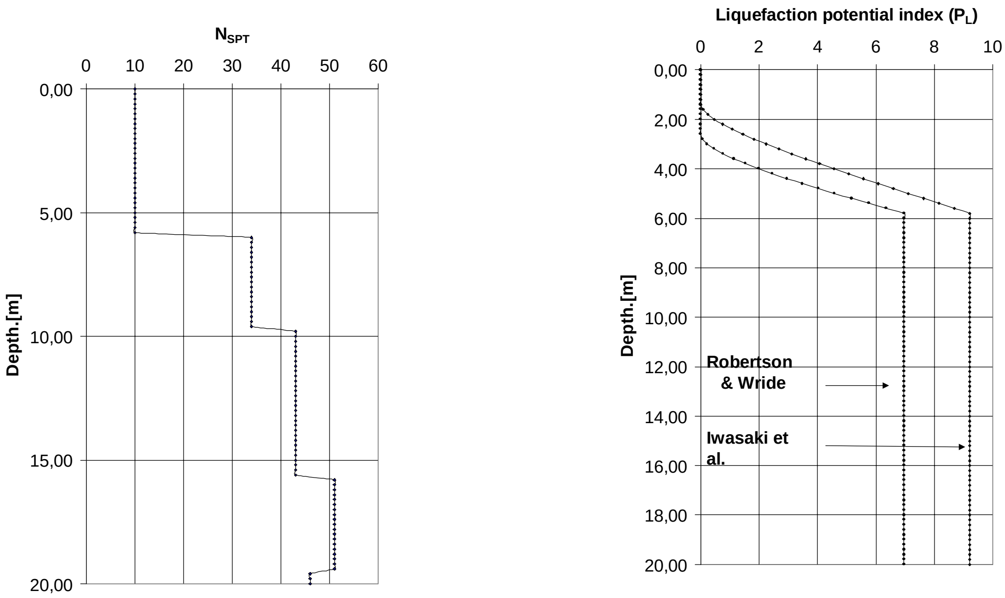

Figure 2.15 - Site 11, boring n.425: a) N_{SPT} profile; b) liquefaction potential index.

Finally a parametric analysis has been performed to investigate the influence of the maximum ground acceleration, a_{max}, on the liquefaction potential index computed according to Robertson and Wride (1997). In Figure 2.16, for the borings of site no.11, the variation of P_L with depth is plotted for a_{max} ranging from 0.30g to 0.45g. Such results clearly demonstrate that the ground acceleration is a crucial parameter: a 0.1g increase of a_{max} produces in fact a doubling of P_L

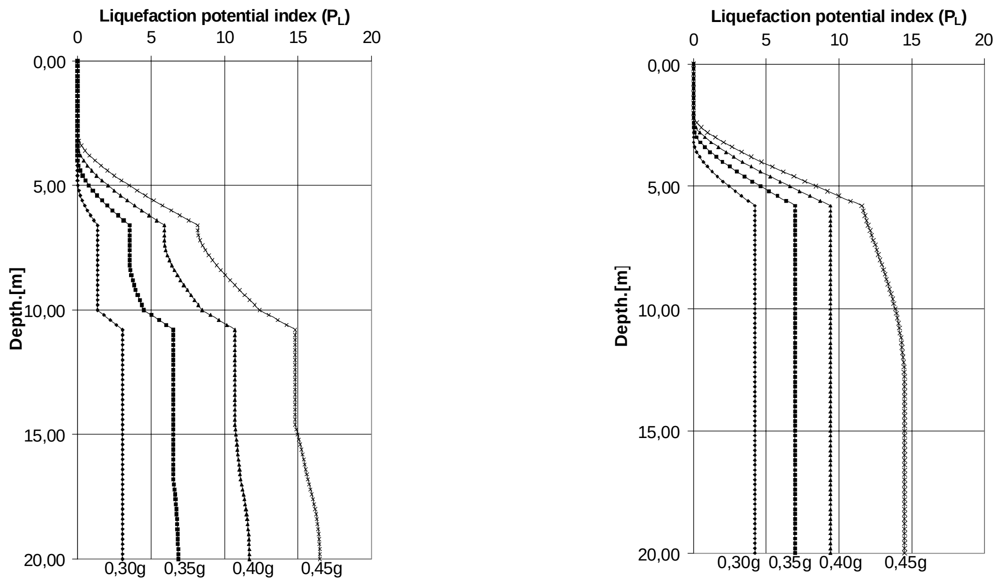

Figure 2.16 - Parametric analysis: a) boring n. 418; b) boring n. 425

2.6.2 *CPT-based evaluation of liquefaction potential*

Cone penetration testing (CPT) is not significantly affected by test equipment, and also allows to obtain a more continuos data profile than standard penetration testing. For these reasons, methods assessing the soil resistance to liquefaction based on CPT data have been developed in the last decade. The most credited among these procedures is at present the Robertson and Wride (1997) method in its most up-to date version.

