3. EMPIRICAL PREDICTION OF GROUND SHAKING FOR LEVEL I AND II SCENARIO EARTHQUAKES

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3.1 Introduction

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 adopted in the present task. Deterministic ground shaking maps for the Catania municipal area were generated via GIS for both a level I, or damaging, and a level II, or destructive earthquake (see sub-section 1.2), incorporating a reliable geotechnical zonation. The shaking description is given in terms of peak ground acceleration and response spectral ordinates.

The applicability of the attenuation relations used was tested by a comparison with the 1990 recorded event (locally known as "St. Lucia earthquake"). A sensitivity analysis on the damage distribution as a function of the ground shaking scenarios has been carried out.

The fairly good agreement found between the present empirical predictions and the results of the advanced numerical simulation (see sect. 4) suggests that the engineering estimates obtained with appropriately chosen attenuation relations can be used for earthquake scenario studies, except in areas where strong source directivity and anomalous site effects can occur. The present work advantageously describes the ground shaking over the whole area of interest (and not only at selected receiver locations, as in the advanced simulations) allowing flexibility in the choice of source geometry, location and magnitude, and in the type of map representation of local geology or geotechnical properties.

3.2 The deterministic scenario for the level I and II earthquakes

Western Sicily was hit by two M> 7 earthquakes, in 1169 and 1693 (see Azzaro, sub-sect. 1.2), but several other lesser events caused damage to the population centres. The city of Catania was completely rebuilt after 1693 and because of its seating on the coast, the uncertain location of the seismic sources and the high sismicity of the region, it can be assumed as representative of the situation of many important Mediterranean towns.

The experience of other countries in damage and loss estimation studies (see Werner et al., 1997; Shinozuka et al., 1997; Rojahn at al., 1997) suggests the use of a deterministic approach as a valid support to the decision makers, because it improves the ability to predict the amount and location of damage (Olshansky, 1997). Furthermore, such an approach is apt provides rapid evaluations and monitoring of information immediately following a strong earthquake (King et al., 1997), in the emergency management phase.

Based on the seismic history of Catania, two deterministic scenario events were considered: the catastrophic 1693 earthquake (I_{MCS} = X), that devastated the city, taken as responsible of the level I scenario, and a damaging earthquake (I_{MCS} = VII-VIII), similar to that of 1818 (level II scenario, see sub-sect. 1.2).

Although probabilistic hazard tools may be helpful in selecting the scenario earthquakes (Whitman et al., 1997), a deterministic shaking description was preferred in this project to a probabilistic one also because it can better account for the complex geology of the area and associated local site amplification, and for the first-order effects on ground motion expected in the near field of a large seismic source (which can be introduced through the last-generation attenuation relations). In any case, a probabilistic analysis was also carried out and the results are discussed in Sect. 11 of this volume.

For blind faults, or earthquakes with an offshore source, it is difficult to associate with confidence a scenario event to a well define fault. For this reason, alternative assumptions were explored concerning the source of the destructive 1693 earthquake (M=7.3), able to generate in Catania an intensity IX or more.

One alternative source interpretation is discussed in sub-sect. 1.3, as being compatible with the 1693 distribution of felt intensities; it is located on the hypothetical NNE-SSW trending fault (EBT78) of Figure 3.1. However, geophysical evidence from offshore reflection profiles (Hirn *et al.*, 1997), and modelling of tsunami (Piatanesi *et al.*, 1996) suggest that the rupture of one or more segments of the Ibleo Maltese fault system (or Malta escarpment), is a more plausible source for the 1693 earthquake. Thus, the simplified source representation adopted (denoted as IMs in Fig. 3.1), consists of two sub-vertical normal faults striking NNW-SSE, connected by a transform segment, for a total length of 70 Km, at an offshore distance of 10 – 12 km from Catania.

