Chapter 6

Geolithological features and site response in the town of Catania

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Abstract

The evaluation of seismic site response in the urban area of Catania was tackled in two test areas potentially favourable to large local amplifications of ground motion. The two selected areas are located in the historical downtown and in the northern part of Catania where the presence of a fault is evident.

Site response was evaluated using spectral ratios of ambient noise and numerical simulations. Such a method is particularly suitable in urban areas where the nature of the outcropping geological units is masked by city growth and anthropic intervention on the surface geology.

A moderate amplification is mainly observed, at a frequency of 2 Hz, in recent alluvial deposits. Other soft sediments show amplitude spectral peaks smaller than those usually reported in the literature for such soils. Evidence for amplifications of site effects (frequency range 6-8 Hz) were observed in the sampling sites located on the fault, with a rapid decrease of spectral amplitude just a few tens of metres away from the discontinuity.

Numerical simulations evidenced the importance of knowing the geolithological features at depth greater than 20-30 m. Besides this, the results strongly confirm the importance of the subsurface geological conditions in the estimate of seismic hazard at urban scale.
1 Introduction

The city of Catania is located in an intensively active tectonic area, which implies a particularly high seismic hazard. The high level of activity corresponds to the development of large earthquakes with intensities up to X-XI EMS’98 and magnitudes ranging between 6 and 7.1 [1, 2]. Examples of major south-eastern Sicily earthquakes are the events of 4 February 1169 (I0=X), 10 December 1542 (I0=IX-X) and 9/11 January 1693 (I0=IX and X-XI, respectively), this last causing many thousands of victims and shattering an area of about 15,000 km² [3]. Recently, the 13 December 1990 earthquake caused severe damage, despite its moderate magnitude (MS=5.5). In particular this earthquake demonstrated that seismic hazard is not only a matter of large but rather rare events, but represents an actual and frequently occurring problem.

Figure 1: Location of test areas.
It is therefore of primary interest to evaluate the seismic response of the urbanized area from moderate to strong seismic input. In particular, the effects on sites having topographical, structural and/or lithological conditions favourable to large local amplifications of ground motion have to be examined. The distribution of seismic energy depends indeed on the lithology, as well as on the complexity of morphologic and structural features of the investigated areas. Experiments performed in California [4] and recently in Italy, during the 1998 Umbria-Marche earthquakes [5], showed that both active and inactive faults behave like wave-guides when struck by a wave front. The aim of the present study is to investigate peculiar site responses in two test zones located in the urban area of Catania (Fig. 1).

The first zone was selected in the historical downtown area of the city. It crosses the most representative lithotypes outcropping in the study area and reliable information about the lithostratigraphic units and their geotechnical parameters are available from well data. The second zone is located immediately to the north of the town, in an area extensively covered by homogeneous lava flows and crossed by a dip-slip fault. This area was chosen in order to investigate focusing effects in the gouge zone of a fault, where stationary waves are generated by the impedance contrast between the “cataclastic” area and the surroundings rocks [6].

2 Geological settings

The surface geology of Catania is mostly characterized by massive and scoriaceous lavas which derive from several flows that in both prehistoric and historic times covered the area. The volcanic rocks infill deeply entrenched valleys that formed the original morphology of the sedimentary substratum that, at present, outcrops only in small areas. This is made up of a Lower-Middle Pleistocene succession of marly clays, up to 600 m thick, containing levels of pre-Etnean submarine and subaerial basalts. The overlying terraced deposits, of both coastal alluvial and marine origin, are characterized by several metres thick sands, conglomerates and silty clays. They rest on abrasion platforms distributed at different elevations dating to the sea level high-stands between 200 and 40 kyr [7]. Horizons of detritus several metres thick outcrop in different zones of the town. This can be due both to slope detritus as well as archaeological materials and ruins of buildings struck by the last destructive earthquakes of 1169 and 1693.

