GEOTECHNICAL ANALYSIS OF SEISMIC VULNERABILITY OF MONUMENTS AND HISTORICAL SITES

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Chapter 9

THE EARTHQUAKE ON JANUARY 11TH, 1693 IN SOUTH-EASTERN SICILY: MACROSEISMIC ANALYSIS AND STRONG MOTION MODELLING IN NOTO

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ABSTRACT

A macroseismic characterisation of the 1693 earthquake related to the strong motion modelling in Noto is proposed, aimed at define epicentre and attenuation directions consistent with the geostructural framework of the seimogenic zone.

1. INTRODUCTION

In ancient times south-eastern Sicily was shaken by strong earthquakes that destroyed Augusta, Noto and Siracusa, which were rich cities and blossoming, both historically and artistically. Altogether, the seismic history of this area is still marked by a few earthquakes of high energy, divided by long periods of time characterised by moderate activity, both in number and low relaxed energy. Over the last 9 centuries the strongest earthquakes, with I_o epicentral intensity falling within the interval VIII ≤ I_o ≤ XI MCS, have totalled only 8, and the last of these, with I_o= VIII MCS, dates back to January 11th,1846 (Boschi et al., 2000; Camassi and Stucchi, 1998). After this, the strongest earthquake, occuring about 140 years later, was the December 13th,1990 one with its epicentre close to Augusta and I_o= VII-VIII MCS.

The old city of Noto, located in the upper part of the present city, was destroyed by the January 11th,1693 earthquake; both built-up areas sustained heavy damage during the January 7th,1727 earthquake. The recent December 12th,1990 earthquake damaged several eighteenth century constructions in Noto and called for the need to safeguard the artistic-monumental patrimony of this city, which represents the greatest expression of Sicilian Baroque style.

Lacking suitable instrumental records, the goal of checking the seismic vulnerability of soils in Noto city, resulted in the use of synthetic accelerogram modelling, In consistence with the knowledge of the geologic-structural characteristics of the Iblean foreland, this needed the preliminary individualisation of a seismogenic structure, suitable for causing an earthquake of a relaxed energy comparable with those of the strongest events of the seismic history of this region.

2. GEOLOGIC-STRUCTURAL CHARACTERISTICS OF IBLEAN FORELAND

The area of prevailing interest falls within the eastern sector of the foreland (Fig. 1) which is one of the most important structural elements of eastern Sicily. It represents the emerged part of the northern margin of the African plate, a stable zone towards which the Neogenic nappes of the Apennine-Maghrebide Orogene converge (Finetti et al., 1996).

The Apennine-Maghrebide Orogene consists of a complex system of thrust nappes with African vergence that overthrust onto the Iblean foreland, that is tending to subside through a series of normal faults arranged as steps. Off the Ionic coast, the foreland is interrupted by the Iblean-Maltese escarpment that separates the continental platform and the Malta channel from the Ionic coastal plain.

The stratigraphic succession that surfaces in the Iblean area is characterised by prevalently carbonate sediments which can be dated between the Cretaceous and the Quaternary eras, separated, at different levels, by layers of basic vulcanites. The deepest element reached by petroleous drillings carried out for petroleous research, is represented by the limestone of the upper Trias over 4800 metres thick (Patacca et al., 1979).

The Iblean-Maltese escarpment was formed by a system of step faults that delimited the Ionic coastal plain from the east; it was active during the last 5 million of years, as shown by the geodynamic evolution of the Western Iblean border (Carbone et al., 1982), and would be related to the progressive collapse of the Western border of the Ionic Basin. This system of faults, with a NW-SSE direction, would be placed onto an old crustal weakness zone, already present in the upper Cretaceous, as shown by the great thickness of vulcanites, present from the Iblean zone to the Maltese one.

