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SEISMIC MICROZONATION STUDIES IN THE CITY OF RAGUSA (ITALY)

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ABSTRACT

The geotechnical zonation of the subsoil of the city of Ragusa suggests a high vulnerability of the physical environment added to site amplification of the ground motion phenomena. These elements concur on the definition of the Seismic Geotechnical Hazard of the city of Ragusa that should be correctly evaluated, through geo-settled seismic microzoning maps. Based on the seismic history of Ragusa, the following scenario events have been considered: the "Val di Noto" earthquake of January 11, 1693 (M=7.3), the "Etna" earthquake of March 1, 1818 (M=5.9), the 1895 earthquake (I_{MAX}= 7 EMS), the Modica earthquake of January 23, 1980 (M_W = 4.63) and the "Sicilian Earthquake" of December 13, 1990 (M_L=5.6). Despite of its lower magnitude, a medium size, local earthquake, such as the 1990 "Sicilian" event, has to be accounted for the seismic hazard assessment of Ragusa, since it may cause heavy damage to the most urbanized area. According to historical data, the epicentre of this earthquake was located in the sea. This earthquake is considered a tectonic earthquake and is associated to the strike-slip segment of the Ibleo-Maltese fault system. This fault system is the major seismogenic structure of Eastern Sicily, and it is considered the responsible of the major historical earthquakes which struck this area in the past. According to the response spectra obtained through the application of the 1-D non-linear models, the city of Ragusa has been divided into some zones with different peak ground acceleration at the surface. Shaking maps for the central area of the city of Ragusa were generated via GIS for the scenario earthquakes. The maps represent an important tool for the seismic improvement of the buildings, indispensable for the mitigation of the seismic risk.

INTRODUCTION

The Val di Noto earthquake of January, 11 1693 is the best remembered by Sicilians. Telluric movements started at 9 p.m. (Barbano, 1985) of January 9: at the first shake many buildings collapsed and were badly damaged in all of the towns in the south-east of Sicily spanning from Catania to Noto (Barbano, 1985). But the real destructive shock hit two days later, on January 11 at about 2 p.m. (corresponding to 9 p.m. local time) (Barbano, 1985); the area had already been stricken and so the result was that two earthquakes overlapped causing great damages over an area of 14.000 km square. Due to the huge number of people died (nearly 60.000) and the extent of the damage (more than 45 towns and small villages) this seismic event may be considered alongside the one that stroke Messina in 1908 the strongest earthquake ever occurred in historic times. The shock of January 9 which hit Lentini, Augusta and Catania had an intensity measuring VII on MCS while that of January 11 which developed from the epicentre (situated at sea but not far from the coast) measured XI on MCS (Barbano, 1985), as it resulted from the buildings destroyed and the persistent damages on the soil) and IX-X on MCS in Ragusa (Barbano, 1985).

The Etna earthquake that took place on February 20, 1818 was one of the feeblest ever occurred but its effects were noticed over a vast area. In fact, this quake was sensed in almost every part of Sicily and in the south of Calabria (Imposa and Lombardo, 1985). The quake occurred at 18:20 (G.M.T.) and destroyed many villages on the south-east side of Mt Etna. A total amount of 72 people died because of the great number of houses that collapsed. The isoseismal map explained that the earthquake was perceived almost in every part of Sicily from Siracusa to Noto and Palermo. Probably at Ragusa major damages were caused by the shock of March 1, 1818 with epicentre located near the city (M=5.9, Ioss = 7 EMS). The Modica earthquake of January 23, 1980 (M_W = 4.63) with epicentre near the city of Ragusa represents the "medium" event for the ZS 78.

The earthquake of December 13, 1990 brought to an end a period of seismic dormancy lasted a long time thus reaching a local magnitude M_L = 5.4 with a focus depth of about 6-12 km. Even if it was internationally recognized as a "moderate" earthquake it provoked serious damages to many buildings. The accelerations recorded are influenced by episodes of local amplification as it is shown by the response test of the soil. The analysis of the available data showed that the greatest effects of the earthquake were felt in Augusta (near Siracusa) with an intensity of VIII MCS causing considerable damages even in modern r.c. buildings. Moreover, the analysis revealed the presence of local factors which provoked the amplification of the effects of the shake. The damages are also to be attributed to a seismic activity characterized by subsequent shakes of minor entity in comparison with the main one. In the south-eastern Sicily there are two areas where seismicity is mainly distributed: long the Ionian coast (earthquakes of magnitude M > 7.0) and in the hinterland area (earthquakes of magnitude lower than 5.5). There are evidences from the late Quaternary period that the Ibleo-Maltese fault system is the most probable source for the great earthquakes that struck the region (1169, 1693,1818 earthquakes). This fault system is mainly made up of normal faults NNW-SSE oriented, divided into three segments of fault, the most northern of which continues on the ground up to the Etnean area (Timpa), the central segment reaches the Gulf of Catania while the most southern part lies at sea between Augusta and Siracusa (see figure 1).