In particular, the historical downtown area chosen for the simulation (Fig. 2), including the oldest buildings in the city surrounded by the 16th century fortifications, is characterized by a complex sequence formed by soft sediments, constituted by T6 and T7 terraced deposits [7], interbedded between the marly-clayey bedrock and upper massive and scoriaceous volcanic layers. These latter have been attributed to the A.D. 252 lava flow, drilled in the northern border of fortifications, and the 1669 lava flow which surrounds the western and southern borders of the fortifications. The T6 terraced deposits [7] are mostly composed of dark epiclastic sands and microconglomerates, up to 30 m thick, containing
levels of quartzose sands and pebbles of quartzarenites. Though the big 13th century Swabian Castle of Catania is surrounded by the 1669 lava flow, several bore-holes along the perimeter and in the courtyard revealed the presence of coastal sediments at elevations of 10-15 m a.s.l. These deposits, attributed to the terrace T7 [7], are constituted of up to 7 m thick silty sands upwardly evolving to sands and poligenic conglomerates. As regards the marly-clayey bedrock, two interlayered levels of massive basalts, up to 30 m thick, have been drilled in the area of the Ancient Theatre by several wells. Finally, in the ancient part of the city, the uppermost stratigraphic horizons consist of up to 10 metres thick levels of earthquake ruins.

Figure 2: Geological map of Catania downtown.
3 Methodology

The experimental estimation of ground motion can be carried out using earthquake data, in areas having a sufficient seismicity and an adequate coverage of recording stations. Processing of recorded data is usually handled using either a reference rock station or taking the horizontal-to-vertical component ratio. Many authors have recently demonstrated that the H/V spectral ratios from microtremor measurements are consistent in shape with H/V spectral ratios from earthquake recordings, and with earthquake spectral ratios using a reference bedrock station [8]. This method is quite sensitive to the features of the layering of sediments itself which strongly affect the frequency band and the shape of the dominant peaks in the H/V spectra [9] and it achieves good performance when a strong velocity contrast between the bedrock and the soft upper layers exists. Even though there is not unanimous agreement about a theoretical explanation of the observed similarity, the use of ambient noise has become very attractive in recent times because it is both fast and cheap. It is particularly suitable in urban areas where the nature of the outcropping geological units is masked by city growth and anthropic intervention on the surface geology.

In the present study, site response was evaluated using spectral ratio technique taking the horizontal-to-vertical component ratio of ambient noise [10]. Inferences from microtremor measurements were compared with results from synthetic accelerograms and response spectra computed at the drillings available for the area. A validation of these methodologies using data from earthquake recordings was not attempted since the number of recorded data is, at the present time, not enough to represent significantly the different site conditions. About 200 time histories of microtremors were recorded in 40 measurement sites that are roughly aligned in three profiles; the first, trending about N-S, is located in the historical part of the town (Fig. 2) and the remaining two are perpendicular to the fault located in the northern part of the city (Fig. 3).

Measurement sites had an average spacing of a few hundred metres in the downtown profile, while in the two remaining sections spacing ranged from ten metres to up to one hundred metres. Time histories of ambient noise were recorded using a three-component 1-Hz Mark L4C 3-D seismometer connected to a 12 bit analog-to-digital converter and a notebook PC. Sampling frequency was 100 Hz, two antialiasing filters cut higher frequencies with a 10 db/oct slope. At each site five time series were recorded, each with a length of 120 s. The time series were base-line corrected in order to remove spurious offsets and low-frequency trends. After the application of a 10% cosine-tapered window, a Fast Fourier Transform algorithm was applied to obtain spectra in a frequency band 0.5–15 Hz. The lower limit of 0.5 Hz was assessed through the low-frequency cut-off where the microtremor standard deviation becomes equal to the natural noise fluctuation of the 12-bit digitizer. Amplitude spectra of the three components were corrected for their instrumental response. For each time history the amplitude spectrum of the arithmetic average of horizontal components was divided by the vertical component spectrum, providing the mean H/V spectral ratio at each measurement site. A running smoothing function of 0.1 Hz was also used, both on the spectra of each single component and on the
final ratio, to reduce spectral fluctuations. The standard deviation evaluated for H/V spectra obtained at the bedrock (clayey sites) is of the order of ±0.5 units, around mean amplitude values not exceeding 2 units. Based on these fluctuations only spectral peaks higher than 3 units were taken into account as statistically significant.

Figure 3: Geological map of the northernmost area of Catania.

A validation of results obtained with the aforementioned methodology was achieved, in the present study, through a synthetic approach. The simulation of strong ground motion in the urban area of Catania took advantage of the large amount of shallow borehole data that were available [7] whereas information about the deeper geology of the area was obtained from AGIP [11] and Lentini [12]. Finally, knowledge on the seismotectonic setting in South-eastern Sicily has been boosted by the analysis of the 13 December 1990 earthquake and its aftershocks. These events form the first digital data set of the area disclosing the possibility of investigating spectral source parameters, attenuation and seismic scaling laws of the south-eastern Sicily seismic zone [13, 14, 15, 16].