The tectonic framework, that characterises the Iblean foreland, was already formed by the upper Miocene in the western sector and by a successive epoch in the eastern one. The northern border of the plateau is furrowed by graben delimited by faults, with a NE-SW direction, which form the border structures of the Plateau before the deflection and the underthrust below the Gela nappe (Carbone et al., 1982). From the Maddalena peninsula to Agnone, the faults have a subparallel trend to the contiguous Iblean-Maltese escarpment; the structures delimited by them are, generally, rhombic graben, elongated towards the NE-SW, medially, divided by horst with a subparallel trend. The filling of these tectonic lows, that began to form between the Pliocene and the Pleistocene, is provided by infrapleistocenic biocalcarenites that reach one hundred meters in thickness.

The fault systems that delimit graben are to be related to the recent tectonic evolution of the Iblean-Maltese escarpment and to its progressive recession and, which, following lower Miocene deformations along the Ionic coast, are represented by faults with an E-W trend that cross the infrapleistocenic biocalcarenites.

Another important faults system is the Scicli line, NNW-SSE oriented, with evidence of activity up to the Middle Pleistocene, which is a first order transcurrent zone (Azzaro and Barbano, 2000).

3. MACROSEISMIC ANALYSIS OF THE EARTHQUAKE ON JANUARY 11TH 1693

With the aim of having more indications about the seismogenic structure to be assumed for the generation of the synthetic accelerograms, the seismic intensity distribution of the January 11th,1693 earthquake, which, historically, is the earthquake that produced the strongest damage in the city of Noto, has been analysed.

The macroseismic field designed by Barbano (1985) is characterised by isoseismal lines with an irregular form, elongated towards NNE-SSW approximately, and open because of the sea. (Fig.1). The epicentre can be located close to the coast between the cities of Agnone and Augusta with I_0 = XI MCS; The territory of Noto city falls within the X MCS grade area. Nevertheless, it is to be noticed that the observed intensity distribution is difficult for a satisfactory modelling of the field and in particular of the mesoseismic area. In fact, the few maximum intensity sites are not suitable for arranging the first isoseismal line in a good way.

A different approach of intensity modelling, of vectorial type, (Teramo et al., 1995a, 1996), has been adopted to carry out a better intensity distribution modelling and a more careful determination of the macroseismic epicentre and seismic source strike.

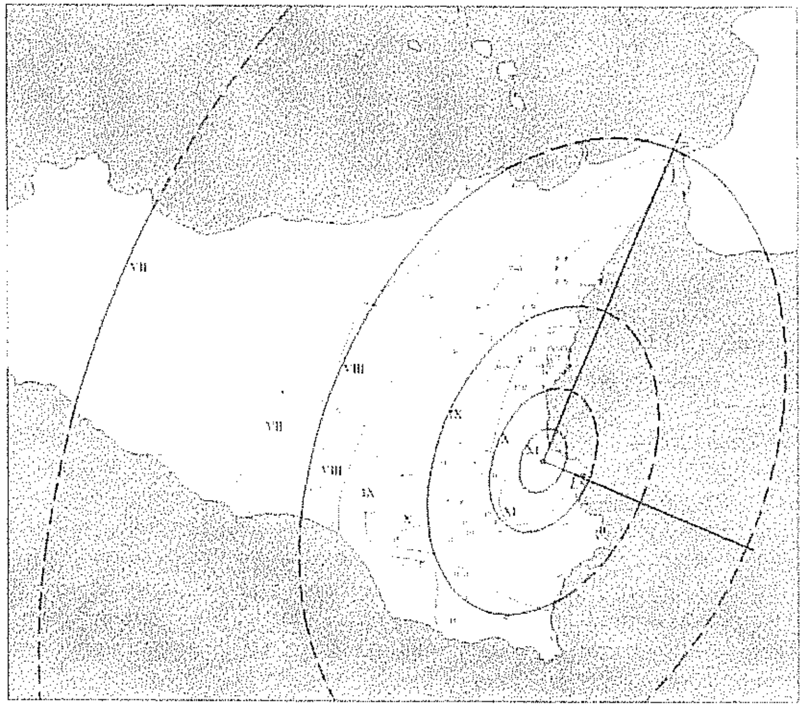

Figure 1 - Macroseismic field, local virtual intensity distribution, epicentre and principal attenuation directions