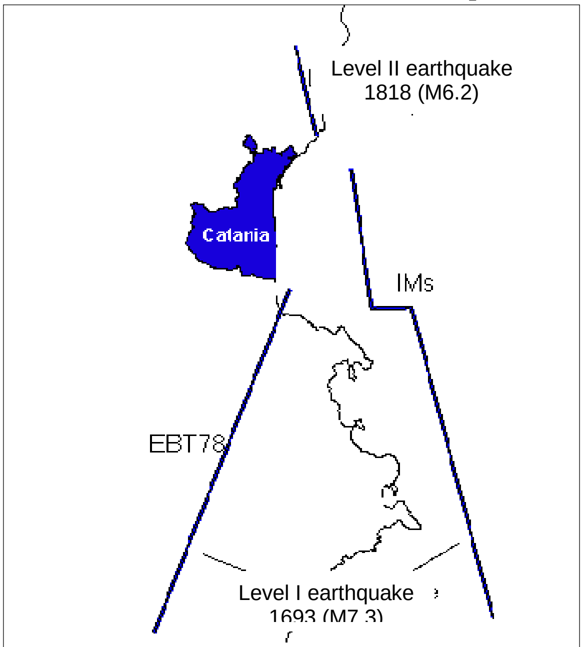

Fig. 3.1 - Level I and II scenario earthquakes in Eastern Sicily

With the powerful support of Geographic Information Systems (GIS), it is indeed straightforward to test different modelling approaches as well as different sources (varying in location, ranging in magnitude). The generation of scenarios with both the EBT78 and the IMs sources led to estimate comparable ground shaking values in the city area, because the involved distances of the city centre from IMs and EBT78 are comparable.

For the level II hazard scenario, some damaging events, with higher probability of occurrence were considered. Among the candidate events of 1542, 1818 and 1848 (see sub-sect. 1.2), having I_{MCS} = VII - VIII, the 1818 (M6.2) earthquake was chosen for its proximity to the city; the location of the inferred causative fault in shown in Figure 3.1. The main purpose of the level II scenario is to satisfy the local administration needs with respect to non-catastrophic emergency response planning.

3.3 Local ground condition and attenuation relationships

3.3.1 *Local ground condition*

Since the geotechnical soil properties and the near-surface geology have a strong influence on the distribution of the seismic energy affecting the structures, these factors have been carefully considered in the hazard scenario generation. The geological setting of Catania is rather complex: the city is built at the foot of Mt. Etna volcano, part on lava flows, widely varying in thickness, and part laying on older clayey formations or on unconsolidated deposits and artificial fills. Sub-sect. describes the procedure by which a reliable geotechnical zoning map has been constructed. Thus, in addition to using attenuation relations that group all surface formations in a few broad classes (see Fig. 2.1) and treat them by a simple site index, the detailed description of the dynamic soil properties has allowed to use the local V_{s30} value (estimated average S wave velocity in the uppermost 30 m of soil, see Fig. 2.2).

The two representations were tested through a sensitivity analysis on the differences in damage estimation (sub-sect. 3.5.2), aiming at an evaluation of the level of approximation of the simpler method.

3.3.2 *Choice of attenuation relations*

Depending on the application, the ground shaking hazard can be described by different parameters. For engineering purposes the representation in terms of response spectral ordinates (Whitman *et al.*, 1997; Kircher *et al.*, 1997; Shinozuka *et al.*, 1997) is appropriate; in some methods of hazard estimation only the zero period spectral acceleration (or PGA, peak ground acceleration) is actually used.

Herein, several attenuation relations have been tested, which differ in terms of underlying database, characterisation of site conditions, and. The relations are

- SFH97 (Spudich et *al.* 1997), 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 128 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.
- SP96 (Sabetta and Pugliese 1996), that also makes use of a simple classification of site conditions. It is of special interest because it is based exclusively on Italian earthquake recordings (190 horizontal components) in the 0 - 100 km distance range. Since it is not constrained by observations for M > 6.8, it is used here only

for a comparison with recorded data for a local earthquake of lower magnitude (the M5.8 event of the 1990) and for the level II scenario generation.

- AMB95 (Ambraseys 1995), for PGA values, allows considering the V_{s30} value as indicator of the local site conditions (for this reason it is classified as *detailed* in Table 3.1). It can be confidently used in Europe because an important part (about 37%) of its dataset consists of earthquakes occurring in Europe and adjacent regions.
- BECL98 (Bommer *et al.* 1998), provides displacement response values, and is based on a reviewed database selected from the European earthquakes used in AMB95.