The approach used here contains various simplifications, such as the use of a 1-D structural model or the limitation to SH-waves. These simplifications, which can be justified for the given overall conditions of the studied area, render the calculus simple and fast and account for the high frequency content of the signal.
The number of parameters necessary for the description of the model remains limited, which is important for methods applied to seismic zoning purposes where only limited information is available for the single sites.

The acceleration source time function was simulated according to the procedure proposed by Boore [17], modified by Langer [18]. Its essence is the generation of a band-limited random sequence of random pulses. Global source parameters are accounted for by applying a band-pass filter to the Gaussian white noise, i.e. \( C M_0 S(f, f_0) P(f, f_{\text{max}}) \) where \( C \) is a constant for geometrical spreading and radiation pattern, \( M_0 \) the seismic moment of the event, \( f_0 \) the corner frequency, \( S(f, f_0) = f^2/(1+(f/f_0)^2) \), \( P(f, f_{\text{max}}) = (1+(f/f_{\text{max}})^2q)^{-1/2} \), and \( q \) the parameter of the steepness of the high frequency decay (here \( q=4 \)).

The corner frequency \( f_0 \) can be related to the size of the source (its radius \( r_0 \)) after Brune [19] by: \( f_0 = 0.372 c/r_0 \), where \( c \) is the shear-wave velocity. Finally the seismic stress drop is given by: \( \tau = 7M_0/(16r_0^3) \).

Table 1: Geotechnical parameters of subsurface layers (a) and deeper underground (b).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (m)</th>
<th>C (m/s)</th>
<th>Density (Kg/m$^3$)</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Lavas</td>
<td>10</td>
<td>1000</td>
<td>2000</td>
<td>30</td>
</tr>
<tr>
<td>Sands</td>
<td>15</td>
<td>400</td>
<td>1800</td>
<td>20</td>
</tr>
<tr>
<td>Terraced alluv.</td>
<td>15</td>
<td>300</td>
<td>1700</td>
<td>15</td>
</tr>
<tr>
<td>Detritus</td>
<td>10</td>
<td>100</td>
<td>1700</td>
<td>10</td>
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<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (m)</th>
<th>C (m/s)</th>
<th>Density (Kg/m$^3$)</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>100</td>
<td>600</td>
<td>1800</td>
<td>20</td>
</tr>
<tr>
<td>Claystone</td>
<td>500</td>
<td>1500</td>
<td>2100</td>
<td>70</td>
</tr>
<tr>
<td>Marls</td>
<td>5000</td>
<td>1700</td>
<td>2200</td>
<td>100</td>
</tr>
<tr>
<td>Limestone</td>
<td>300</td>
<td>2600</td>
<td>2500</td>
<td>150</td>
</tr>
<tr>
<td>Basement</td>
<td>∞</td>
<td>3500</td>
<td>2800</td>
<td>300</td>
</tr>
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Strong ground motion is seriously affected by wave propagation effects caused by changes due to absorption, reflection and refraction at the boundaries of the geological structures. In particular the subsurface geological structure is of principal importance in this context. Since there is no simple way to account for wave propagation effects we have calculated the transfer function of the propagation medium using Haskell matrices for a 1-D model. This is certainly a simplification, which however can be justified for the given conditions in the urban area of Catania following the analysis carried out by Bard and Bouchon [20]. Significant errors may be induced from a 1-D model only in the case of deep valleys filled with low impedance material. Bard and Bouchon [20] consider the aspect ratio of a valley given by the relation of depth and lateral extension. They show that 2-D effects dominate over 1-D resonances if both aspect ratio and impedance contrasts are high. This situation is typical for valleys in mountain areas like the Alps but can be widely excluded for the city of...
Catania. As a further simplification we restricted ourselves to SH-waves since these are the most important ones for our purposes and it can be shown that SV-waves behave similarly to SH-waves for the steep ray incidence occurring in our models.

The strongest earthquake scenario for Catania is the shock that occurred on 11 January 1693. Its epicentre was situated probably offshore, at a distance of about 20 km from the Catania downtown area. The seismic moment was estimated to be about $2.5 \times 10^{19}$ Nm, corresponding to a surface wave magnitude of over 7. Assuming a global stress drop of 100 bars we derive a source area of ca. 300 km$^2$.