The procedure used here has been depicted for the macroseismic study of earthquakes whose intensity maps show an observed intensity level distribution not strictly consistent with an anisotropic attenuation of intensity (Teramo et al., 1995b), or are characterised by a remarkable lack of observed data, owing to a particular morphology of the territory, or the closeness of the epicentre to the coast. A preliminary reconfiguration of surface distribution of observed intensity levels is obtained through the construction of the macroseismic plane (Teramo et al., 1996), and the following application of filtering procedures aimed at the approximation of non integer intensity levels to the immediately higher or lower integer ones, or, to a reshaping of integer intensity levels through an analysis of their spatial distribution, respectively. The construction of the so called *1st and 2nd-level filtered macroseismic planes* allows, in fact, their consistency with an anisotropic model of intensity attenuation to be verified (Termini et al., 2003a), highlighting, at the same time, the importance of observed intensity filtering, strictly related to the need to remove unacceptable error levels from data, through a reshape of intensity level distribution to be assumed as a reference for the determination of the macroseismic parameters of the seismic event, as the epicentre and the principal attenuation directions.

A further procedure aimed at the redefinition of filtered macroseismic planes is referable to the construction of intensity virtual areas (Termini et al., 2003b) that supplement the observed intensity distribution in correspondence to areas very close to the coast, as in this case, the sea zones close to the maximum shaking area of the earthquake. The construction of such virtual areas is carried out with reference to the lines that envelope the homonymous points of observed intensity, depicted in accordance with ellipses that have centres coinciding with the observed epicentre of the earthquake. The following modelling of the whole intensity distribution is thus depicted through a plurality of isoseismal areas bounded, on one hand, by the ellipses relative to two subsequent levels of observed intensity, and on the other, by the areolas of filtered macroseismic plane relative to the same intensity levels.

The reliability of such procedures is checked with a double level of verification, through analytical determination, with vectorial procedures, of epicentre and principal attenuation directions, that have to be consistent with the baricentre of the maximum shaking area and the geo-structural framework of the area within which the seismic events falls.

The determination of a virtual intensity distribution, both *local* (Termini et al., 2003a), relative to an earthquake, and *regional* (Teramo et al., 1998), relative to all seismic events belonging to a given seismogenic zone, completes the modelling of the intensity distribution. Such an intensity distribution individualises a distribution of reference that is characteristic both for the single earthquake, and for the set of earthquakes belonging to a seismogenic zone. Geometrically, it is represented by a set of similar ellipses, to each of which an intensity level is associated with centres coinciding with the virtual epicentre of each seismic event or the seismogenic zone in study. Their semiaxes, oriented towards the virtual directions of maximum and minimum attenuation, are proportional, by amplification factors, to the semiaxes of the first ellipse.

If, on the one hand, the application of such a procedure to the earthquake on January 11th 1693, allows an intensity distribution consistent with the observed one to be obtained, on the other, it provides an important contribution in defining the crux of the

