Transactions on the Built Environment vol 38 © 1999 WIT Press, www.witpress.com, ISSN 1743-3509

Strong ground motion simulation in the urban area of Catania on the basis of a detailed geological survey

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Abstract

Catania is one of the cities with major seismic hazard in Italy. In history the city was repeatedly hit by destructive earthquakes, e.g., the events of 1169, 1542 and 1693, all with estimated magnitudes around or above 7.

The purpose of our research is the study of site effects and response of soil in the Catania urban area based on synthetic simulations. We have considered three scenarios with earthquakes whose magnitudes range from 5.5 to 7.0 and whose epicentral distances are supposed to be in the range 12-35 km.

The subsurface geology of the urban area of Catania is characterized by a marly-clay substratum overlain by lavas, sands and conglomerates. The lava thickness range from a few to over 60 meters, while the thickness of sand terraces ranges from a few to 30 meters. Our study is based on ca. 100 boreholes from which geotechnical and geophysical data were available. We calculated synthetic accelerograms and response spectra at all borehole sites. The results highlight the importance of the subsurface geological conditions, in particular the presence of low velocity layers which enhance seismic loading. On the other hand thick lava layers act as "protecting shields" against earthquake shaking.

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1 Introduction

Southeastern Sicily belongs to the most earthquake prone areas of Europe. Its seismicity is related to the pattern of tectonic movements along the collision front between the African continent and Southern Europe. The active tectonics of the plate boundary is accompanied by recent volcanic activity in the Hyblean Platform and Mount Etna.

The high level of tectonic activity in this area corresponds to the development of large earthquakes, whose magnitudes may reach values of M=7 or even higher. Examples of major Southeastern Sicily earthquakes are the events on 4 February 1169 (I_0=X on the MSC scale), 10 December 1542 (I_0=X) and 9/11 January 1693 (I_0=X and XI, respectively) the latter causing many thousands of victims and shattering an area of about 15,000 km^2.[1] Recently, the 13 December 1990 ("Santa Lucia") earthquake has caused severe damages, despite its relatively modest magnitude (M_S=5.5). In particular the latter earthquake has made clear that seismic hazard is not only a matter of large but rather rare events but represents an actual and frequently occurring problem.

The task of estimation of ground motion can be attacked in different ways. First, the analyst could cull together data sets of accelerograms actually recorded in the zone of interest or in other parts of the world, trying to find examples which duplicate source, travel path and site conditions. Statistical regression techniques, bringing together the available strong motion data, recorded under different source, travel path and local site conditions, have been used to define empirical relations for the estimation of strong ground motion for the varying earthquake scenarios. The drawbacks of these approaches are known: (i) the recorded material is rarely sufficient to permit finding a "suitable" example seismogram, (ii) the statistical approach presumes that the data set at its base is representative also for the specific zone, which often can be argued (see, e.g., the discussion of Lee[2] on the paper of Ambraseys et al.[3]).

A way to overcome these problems is the generation of synthetic strong ground motion seismograms, particularly if significant information about source and geotechnical parameters of the propagation medium is available. In the city of Catania a large amount of shallow borehole data have been collected during recent years. The deeper geology of Catania was investigated in various studies, e.g., AGIP[4], Lentini[5], Faccioli[6]. Finally, the knowledge on the seismotectonic setting in Southeastern Sicily has been boosted by the analyses of the 13 December 1990 "Santa Lucia" 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 Southeastern Sicily seismic zone (see, e.g., Amato et al.[7], Giardini et al.[8], Di Bona et al.[9], Tusa[10]).

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2 Stochastic site dependent strong ground motion simulation

A central problem with realistic strong ground motion assessment are the very irregular and non-uniform waveforms of acceleration seismograms even for similar earthquakes and similar environments. Following Hanks & McGuire[11], high frequency strong ground motion is best to be characterized as "band limited Gaussian white noise with finite duration". In terms of source models these signal characteristics can be understood as a consequence of heterogeneities ("barriers" or "asperities", Kanamori & Stewart[12], Aki[13]) within the seismic source. In both models a rupture front is assumed to move across patches with varying medium properties radiating acceleration pulses of varying amplitude and phase. The resulting acceleration source time function may be simulated as proposed by Boore[14] generating a large number of simple pulses varying randomly with time. Global source parameters are accounted for by applying a band-pass filter to the Gaussian white noise, i.e.,

$$C\, M_0\, S(f, f_0)\, P(f, f_{max})$$

where C is a constant for geometrical spreading and radiation pattern, M_0 the seismic moment of the event, f_0 the corner frequency, $S(f,f_0)=f^2/(1+(f/f_0)^2)$, $P(f,f_{max})=(1+(f/f_{max})^{2q})^{-1/2}$, 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[15] by: $f_0 = 0.372\, c/r_0$, with c shear-wave velocity. Finally the seismic stress drop is given by: $\tau = 7M_0/(16r_0^3)$.