The Hyblean foreland may be considered as part of the northern margin of the African continental crust, which is bounded to the north by the thrust front of the Apennine allocthonous units.

ESTIMATION OF THE SEISMIC HAZARD FOR THE CITY OF RAGUSA

From figure 2 that shows the seismic history of the city of Ragusa (Gresta et al., 2004), it is possible to observe that there is a low frequency of occurrence for seismic events with MCS intensity I>5-6 and also for those with 3<I<5-6.

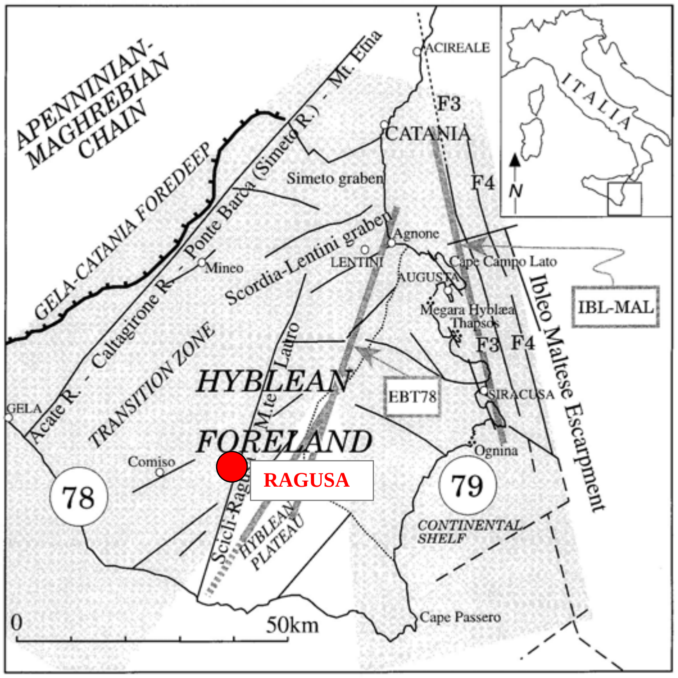

Figure 1. Tectonic sketch of SE Sicily. All kinds of faults, more (continuous) or less (dashed) reliable, are indicated with simple lines. EBT78 and IBL-MAL (heavy segments) are the tentative sources for the 9 January and 11 January 1693 earthquakes. N. 78 and 79 indicate seismogenic areas.

Catalogue is used to estimate the return period (figure 3) and probability of occurrence (figure 4) of earthquakes using the approach proposed by Gresta et al., 2004.

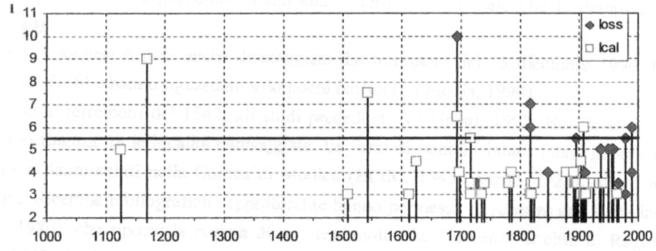

Figure 2. Seismicity distribution of the city of Ragusa, after Gresta et al., 2004.

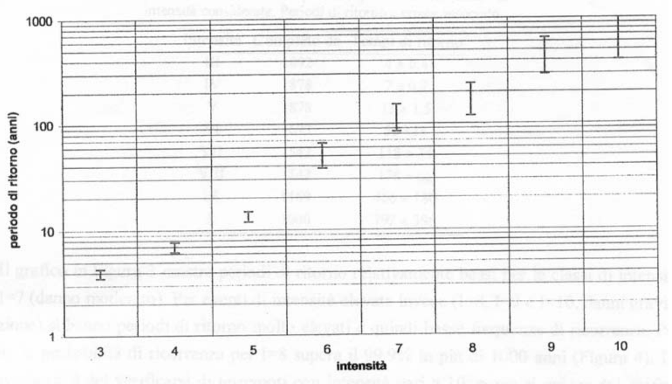

Figure 3. Return period vs MCS intensity, after Gresta et al., 2004.

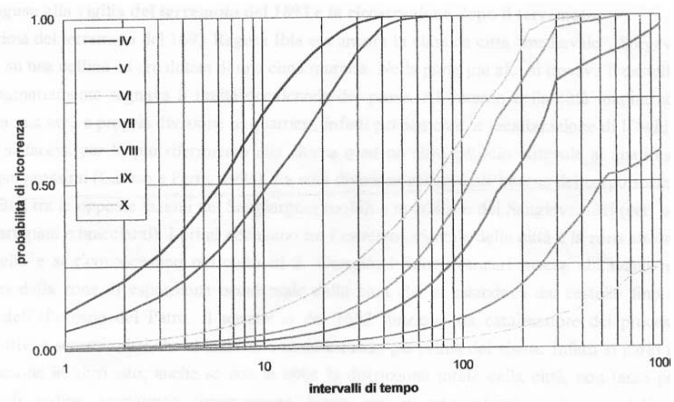

Figure 4. Probability of occurrence vs time period, after Gresta et al., 2004.