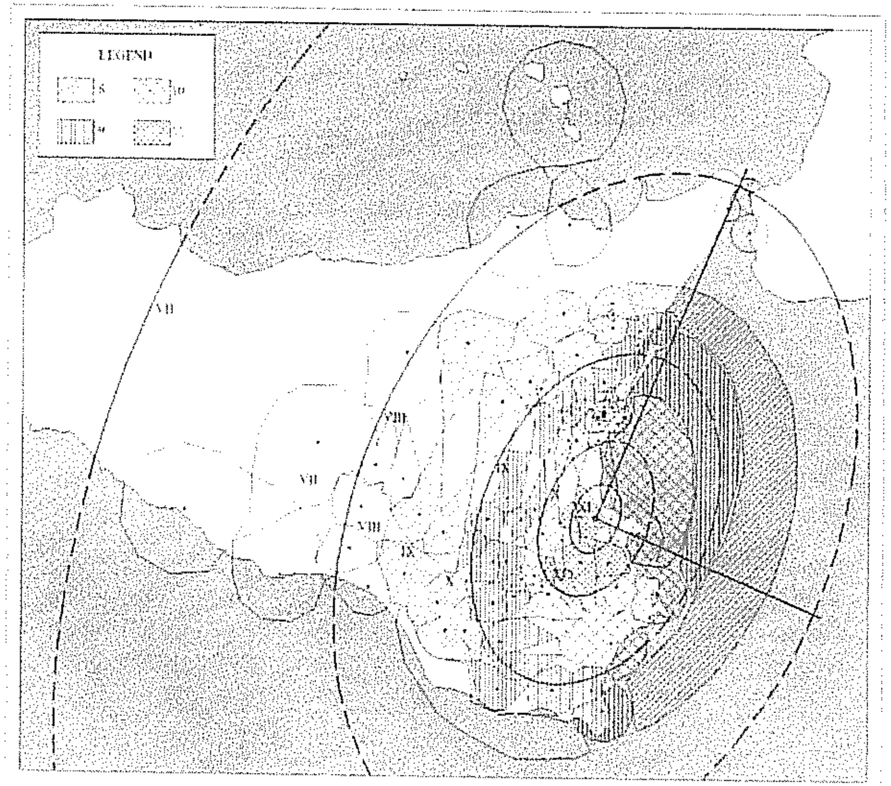

Figure 2 - Ellipses of the local virtual intensity distribution superimposed onto 1st and 2nd-level filtered macroseismic planes supplemented by virtual intensity areas

seismological study of the area that identifies the structure from which the earthquake on January 11th 1693 originated in the Iblean-Maltese escarpment.

Fig. 2 highlights the construction of the 1st and 2nd filtered macroseismic planes, depicted together with the virtual areas owing to the lack of observed data points in the sea zones (Termini et al., 2003b). The determination of the local virtual intensity distribution through vectorial procedures (Teramo et al., 1996), superimposed onto the macroseismic field of the earthquake on January 11th 1693 (Barbano, 1985) (Fig. 1) or onto the macroseismic plane (Fig. 2), shows a good consistency of the two different intensity distributions with the epicentre located very close to the coast, twenty kilometres far from the Iblean-Maltese escarpment, and the NNE-SSW oriented minimum attenuation direction.

From an analysis of the surface distribution of observed intensity, important elements arise that supplement the macroseismic study with further contents that show themselves to be consistent with the results of a seismological study. In such a context, it is to be pointed out, from a strictly macroseismic point of view, that the surface distribution of the XI MCS grades (Fig. 2) is delimited by an area NNE-SSW oriented (from the city of Lentini to Cassaro), whereas the X MCS grades delimit the XI MCS ones in the East, from the city of Avola to Augusta; in the West, from the city of Giarratana to Francofonte; in the North, from the city of Motta S. Anastasia to Catania; in the South, from the city of Avola to Giarratana. Another element of particular importance is related to the epicentre and minimum attenuation direction, analytically determined, that do not seem consistent with the Iblean-Maltese escarpment, but rather, with the Scicli line (Fig. 3), whose seismogenic potential is nevertheless smaller than that of a structure suitable for generating an earthquake like that occurred on January 11th 1693.

All this considered, unless a reduced level of reliability is attached to the observed intensity levels and their surface distribution, an epicentre located in the East, in correspondence with the Iblean-Maltese escarpment, depicts itself as hardly probable. Whereas, it can form, as is more probable, a complex shaking area characterised by a rupture of the northern part of the Iblean-Maltese escarpment that involves the Scicli line through the Scordia-Lentini graben. It is, in a such way, consistent with both the observed intensity distribution and the geometry of the structure, and through the seismogenic potential of which, the observed XI MCS grades are referable.