A summary of the attenuation relations used herein, and of the scenarios where they have been applied, is given in Table 3.1. A further attenuation relation (Boore *et al*. 1993, 1994), catalogued as "detailed" as it uses V_{S30} data, was not considered because it provides higher values of the shaking parameters (see e. g. the PGA values in Table 3.2).

Table 3.1: Attenuation relations adopted in this work. The M7.3 hazard scenarios, used in the damage evaluation (see sect.11), were created applying the attenuation relations indicated by shading.

	Attenuation relations	1990 Event (M5.8) PGA	1693 Event (M7.3) PGA	1693 Event (M7.3) Disp.spectra	Notes
Simpler	SP96	X	-	-	valid for M < 6.8
	SFH97	X	X	X	-
Detailed	AMB95	X	X	-	provides accel. spectral values
	BECL98	-	-	X	provides displ. spectral values

A preliminary test has been made using the SFH97, SP96 and AMB95 attenuation relations, by comparing the respective PGA predictions with the recorded data of the quoted 1990 Eastern Sicily earthquake. The comparison is not easy because this event is rather poorly constrained in terms of location and magnitude (see Pessina, 1990, for details); the anomalous trend of all strong motion recordings, only one of which obtained in the Catania area, has been previously recognised (e.g. Di Bona *et al*., 1995).

The trend of predicted PGA values is shown in Figure 3.2 together with the standard deviation. The calculated mean SFH97 values have been increased by 15% to make the prediction consistent with those of the other relations using the maximum value.

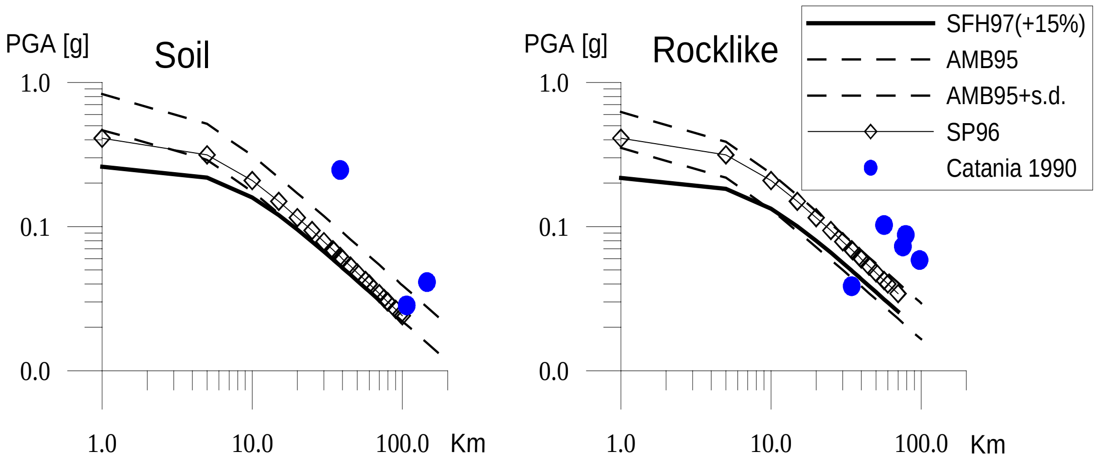

Figure 3.2 - PGA values predicted by the most common attenuation relations show an underestimation of the values (solid circles) recorded during the 1990 Eastern Sicily earthquake (M = 5.8).

For alluvium sites (Fig. 3.2, left), the comparison of recorded values with the predicted ones is rather difficult: AMB95 seems to yield the best agreement with observations far from the source, while the anomaly of the Catania record (~ 30 km distance) could be mostly due to source effects (see sub-sect. 4.2.4) and some anomalous site amplification. For rocklike sites (Fig.3.2 right) the recorded acceleration peaks, plotted against the shortest distance from the surface projection of the fault rupture exceed the mean+1σ prediction for M = 5.8, except for one site (Giarre station).

3.4 The shaking maps

Ground shaking scenarios have been constructed both in terms of PGA and of response spectral displacements, to satisfy the demands by the two methods used for predicting damage (Faccioli et al., 1999). One method relats damage to PGA through a statistical score attribution of vulnerability, while the other requires displacement response spectral ordinates at approropriate vibration periods and damping values (Calvi, 1999).