From figures 3 and 4 it is possible to observe that return period is low for intensity classes I=6 and I=7 (moderate damage). For higher intensity classes (I=8, I=9, I=10, heavy damage), the return periods are high, so that the probability of occurrence is very low.

Historical maps of the city of Ragusa allowed to reconstruct the damage frame of the city for the scenario earthquakes.

Damage scenario for the Val di Noto earthquake of January 11, 1693 is represented in the figure 5, reporting the EMS 98 damage of the typical “*forma piscis*”.

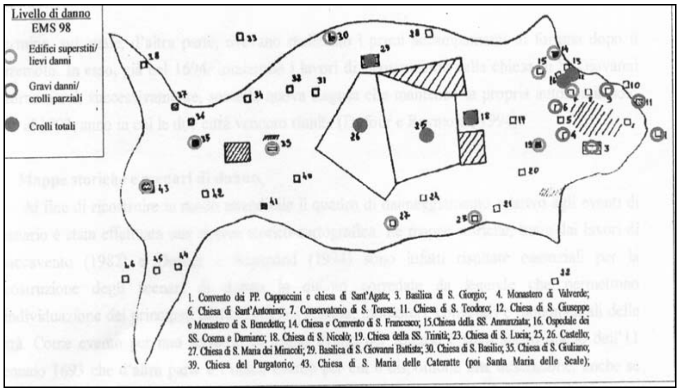

Figure 5. Map of the city of Ragusa representing the damaged ecclesiastical and monumental buildings by the 1693 earthquake.

GEOLOGICAL FEATURES OF THE CITY OF RAGUSA

The city of Ragusa and in particular the part of Ragusa-Ibla is located on an elongated and almost flat calcarenite hill in the south-easternmost part of the Hyblean plateau (see figure 6). The detailed geological survey (scale 1:2000) of the urban area pointed out a rather simply picture characterized by the sub-horizontal alternance of soft and hard carbonatic layers belonging to the Oligocene-Miocene Formazione Ragusa (Gresta, 2004). It is made up by three main lithological units named, from the bottom to the top, (i) Membro Leonardo (marls and calcilutites), reaching thickness of 150 m, (ii) Membro Irminio II (calcarenites), about 50 m thick, and (iii) Membro Irminio I (marls and calcarenites), less than 50 m thick. At depth, the substratum is made up of a succession of Mesozoic consolidated limestones and volcanics. After all, the total thickness of the layer stack overlying the crystalline basement reaches about 4000 m.

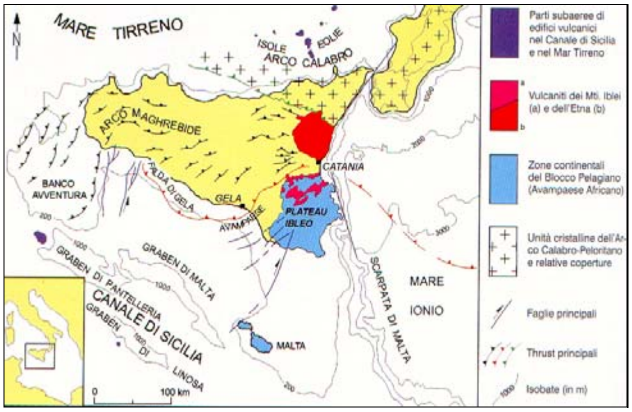

Figure 6. Tectonic scheme of Sicily with localization of the Hyblean Plateau.

In some part of the urban area, detritus was found.

The subaerial part of the Iblean Plateau is constituted by a complex sedimentary and volcanic sequence, characterized by shallow water marine sediments and both sub aqueous and sub aerial volcanics. Late Triassic-Early Jurassic volcanic rocks are not exposed, but they were encountered in drill holes (Patacca et al., 1979). The most ancient outcropping volcanic rocks were emplaced in Upper Cretaceous (Barberi et al., 1974; Grasso et al., 1983) and are constituted mainly by submarine lavas and pillow breccias.

The area was a stable promontory of the African continental margin throughout this tectonic regime. Opening of the Ionian Sea along the Sicily-Malta escarpment began in Late Triassic-Early Jurassic time as a result of the sinistral movement of the European plate. This gave rise to the NNW-SSE trends in the Ragusa basin, Melita basin and other pull-apart basins of the area. Tectonism in the western Pelagian was also controlled by movements of Late Triassic/Jurassic evaporites. Subsequent dextral movement of Europe in latest Tertiary time gave rise to renewed extensive rifting and formation of pull-apart basins across the area. This produced a second major tectonic trend in the area: the NW-SE trending Plio-Quarternary Sicily Channel rift complex which extends from Pantelleria to the Medina Bank.