Numerous seismic logs are available for the study area so we were able to derive standard values for all the formations making up the geology within the area of Catania (Table 1).

4 Results and discussion

Prior to the description of results obtained it must be specified that since noise measurements were made in densely urbanized areas, it was necessary to check the effect of nearby buildings. Tests performed showed that the natural age of buildings does not significantly contaminate the peak response at sites [21]. The H/V spectral ratios obtained for the investigated areas are shown in Fig. 4. It is fairly evident that there is a lack of strong differences in the H/V spectral ratios within the urban area. Spectra obtained from measurements on the clayey basement show a flat shape in the frequency band 2-10 Hz [21]. A similar behaviour is observed for all the sites located on massive lavas (45a, 46a, 37m, 47m, 51m). Spectral peak amplifications near 2 Hz is observed in some sites located on recent alluvial deposits (48m, 50a, 51a). At soft sites like sands, gravelly sands and detritus (4m, 21m, 22m, 23m, 34m, 35m, 36m, 54m), amplification of the microtremor H/V spectral ratios tended to be smaller than that usually reported in the literature for such soils. Similar behaviour was observed in other surveys performed in the Catania area [22, 23]. A moderate impedance contrast of sand and gravel deposits with respect to the basement clays may be hypothesized as a possible explanation for the diffuse low-amplitude H/V spectral ratios at soft sites [21].

In Fig. 5, the selected cross-section is plotted together with some examples of the H/V spectral ratios, the values of simulated peak accelerations and 5% pseudo-acceleration at 1 and 5 Hz, respectively. From our simulations we conclude that the estimated PSA at 1 Hz is not significantly affected by the local geolithological features. On the contrary, the evaluation of peak spectral acceleration in the case of relatively high-frequency oscillators e.g. small buildings (5 Hz), depends on the shallow lithological features of the site, but is sensitive to the contribution of deeper reflectors as well. The lithostratigraphic situation at a distance of about 1600 m from the origin of the profile, is a typical example. In this case, seismic waves propagating in the low impedance clayey basement are trapped between two higher impedance reflectors given by two lava bodies.
Figure 4: H/V spectral ratios for different sites in Catania downtown.

Figure 5: Geolithological cross-section of Catania downtown with modelled peaks accelerations and examples of H/V ambient noise spectra.
Similar behaviour can be postulated for seismic waves propagating through the gouge zone of a fault. Such an interesting feature may be inferred from the spectral ratios H/V along the cross-sections (Fig. 3) of the tectonic structure located in the northernmost part of Catania. The H/V spectra show a tendency towards the amplification of spectral peaks (6-8 Hz) in the sampling sites located on the fault (Fig. 6). A rapid decrease of spectral amplitude is observed just a few tenths of metres away from the discontinuity. The H/V spectra reported in the cross sections A-A’ (sites 42, 43) and B-B’ (sites 17, 32) show a good example of this behaviour. A similar tendency of spectral peaks amplification in the range 4-6 Hz is observed for H/V spectra obtained in some sites located on the eruptive fracture zone (site 48 in A-A’). All other measurements do not show any particularly significant dominant peaks apart from single cases (e.g. 13, 31, 52) where peculiar local conditions such as the presence of weathered lavas and detritus are found.

![Geolithological sections across the fault and H/V spectral ratios.](image)

**Figure 6:** Geolithological sections across the fault and H/V spectral ratios.

**5 Concluding remarks**

The present study faced the problem of site response evaluation in the urban area of Catania by investigating possible amplification effects that can be observed
through detailed studies on some peculiar lithostratigraphic sequences and structural features. The results, on the two selected test sites, strongly confirm the importance of the subsurface geological conditions in the estimation of seismic hazards at urban sites and allow us to draw the following conclusions:
- the H/V microtremor spectral ratios do not show pronounced spectral peak amplifications in most of the sampling sites investigated along the downtown profile, except those located on the recent alluvial deposits;
- the lack of widely observed amplifications does not mean that site effects are not possible, but such behaviour is rather linked to the poor wave velocity contrast between the lithotypes forming the sedimentary sequence outcropping in the study area;
- numerical modelling highlights the importance of taking into account besides the features of shallow (few tens of metres) lithotypes, the existence of deeper (hundreds of metres) structures as well;
- significant amplification effects are observed through numerical simulations; this result is mainly evident in 5 Hz pseudo-accelerator computation;
- amplification effects due to focusing of seismic energy in the gouge zone of a fault were evidenced too.

References