To provide guidance in future applications where only a simple local geological map may be available, SFH97 has been used to produce a shaking scenario for PGA and displacement spectral values (obtained from pseudo-velocity response values at 5% damping, expediently scaled for different damping values). On the other hand, to make full use of the detailed geotechnical zoning map available for Catania, where V_{s30} values are known, AMB95 has been used to create the PGA map, and BECL98 to create spectral response scenarios (shaded entries of Table 3.1).

Starting from the assumed fault location and magnitude, and from the geotechnical and V_{s30} maps, 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.

3.4.1. *Peak ground acceleration (PGA) map*

There is a reasonable agreement between the PGA maps for the level I scenario obtained with the SFH97 and AMB95 attenuation relations, as indicated in Table 3.2 It is worth recalling that the standard error of prediction is of the order of ± 80 % around the mean value. Table 3.2 also shows the probabilistic PGA predictions on hard ground for 475 years return period in Catania, taken from recent earthquake hazard maps for Italy (Slejko et al., 1998), and the PGA value estimated for the M6.2 level II earthquake. A recently revised version of Spudich's attenuation relationship was available at the end of the project; for such a reason it was not used to create shaking maps, but a comparison of its values (SFH99 in Table 3.2) suggests the possibility of higher level of damage scenarios.

Table 3.2:. PGA values (in g) in the Catania municipal area for the different assumed scenario earthquakes. Shaded are the attenuation relations that provide the final results used in the risk evaluation Project

Earthquake scenario	Max. PGA	Min. PGA	PGA in densely populated area
IMs (M7.3) AMB95	0.359	0.176	0.25 - 0.30
IMs (M7.3) SFH97	0.364	0.150	0.25 - 0.30
IMs (M7.3) SFH99	0.478	0.193	0.30-0.40
IMs (M7.3) Boore et al	0.444	0.228	0.30 - 0.40
Seismic hazard map (475 yr return per.)	0.200	0.200	0.200
1818 (M6.2)AMB95	0.310	0.089	0.15-0.20

Fig. 3.3 illustrates the PGA maps for the level I and II scenario, based on AMB95. The level I scenario PGAs range between 0.15 g and 0.35 g, and although a general decreasing trend with increasing distance from the coast is evident, a certain complexity in the spatial distribution arises because of the influence of site conditions. Due to the proximity of the level II earthquake to the densely populated area, the estimated PGA values are in the 0.15 - 0.20 g range in the historic centre, and they increase up to 0.25 g in the North-eastern part of the municipality, where recent edification predominates.

3.4.2. *Response spectral displacement (SD) maps*

Ground motion maps in terms of response spectral displacement were created for different values of the vibration period T; displayed in Fig. 3.4 are those for level I scenario, based on BECL98, at T = 0.4 s and at T = 1 s and damping ratio 0.05. These values refer to the severe damage limit in masonry structures and to the dominant non-structural damage in reinforced concrete (RC) buildings, respectively, according to the approach based on displacement limit states (sect.11).

As shown in Table 3.3, differences between SFH97 and BECL98 values become larger for increasing T, and it is believed that the SFH97 values are an underestimate.

Table 3.3: Comparison of displacement spectral ordinates for the level I earthquake, at 0.05 damping.