The local tectonics is also dominated by a series of shear faults (ca. NNE-SSW trending), one of which affects the westernmost sector of the city where fault breccias are well evident.

Figure 7 shows the geo-lithological map of the city of Ragusa at the scale 1:10.000. This map represents the merge of some geological maps and in particular of the PRG geological map of the city of Ragusa (1:2000 and 1: 25.000), of the geological map of the province of Ragusa (1:50.000) and of the geological map of Ragusa Ibla area.

The obtained geo-lithological map with precise boring location, has been geo-settled into the Land Information System (LIS) of the city of Ragusa using a GIS. This map represents the first result achieved by the microzonation studies of the city.

Figure 8 shows the geo-morphological map of the city of Ragusa at the scale 1:10.000. On this map are reported the landslides, the detritus zones, the cavities and the hypogeal structures (*latomie*) with the precise localization of the entrance. The obtained geo-morphological map has been also geo-settled into the Land Information System (LIS) of the city of Ragusa using a GIS. Also this map represents a result achieved by the microzonation studies.

Presence of cavities and hypogeal structures defines a high level of hazard for the historical centre of the city of Ragusa.

These cavities have been localized and geo-settled (Schilirò et al., 1995); some of these structures have been studied in detail because may contribute to modifying significantly the seismic action on the surface. Cavities and hypogeal structures can both modify in a significant way the seismic action on the surface and represent a further factor of geotechnical hazard for the buildings above or for those close to such cavities.

The collapse of the vaults of these cavities represents a further factor of risk for the structures inside the cavity itself.

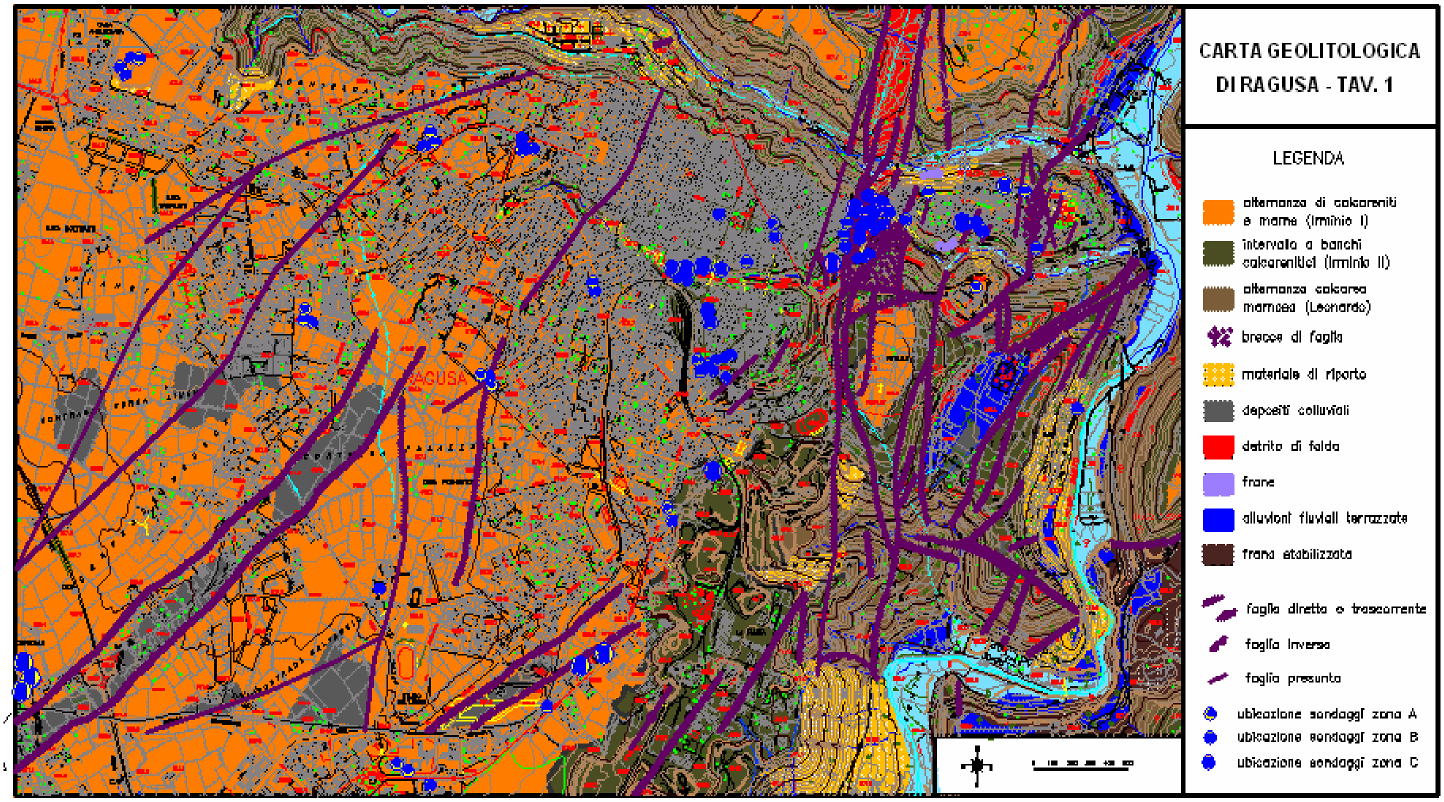

Figure 7. Geo-lithological map of the city of Ragusa with precise boring location (Scale 1:10.000)