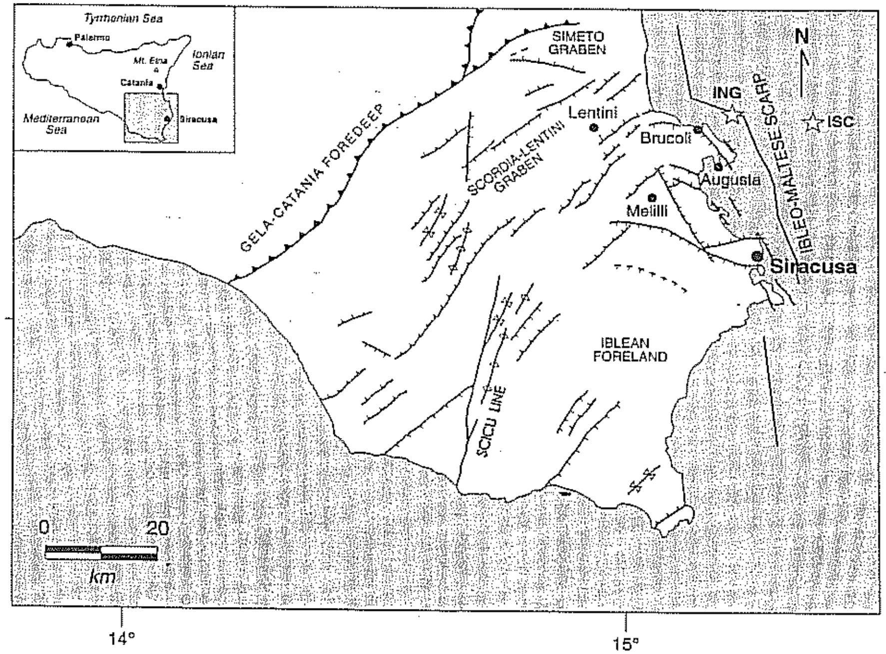

Figure 3 - Geologic map of South-Eastern Sicily (modified after Bianchi et al., 1987)

Moreover, through the procedure proposed by Termini et al., 2003e, the macroseismic magnitude of the 1693 earthquake was determined in 7.3, through a felt area depicted on its local virtual intensity distribution:

$$M = 0{,}42\ ln\ \alpha_i\ (A_i\, I_i^2) \qquad (1)$$

where A_i and I_i represent the extent in km² of isoseismal areas of local virtual intensity distribution and the corresponding intensity levels, determined for i = I_0 ,..., IV MCS, respectively. Such a characterisation of macroseismic magnitude establishes a further element of consistency between the observed intensity distribution, the virtual intensity distribution determined analytically and the geostructural framework of the seismogenic zone.

4. STRONG MOTION MODELLING AT NOTO

Based on the geological and the macroseismic observations of the earthquake of January 11th 1693, the Authors have modelled the strong motion field in Noto, considering the Iblean-Maltese fault as the seismogenic source of the target earthquake.

The fault has been modelled by two rectangular subfaults (Fig. 4) characterised by the southern segment 51 km long and 13 km wide and the northern one 22 km long and 13 km wide. The longest segment, with a 346° strike, is facing the coast between Siracusa and Augusta; the shorter section, with a 352° strike is placed in the Gulf of Catania. Both the subfaults, have a minimum depth of 0.5 km from the surface, and a focal mechanism

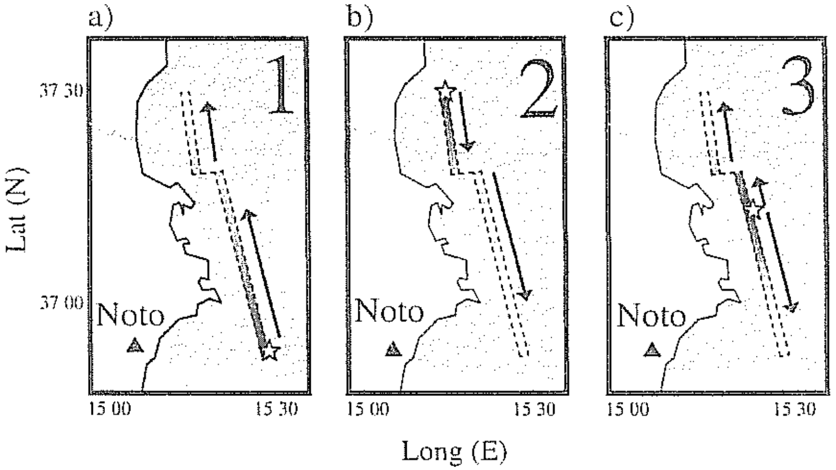

Figure 4 - Rupture propagation models used for the computation of the synthetic accelerograms at Noto. The star indicates the rupture nucleation. The rupture propagates with constant velocity unilaterally from South to North in model 1(a), from North to South in model 2 (b), and bilaterally in model 3 (c)