T (s)	SFH97	BECL98
0.4	1 - 3 cm	2 - 4 cm
1	1.5 - 4 cm	6 - 17 cm

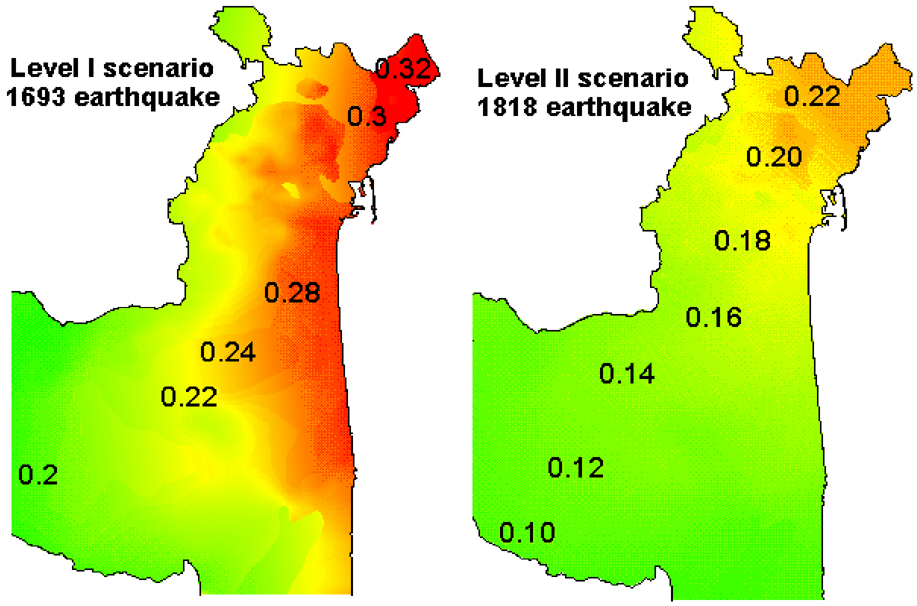

Fig. 3.3 - Maps of PGA (in g) for the level I scenario (left) and level II scenario (right), according to AMB95

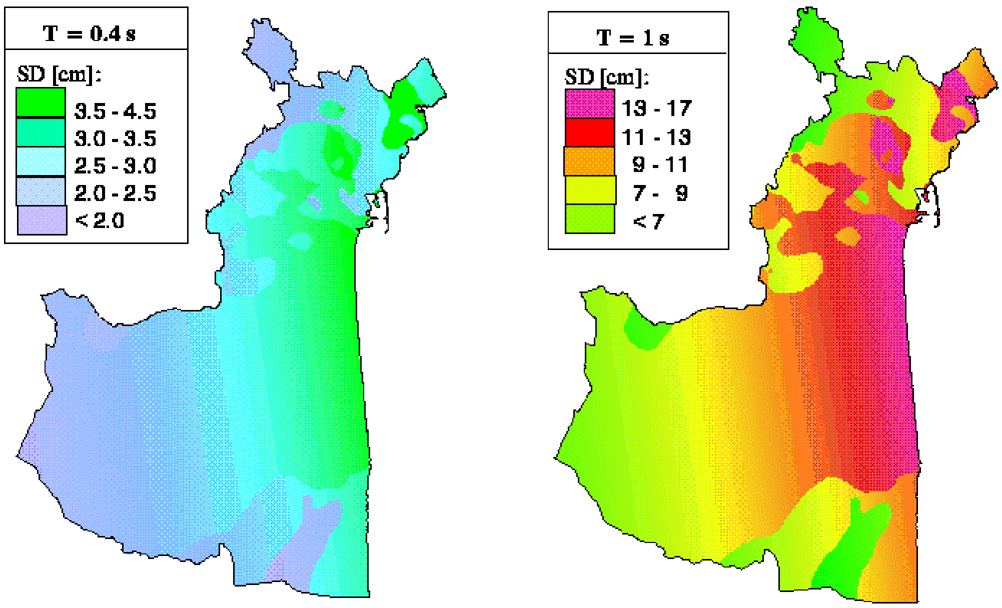

Fig. 3.4 - Displacement spectra maps for the level I scenario according to BECL98 at T= 0.4 s (left) and T = 1 s (right), for 0.05 damping value

3.5 Comparison and sensitivity analysis

3.5.1 *Comparison with the results of advanced numerical simulations*

As extensively described in Sect. 4, source and wave propagation modelling of acceleration synthetics in 2D and 3D was also performed using different methods. The results have mainly beenn applied in the seismic response analysis of specific building and bridge structures in Catania.

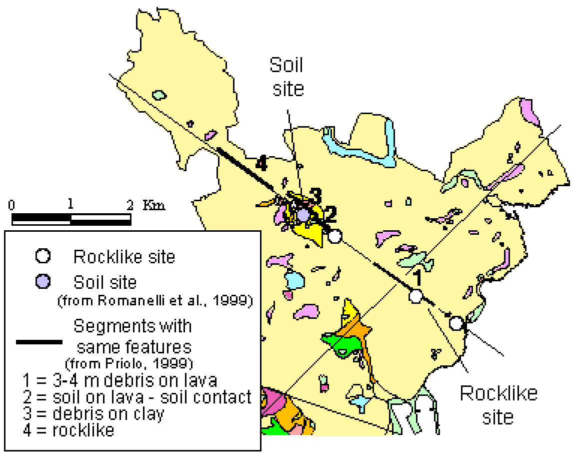

Fig. 3.5 – Map of test sites

A comparison of the present results, obtained essentially by an empirical approach, and those derived from synthetic seismograms provides an independent validation of the use of attenuation relationships in the hazard scenario construction.