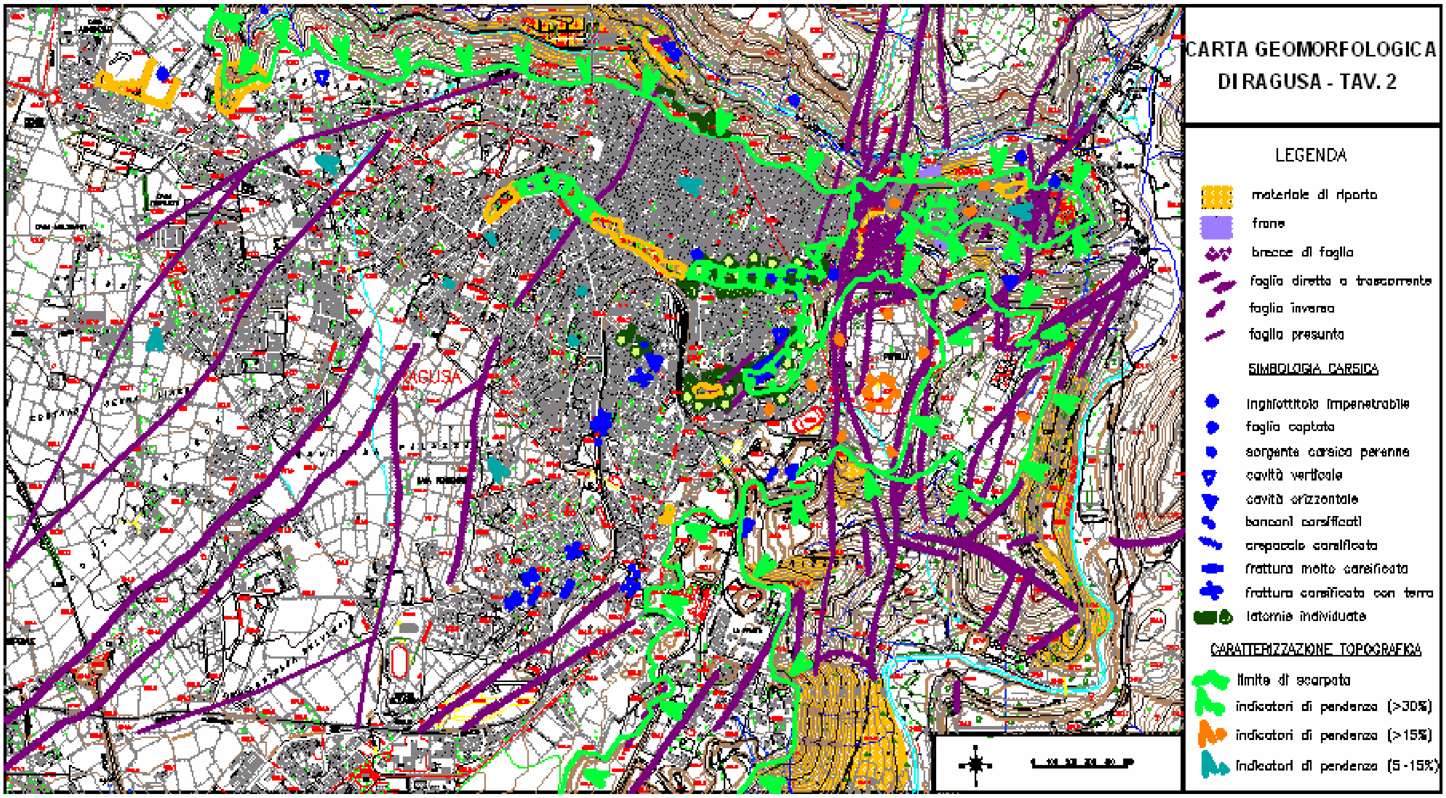

Figure 8. Geo-morphological map of the city of Ragusa with fault and cavities location (Scale 1:10.000)

GEOTECHNICAL SOIL CHARACTERIZATION

The data largely consist of the stratigraphic log of borings, 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 120 boring locations, with a density distribution of the investigation points highly varying from site to site. Processing of this information has resulted in the via GIS geo-settled map of geotechnical units. Boreholes driven to a maximum depth of 30m were performed and undisturbed samples were retrieved for laboratory tests including shear strength tests performed into static conditions.

Because of their relevance on the estimation of local ground shaking and site effects, data from in-hole geophysical surveys (Down-Hole, SASW and seismic tomography measurements) have been examined with special attention, particularly for S wave velocity measurements.