Eleven CPT tests are available for site no.11, which is located in the area called San Giuseppe La Rena, near the seashore and the airport. The site consists of alluvial deposits resting on a very thick clay formation (see 2.2).

Figure 2.17 provides a plot of the liquefaction potential index for CPT no.1 (located near borehole no.425 of the boring database) which attains the maximum value 6.73 at a depth of 10.4 meters. Therefore, for the first level scenario ground motions, the liquefaction risk must be considered to be high, since the threshold P_L = 5 is exceeded.

It is reminded that in this project the first-level scenario ground motions have been deterministically estimated (see 3. below), having in mind a possible repetition of the catastrophic 1693 earthquake, and that a second-level scenario was also considered for events of less severity, and a shorter return period. For the latter, the damaging earthquake that occurred in 1818 was used as reference. Since in both cases 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 P_L. The results obtained are shown in Figure 2.18 and in Table 2.4. For magnitude M lower than 6.5, and a maximum acceleration lower than 0.5g, the liquefaction risk is low. For more severe earthquakes, the liquefaction risk can be high, but never very high.

Table 2.4 - Effect of earthquake magnitude M and of a_{max} on the liquefaction potential index P_L.

M	**5.0**	**5.5**	**6.0**	**6.5**	**7.0**	**7.5**	**8.0**	**8.5**
a_{max}/g								
0.10						0.03	0.18	0.31
0.15				0.01	0.22	0.43	0.81	1.40
0.20			0.07	0.27	0.57	1.26	2.24	3.75
0.25		0.03	0.26	0.57	1.34	2.79	4.40	5.97
0.30		0.20	0.49	1.20	2.59	4.56	6.26	7.93
0.35	0.08	0.32	0.91	2.05	4.10	6.13	7.91	9.67
0.40	0.20	0.53	1.42	3.27	5.42	7.55	9.43	11.01
0.45	0.30	0.88	2.15	4.41	6.67	8.90	10.65	12.06
0.50	0.44	1.26	3.13	5.47	7.78	10.05	11.63	12.89

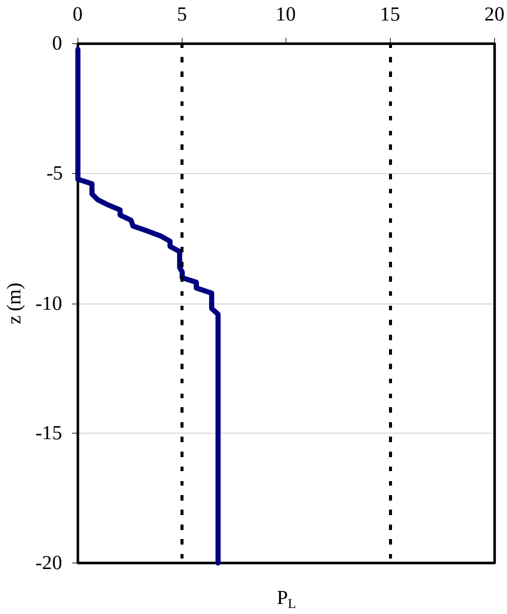

Figure 2.17 - *Liquefaction potential index P_L for CPT n.1.*

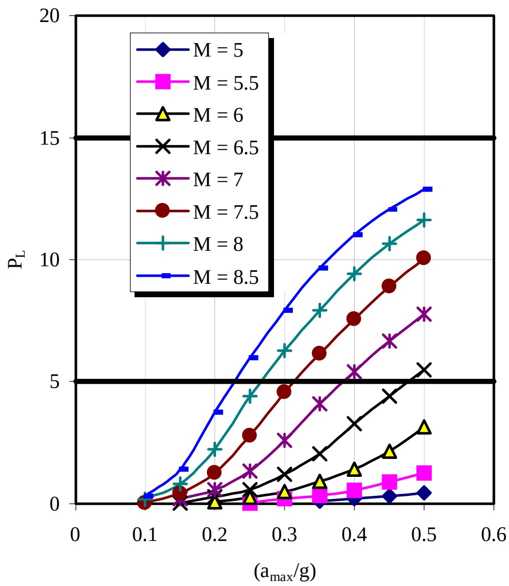

Figure 2.18 – Effect of magnitude and of a_{max} *on the liquefaction potential index* P_L.