Some reference sites were considered, located along the cross-section T3-T3 (as depicted in Figure 3.5). This is of considerable interest for assessing the structural response and estimating damage because, on one hand, T3-T3 crosses the densely populated urban centre of Catania and, on the other hand, it exhibits significant differences in soil conditions when sedimentary materials outcrop amidst lava flows.

The 0.05 damped acceleration response spectra generated by the different methods are illustrated in Figure 3.6, for rocklike conditions (reference site 1 in Fig.3.5, at 13 km from the IMs fault) and a soil site (no. 3 in Fig.3.5, at 17.5 km source distance).

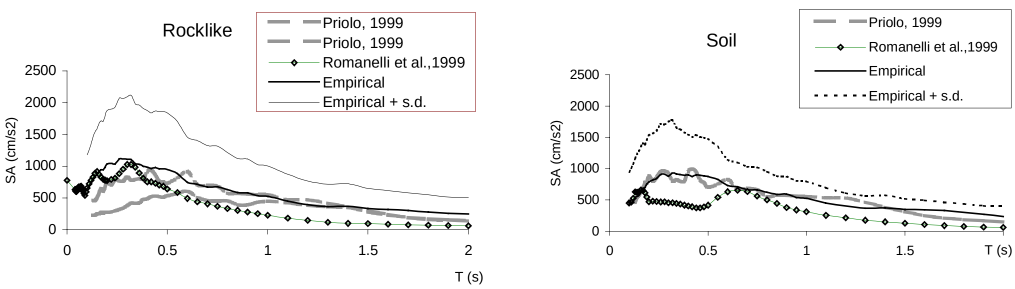

Fig. 3.6 – Comparison of acceleration response spectra from synthetic seismograms and from attenuation relationships, on rocklike and soil sites.

The remarkable agreement among the mean empirical spectrum and the spectra of the synthetics supports the use of attenuation relations to create ground shaking scenarios for an urban area (such as that occupied by a large town), where the results of 2D numerical simulations can not be easily extrapolated. It also indicates that, except perhaps for cases of near-field locations where source rupture effects can be of primary importance, the simpler approach is apt to provide quick, realistic estimations of the ground shaking scenario.

A further comparison on PGA values has been made at the same site of rocklike and soft soil conditions. The PGA values of advanced numerical simulations lie between the mean and mean+1σ values estimated by both the attenuation relations used.

3.5.2 *A sensitivity analysis on damage distribution*

As the predicted ground shaking is at the base of the earthquake damage distribution, the sensitivity of the predicted damage levels to the use of different attenuation relations has been analyse in more detail.

Among the available data on residential buildings in Catania, the ISTAT data (see sect. 5) have been used to evaluate damage level according to the score assignment approach (see sect. 11), for the level I scenario. The damage in residential buildings is described through the damage factor, i. e. the cost of repair in proportion to the replacement cost (normalised value ‘d’ in 0-1 range).

Figure 3.7 (left) shows the PGA distributions as the percentage of land cells (40x40 m) having the same shaking level. These distributions, calculated for AMB95 and SFH97, present comparable trends except at the tails (see Table 3.4 for a comparison on the mean values, or Table 3.2 for the range of PGA results). On the other hand, the relative damage distributions displayed on the right in Figure 3.7 are dissimilar because of the non-linearity of the damage-PGA correlation. The damage distribution for masonry building peaks at d = 0.8-0.9 for SFH97, while it sharply increases for AMB95, reaching a maximum value at d = 1. The distribution of damage for reinforced concrete (RC buildings), not shown in the figure, exhibits the same trend.