Microtremor measurements were also carried out at the ground surface of 46 sites. Many of them were made in coincidence or very close to drilling sites where detailed information about the subsurface structure are available (Gresta el al., 2004). The noise signals have been recorded with a tridirectional sensor Lennartz 3D-Lite (1 Hz frequency), connected with a 24 bit digital acquisition unit PRAXS-10 and a personal computer board 486 (100 MHz).

Down-Hole data were available from previous investigations at several different test sites, in the urban area. The boring data have been summarised according to a simple lithological description, through the choice of few fundamental classes. Making reference to the geological model of the area, the geotechnical units have been defined and characterised. The denominations of the fundamental classes are consistent with the definitions of the Italian Geotechnical Association (AGI, 1977): 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). In a second detailed phase of the geotechnical characterisation of the various units identified, characteristic (average) values of some representative geotechnical parameters have been evaluated. 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 shear waves velocity Vs was evaluated on the basis of both empirical correlations with in situ or laboratory tests and by direct measurements.

MICROZONATION OF THE GROUND MOTION FOR THE URBAN AREA OF THE CITY OF RAGUSA

The use of advanced methods capable of generating of synthetic seismograms can give a valuable insight into the evaluation of a seismic ground motion scenario (Priolo, 2000). This approach has been brought in the present work with the aim of defining the ground motion at the bedrock. The reference event was the catastrophic earthquake (M7+) that struck Eastern Sicily on January 11, 1693, assumed as a level I scenario event in the work. The ground motion was computed solving, numerically, the 2-D full-wave seismic equation through the Chebyshev spectral element method (SPEM). The Chebyshev spectral element method (SPEM) is a high-order finite element technique, which solves the variational formulation of the differential equation. The computational domain is decomposed into non-overlapping quadrilateral subdomains, and then, on each subdomain, the solution of the variational problem is expressed as a truncated expansion of Chebyshev orthogonal polynomials, as in the spectral methods. An investigation of SPEM and its application to the solution of both acoustic and elastic wave equations has been described elsewhere (Priolo and Seriani, 1991; Seriani and Priolo, 1994). Through the numeric modelling this survey firstly aims at improving the understanding of how the seismic wave field changes while crossing different soil layers. This method is useful to solve the effects of the propagation of the wave field from an earthquake source through a realistic geologic structure by simulating an irregular topography as well.

The approach adopted is based on the modelling of a design basis earthquake through a 2-D section, that is a vertical plan crossing the source and the relevant sites. A normal pure mechanism ($\lambda = -90°$) with dip $\delta = 80°$ and strike $\phi = 352°$ has been taken into account. The size of the model is about 32 km (length) and 20 km (depth).

The epicentre of the source is at about 50 km from the city of Ragusa, which is considered as the coordinate system source. A magnitude M = 7.3, corresponding to the destructive event which struck Catania in 1693 has been taken into account. The source has been simulated through the overlaying of 5 sources placed at different depths and activated at different times, simulating approximately the propagation of the rupture on the segment fault. For each source a corner frequency of 0.24 Hz has been considered; a frequency equal to that of roughness and the wave field has been scaled to the source mid-shift value, which is estimated at 1.34m. Several distributions of the seismic moment, obtained by applying different amplification factors to the five time series S1-S5, have been applied.

Seismograms have been drawn along a set of six receivers placed at different depths, starting from the surface up to almost 170 m. The seismograms represent the complete frequency interval up to the maximum frequency of 8 Hz.

Some of these synthetic accelerograms have been used as an input for the evaluation of site response made by 1-D non-linear computer code GEODIN with in correspondence of the database of 120 boreholes and water-wells available in the data-bank, while the superficial ones have been used for the comparison. The seismograms have been scaled at the maximum acceleration value of a_{max}= 0.93 m/s^2, considering the epicentrale distance of 50 km.

The code implements a one-dimensional simplified, hysteretic model for the non-linear soil response (Frenna and Maugeri, 1995). The S-wave propagation obtained by D-H, SASW and seismic tomography occurs on a 1-D column having shear behaviour.

Besides considering the synthetic accelerograms obtained by the SPEM method, the recordings of the “Sicilian Earthquake” occurred on December 13, 1990 in Sortino have been also properly scaled and then used.

Although no evidence of tectonics subsequent to the middle Pleistocene is available for the Scicli Line, and for the NE-SW fault system affecting the northern sector of the Hyblean Plateau, the earthquake distribution may be related with minor seismogenic structures, responsible for events with maximum estimated magnitude of 5.2 and 6.4, respectively (Azzaro and Barbano, 1999). The recordings of the “Sicilian Earthquake” occurred on December 13, 1990 in Sortino have been scaled to the maximum acceleration designed for the seismogenic zone ZS78 (M=5.5, focal depth = 15 km), at the value of a_{max}= 0.86 m/s^2.