2.6.3 *Conclusions*

Information from historical sources confirms that the alluvial deposits of the Catania plain have suffered liquefaction effects in past earthquakes not only for very strong shaking ($M_s \approx 7.0$) but also for a moderate one ($M_s = 6+$), as reported in 2.5. On the other hand, the results obtained from site response analyses using in situ *Vs* measurements (see 2.3) show that there is a high probability of liquefaction in the area of the Plaja beach for the first-level scenario earthquake.

In our study, the results obtained from the SPT data (Par. 2.6.1) allow us to draw the following conclusions: the occurrence of liquefaction at sites no.2, 5, 6, 7, 8 and 9 cannot be evaluated because further investigations are required; liquefaction at site no.4 (originally included among the liquefiable sites) is very unlikely due to the high clay content; the liquefaction risk at site no. 10 is very low due to the high soil strength; the liquefaction risk at sites no.1 and 3 is low and occurs only at depths greater than 10 m. Finally, liquefaction under the scenario earthquake at site no.11, in the area called San Giuseppe La Rena, is high both according to the SPT and to the CPT procedures, and is relevant across the whole thickness of the sand layer.

The results obtained from the SPT data for site no.11 using the Robertson and Wride (1997) method compare well with those based on CPT data from the same site. Finally, the parametric analysis showed that the value of the maximum ground acceleration strongly affects the liquefaction potential index.

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2.7 Conclusions

(M. Maugeri and E. Faccioli)

The creation of a database of about 860 boreholes has allowed to make a first, realistic geotechnical zonation of the urban area of Catania, including characterisation of geotechnical units with strength parameters and mapping of the average S wave velocity $Vs_{,30}$ for earthquake engineering purposes (2.2). The database includes borehole locations and profiles accessible via GIS, can be continuously updated, and is a powerful tool for seismic microzonation. Special investigations were carried out for better characterisation of the soil behaviour under the strong ground shaking generated by the first-level scenario earthquake.

Vs profiles with depth have been additionally obtained for some representative local soils by surface wave techniques. Surprisingly, at 15 m depth at one location the *Vs* values (150 m/s) in the 1669 lava flow were found to be lower than in the shore sands (280 m/s). The highest velocities (450 m/s) have been measured in the conglomerates (unit SG), while the *Vs* values in some near-surface prehistoric lavas rank between those of incoherent soils (shore sands) and stiff soils (conglomerates). This would suggest that the seismic basement to be assumed for seismic response analyses in Catania should be taken deeper than 15 m in the city centre, deeper than 30 m for the fluvial deposits (conglomerates and sands), and deeper than 20 m for the shore sands (see 2.3). However, more measurements are needed to draw a firm conclusion, especially in some city areas

Under strong ground motions such as those expected in the scenario earthquake the soil behaves non-linearly. Non-linear soil behaviour of the clay in the Catania central area (unit ASg) has been investigated by cyclic laboratory tests on undisturbed samples retrieved from one borehole (see 2.4). The values of the small-strain shear modulus measured by laboratory tests are in good agreement with those evaluated from in situ down-hole tests. The shear modulus degradation for this clay is close to that evaluated for the Piana di Catania clay (geotechnical unit Alf). The small-strain damping ratio evaluated by cyclic torsional tests is about 1%, considerably less than the value of about 4% evaluated by resonant column tests.

Information from historical sources confirms that the alluvial deposits of the Catania plain are susceptible to liquefaction. The distribution of liquefaction sites over a large area within the X-XI MCS isoseismal of the 1693 destructive earthquake, as far as some 20 km from the epicentre, indicates that the industrial district and the airport area south of Catania may be affected by severe liquefaction damage, with consequent loss of their function (2.5).

Therefore, liquefaction potential analyses have been performed. The results based on data coming from *Vs* measurements show that there is a high probability of liquefaction in the area of the Plaja beach for a scenario earthquake of magnitude 7 (see 2.3). The results obtained from standard geotechnical analyses with SPT data show that the liquefaction risk is high for one area near the seashore (San Giuseppe La Rena); this indication is in good agreement with the procedure based on CPT data (see 2.6).