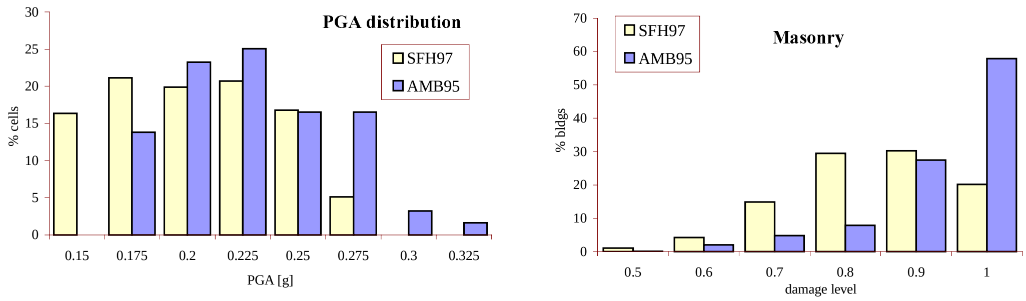

Fig. 3.7 - Sensitivity of the damage distribution with respect to predicted ground shaking distribution. Left: PGA distribution computed on the percentage of land cells having the same shaking level, according to the attenuation relations (SFH97 and AMB95). Right: damage distribution (in percentage) for masonry buildings, corresponding to the previous PGA distributions.

Table 3.4 shows the mean damage values for both types of buildings (RC and masonry), according to both the PGA scenarios created by AMB95 and SFH97.

Considering that a damage factor > 0.8 means that the repair cost is close to the building cost, or that the building has collapsed or is not repairable, one can grasp from Table 3.4 how great is the expected damage for the M7.3 scenario earthquake. Fig. 11.9 in sect. 11 shows the damage distribution for residential building: the most critical areas are located in the historic centre (where buildings are supposed to be more vulnerable) and close to the coastline (where the involved distances from the scenario fault are smaller).

Table 3.4:. Mean PGA values (in g) for the two different assumed scenario earthquakes and consequent mean damage level for masonry buildings.

Earthquake scenario	Mean. PGA [g]	Mean damage level for masonry bldgs	Mean damage level for RC bldgs
SFH97	0.218	0.8	0.825
AMB95	0.242	0.9	0.89

3.6 Conclusions

The main objective of this work has been to provide ground shaking maps of the level I and II scenario earthquake in Catania, to be used for damage estimation to buildings and infrastructures (see Faccioli *et al.*, sect. 11). Maps in terms of PGA and displacement response spectral values were produced for different vibration periods of interest for buildings in Catania. The work itself was made possible by the exploitation of the full GIS technology (ArcInfo and ArcView software, with a resolution of 40 x 40 m), to assess the influence of seismic source location, geotechnical characterisation and of different attenuation relations.

Different relations were chosen (AMB95, SFH97 and BECL98) to compare different scenarios for the 1693 event (M7.3), considered as the main reference earthquake, with the source on the Ibleo Maltese fault (IMs). A comparison of the estimated values with the PGA values recorded in the 1990 Sicily earthquake (M5.8) was made to assess the influence of the attenuation relationships The underestimation of the observed values suggests that the ground motion in future earthquakes could be higher than those predicted because site conditions, directivity effects or regional propagation can give rise to unexpectedly high accelerations.

A less severe scenario has also been considered assuming a repetition of the 1818 (M6.2) event as the reference earthquake, with the aim of predicting the distribution of ground motions for a more frequent event, in order to satisfy the requirements in emergency planning of the local city administration.

A useful practical conclusion is that the use of empirical predictions for the generation of earthquake scenario could be profitably used on a large scale, except in areas where strong source directivity and anomalous site effects can be expected. Indeed, a comparison between the present empirical predictions and the result of advanced numerical simulation of seismic wave propagation (illustrated in sect. 4) shows that the simplified estimates are fairly consistent with the values of synthetic accelerograms.

Another significant test has been performed to evaluate how a more detailed quantification of the local site effects may affect the damage scenario. The sensitivity analysis of the damage distribution with respect to the ground motion scenarios has shown that a detailed geothechnical zonation improves the damage estimation but, on the other hand, when such a zonation is not available, the use of simpler site condition representations gives reasonable results. When resources are limited, they should probably be concentrated on assembling a reliable building inventory rather than on computing advanced shaking scenario because this option is likely to result in a better damage estimation.

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