With the aim to providing ground shaking scenarios as an input for large-scale damage evaluations, an engineering approach based on the use of attenuation relationships was also adopted in the present work. Ground-shaking maps for the urban area of the city of Ragusa were generated via GIS for the scenario earthquakes. The shaking description is given in terms of peak ground acceleration. For this method of hazard estimation only the zero period spectral acceleration (or PGA, peak ground acceleration) has been used. Herein, an attenuation relation has been tested; The relations is SJL99 (SEA99, Spudich et al., 1999), herein chosen for the simpler treatment of site conditions, simply accounted for through the rock (S=0) and soil (S=1) classes. It is calibrated on 142 strong-motion records (26 from Italy) of events in the 5.0 - 7.7 moment magnitude range and 0 - 70 km distance range, and is appropriate for extensional tectonic regimes, such as that predominating in South-eastern Sicily. It makes use of the fault distance, defined as the shortest distance from the surface projection of the fault rupture. As to SEA99, it is a revised predictive relation for geometric mean horizontal peak ground acceleration and 5%-damped pseudovelocity response spectrum, appropriate for estimating earthquake ground motions in extensional tectonic regimes.

Ground shaking scenario has been constructed in terms of PGA, to satisfy the demand by the method used to obtain a Grade-3 map of the seismic geotechnical hazard for the city of Catania, according to the Manual (ISSMGE-TC4, 1999). The desired ground motion parameters were computed via GIS at all points of the study area through the appropriate attenuation relation, with a pixel resolution of 40x40 m. In Figure 9 is presented the ground shaking map in terms of predicted PGA values for the urban area of the city of Ragusa, generated via GIS for the level I destructive earthquake by soil response evaluation at 120 borehole sites.

Figure 10 shows the ground shaking map in terms of predicted PGA values for the urban area of the city of Ragusa, generated via GIS for the level II medium size, local earthquake.

CONCLUSIONS

On the basis of the proposed method it has been possible to obtain a detailed delineation of the spatial variability in seismic responses, which can be used as an improved basis for seismic microzonation mapping. This method has a clear advantage above the “traditional” way of microzonation because it incorporates any a-priori geological and geotechnical knowledge into the model and can yield microzonation. The carried out procedure was to evaluate the design ground acceleration by the 2-D elastic SPEM code and after to evaluate the response spectra at the surface by the 1-D non-linear GEODIN code. The use of non-linear code is needed when the given area is shacked by destructive earthquakes, as in the case of Ragusa, which was affected, in the past, by very strong earthquakes. The spatial variability of the spectral acceleration was determined. Two ground-shaking maps for the urban area of the city of Ragusa were generated via GIS for the level I destructive earthquake and for the level II medium size, local earthquake.

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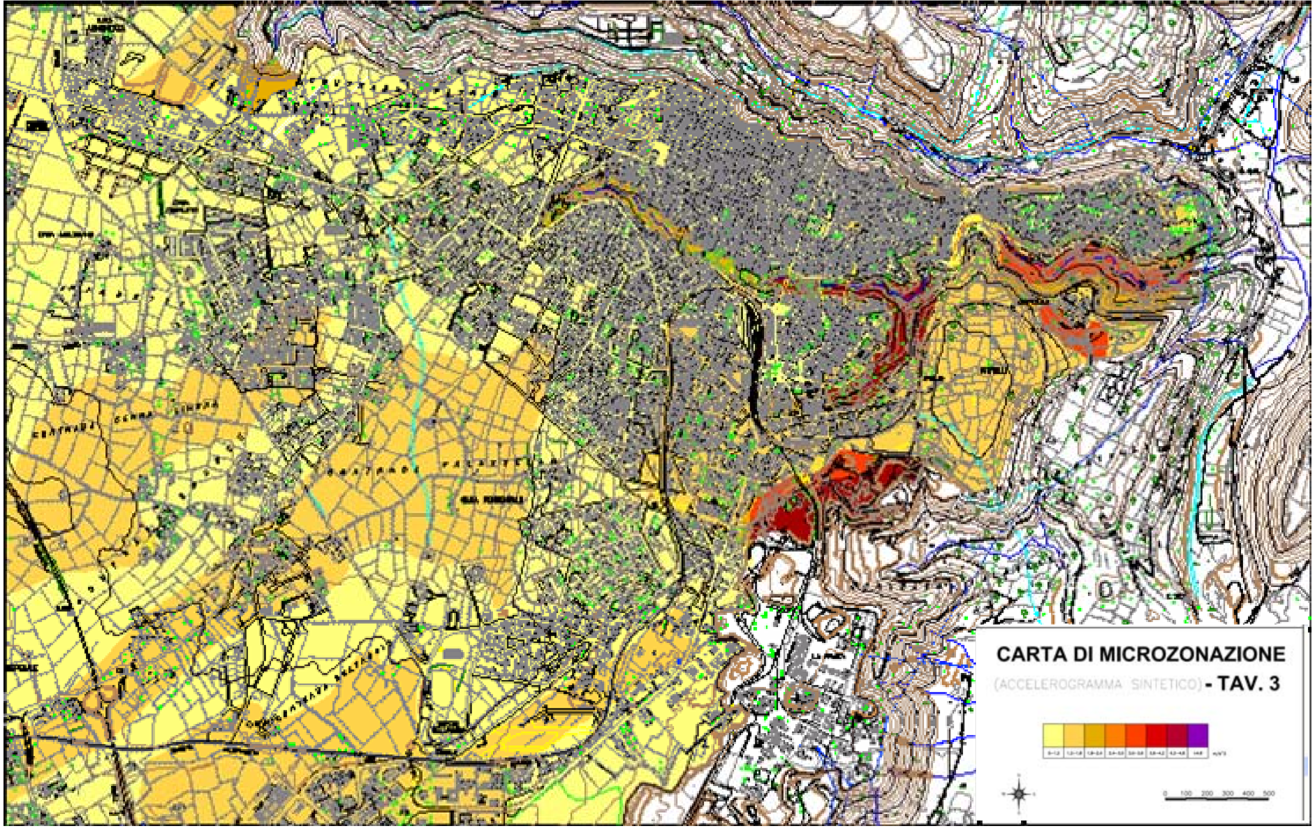