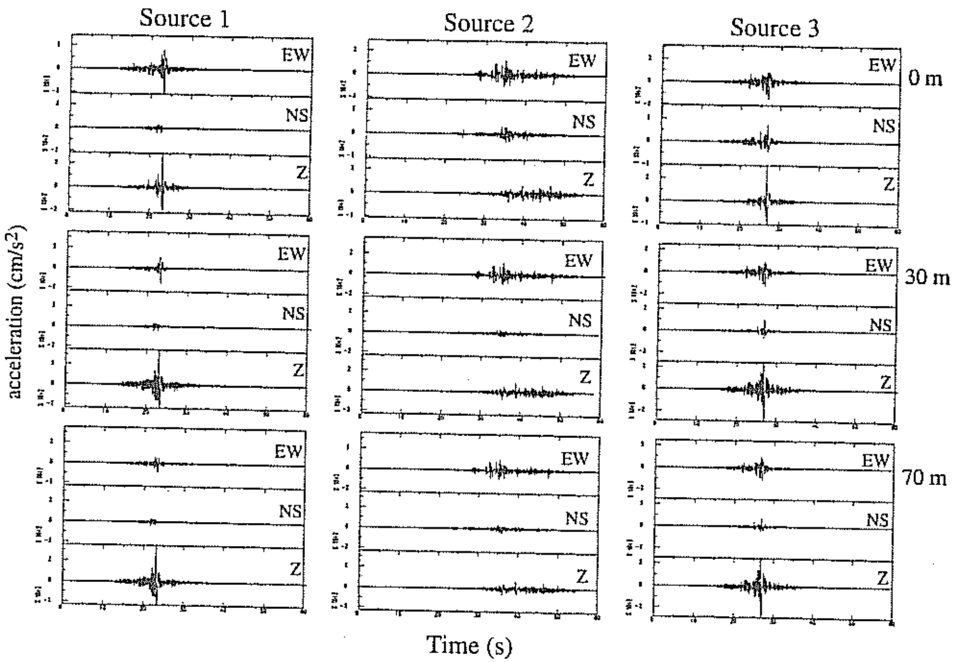

Figure 5 - Three-component accelerograms computed for the rupture models of Figure 4 between 0.1 and 10 Hz

with a dip of 80°, and a rake of 270° (communication by Carlo Meletti). The two subfaults are connected by a third fault segment 6 km long. Only the two main subfaults are considered for the strong motion simulation taking into account the rupture delay due to the third segment.

The two subfaults have been sub-divided by a grid of seismic point sources, each of them generating an earthquake. To avoid aliasing problems the grid spacing has been computed accordingly with the rupture velocity and the maximum frequency of the signal. We sub-divided the subfaults by cells of 20 m along the strike and 50 m along the dip direction, that is, with 949000 point sources (Klinc et al., 1999). For each seismic point source we computed a seismogram by the modal summation method developed by Panza (1985), Florsch et al., (1991) and Panza et al. (2000). The complete signal at the recording station is computed as a sum of point-source seismograms, each one being delayed according to the rupture propagation times on the fault and scaled to include the distribution of energy release on the fault (Panza and Suhadolc 1987; Saraò, 1996; Saraò et al., 1998). At the edges of the fault the slip distribution is smoothed by a 2-D cosine tapering function.

In this study an uniform slip distribution on the fault is modelled and, in order to investigate the effects of directivity, three different rupture propagating models are considered; the rupture is unilateral from South to North in model 1 (Fig. 4a) and from North to South in model 2 (Fig. 4b) and bilateral in model 3 (Fig. 4c). In all the models the rupture propagates with a constant velocity rupture that is 75% of the shear wave velocity of the structural model adopted for this study (Costa et al., 1993). The hypocenter is located at a depth of 13.5 km and the total seismic moment is of dyne cm, corresponding to a moment magnitude Mw=6.7.