Figure 9. Microzoning map of the City of Ragusa for the level I scenario earthquake.

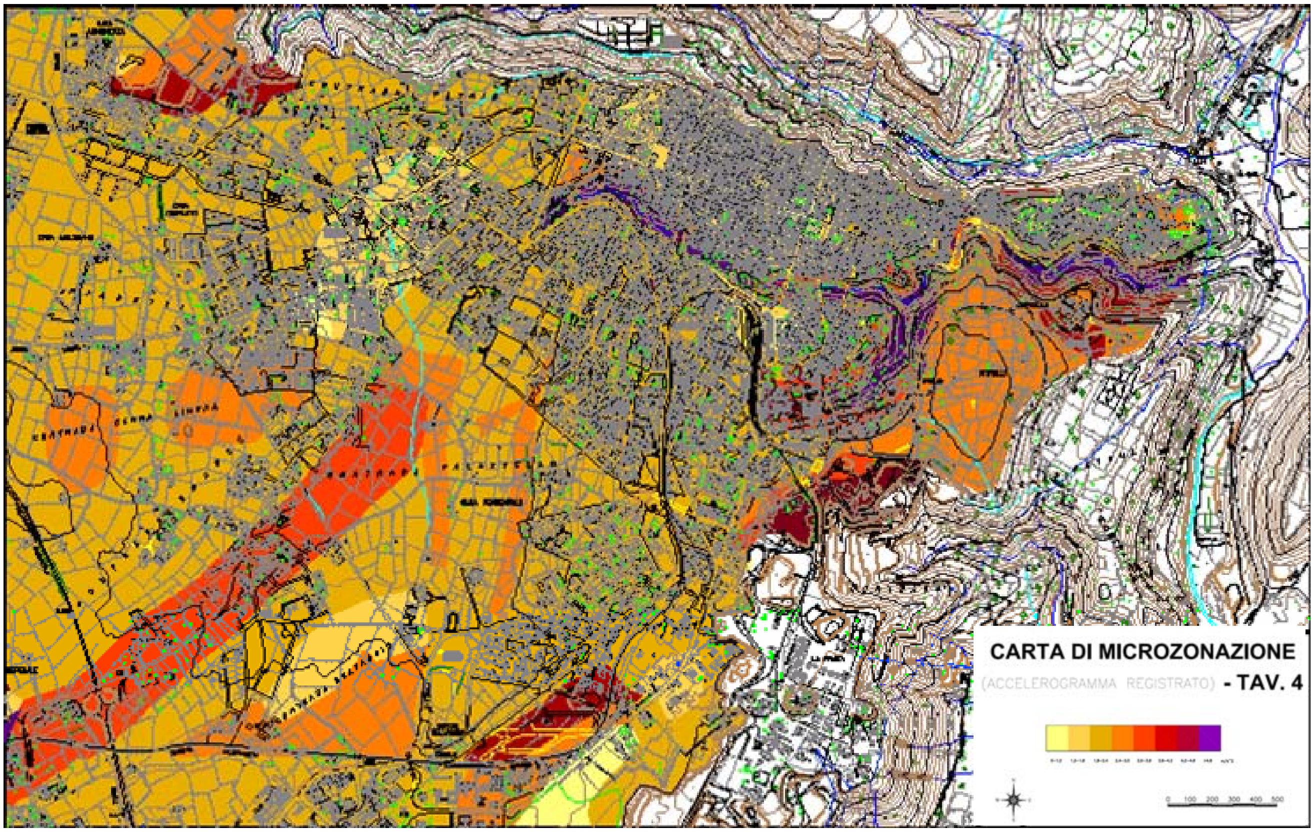

Figure 10. Microzoning map of the City of Ragusa for the level II scenario earthquake.

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