In Fig. 5 the accelerograms computed for the three rupture models and for three different positions of the receiver located on the surface, at a depth of 30 m and at a depth of 70 m. are shown. In Fig. 6 the corresponding amplitude Fourier spectra are plotted. We observe from fig. 5 that the maximum acceleration is obtained on the vertical component Z for Source1 (330 gal) at the depth of 30 and 70 m. From the Fourier spectra, the maximum amplitude is observed at 4 Hz on the Z component for model 1, namely the unilateral rupture from South to North.

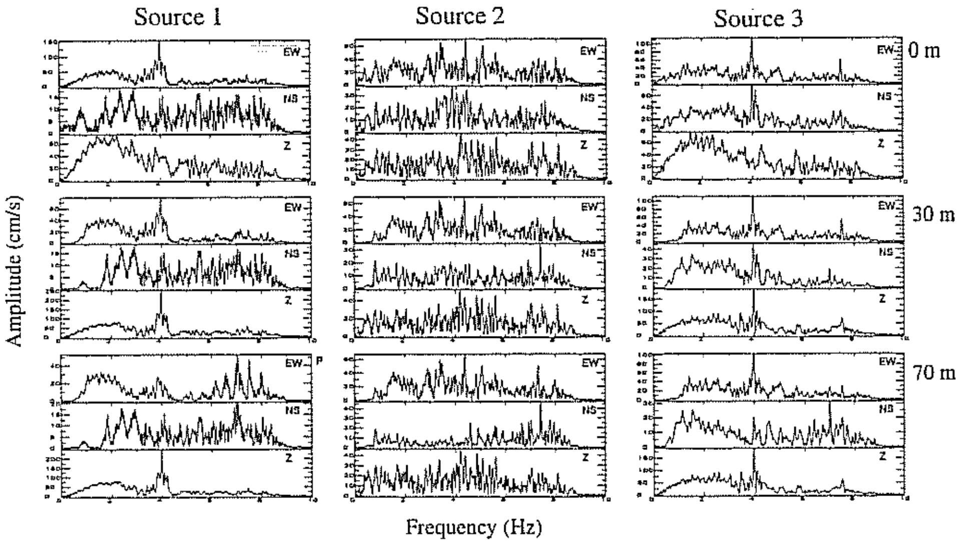

Figure 6 - Amplitude Fourier spectra of the accelerograms shown in Fig. 5

5. CONCLUSIVE CONSIDERATIONS

The goal of modelling synthetic accelerograms, useful for checking the vulnerability of the ground in Noto city, and for different conditions of draping of the bedrock, shows different kinds of difficulties but, principally, in the choice of the seismogenic structure origin of the simulated seismic event, and in the modelling of the synthetic accelerograms consistent with the characteristics of the earthquake that, historically, determined the greatest damage in the city of Noto.

In relation to the first point, it is to be pointed out that the seismic intensity distribution of the earthquake of January 11th 1693, modelled both through isoseismal lines (Carrozzo et al., 1975; Barbano, 1985) and through areolas (Teramo et al., 1996; Termini et al., 2003a), is consistent with a macroseismic epicentre located close to the coast (Agnone). Even the minimum attenuation direction of intensity is substantially the same, being approximately NNE-SSW. Such elements of macroseismic analysis are not to be found in some of the greatest seismogenic structures that cross the Iblean foreland. On the other hand, the unfavourable location of sites of known intensity, already singled out, and the closeness to sea that breaks off all isoseismal lines, make the importance of macroseismic data for a satisfactory location of macroseismic epicentre and for the individuation of origin fault evident.

From a careful analysis of the observed intensity distribution, it was possible, in fact, to depict a rupture of the northern part of the Iblean-Maltese escarpment (to which the seismogenic potential that originated the 1693 earthquake can be associated) that, through the Scordia-Lentini graben, involved the northern part of the Scicli line to which the observed intensity distribution is referable and, which, modelled through suitable vectorial procedures, shows the consistency also with the geostructural framework of the seismogenic zone.

In such a context, the model adopted for the seismic rupture is well defined and bound to the geostructural framework of the Iblean-Maltese foreland, even if some limits related to the approximation level of waveform of accelerometric signals and relative spectral characteristics seem inevitable.

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