It is now commonly accepted that 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. The subsurface geological structure is of principal importance in this context. Since there is no simple way to account for wave propagation effects they must be explicitly included in the simulation. Here we have been using Haskell matrices for the calculation of the transfer function of the propagation medium. We restricted ourselves to SH-waves since these are the most important ones for our purposes and SV-waves behave similarly as SH-waves for the steep ray incidence occurring in our models.

3 The geology of Catania

The geology of the city of Catania is the result of three combined effects related to (i) the volcanic and tectonic processes, (ii) the Late Quaternary sea-level changes and (iii) to human activity.

The backbone of the urban area is represented by a sedimentary *slope* carved by a *flight* of marine terraces. This substratum is made up of a Lower-Middle Pleistocene succession[16] consisting mainly of marly clays with a thickness of up

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to 600 m and which evolve in their upper parts (some tens of meters) to coastal sands and fluvial-deltaic conglomerates. These strata are overlain by terraced deposits of coastal alluvial or marine origin.[17, 18]

This lithologically heterogeneous sedimentary substratum is dissected by entrenched valleys filled with lava flows, which form the most representative rocks cropping out in the city. The lava flows consist mainly of basaltic material, which on its way downhill from Mt. Etna, invaded the urban area in pre-historical and historical times (e.g. 252, 1381, 1669 A.D.). In the ancient part of the city the uppermost stratigraphic horizons consist of several meters of "detritic material", i.e., the material of buildings destroyed by the 1693 earthquake. The resulting geological framework is thus featured by both vertical and lateral heterogeneity.

The subsurface geology and the related geotechnical parameters have been studied by Catalano et al.[19] who compiled about 100 geophysical logs in the urban area of Catania. For the sake of convenience we divided our models in two levels, one related to the subsurface geology and another one to the deeper units. The subsurface geology varies from site to site, whereas the parameters of deeper units are supposed to be constant across the area. The typical values of the subsurface geological units are reported in Table 1.

Layer	*c*	*Density*	*Q*
Lavas	1000 m/s	2000 kg/m^3	30
Sands	400 m/s	1800 kg/m^3	20
Terraces/alluv.	300 m/s	1700 kg/m^3	15
Detritic	100 m/s	1700 kg/m^3	10

Table 1: Geotechnical parameters of subsurface layers.

The parameters of the deeper units, formed by clay, claystone, marls and limestone are reported in Table 2. After all, the total thickness of the layer stack overlying the crystalline basement reaches about 6000 m. For the sake of simplicity we assumed that these parameters do not vary across the area. This seems justified since the extension of the zone is rather small.

Layer	*Thickness*	*c*	*Density*	*Q*
Clay	100 m	600 m/s	1800 kg/m^3	20
Claystone	500 m	1500 m/s	2100 kg/m^3	70
Marls	300 m	1700 m/s	2200 kg/m^3	100
Limestone	5000 m	2600 m/s	2500 kg/m^3	150
Basement	∞	3500 m/s	2800 kg/m^3	300

Table 2: Geotechnical parameters for the deeper underground.

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4 Earthquake scenarios

Catania's history clearly reveals the importance of the seismic activity related to Malta-Ibleo mega fault system offshore to the southeast of the city. The most recent "Santa Lucia" earthquake in 1990 had a magnitude of ca. 5.5, its seismic moment has been estimated to $3.7*10^{17}$ Nm and the seismic stress drop between 200 and 500 bars (see Di Bona et al.[9]). The most prominent earthquake occurred on 11 January 1693. Its magnitude was estimated by various authors to M≅7, which corresponds, according to common relations, to a length of some dozens of km. With a seismic moment of $2.5*10^{19}$ Nm (see, e.g., Priolo et al. [20]) one obtains after Geller[21] a magnitude of about M=7.3. Assuming a seismic stress drop of 200 bars for this event, which corresponds to the lower value estimated for the Santa Lucia earthquake, one obtains a source area of approximately 200 km^2.

Earthquake	M_0	*Epic. Distance*	*Source Area*
1693 M=7	$2.5*10^{19}$ Nm	≅35 km	200 km^2
Santa Lucia	$3.7*10^{17}$ Nm	≅30 km	12 km^2
local M=5.5	$3.7*10^{17}$ Nm	≅12 km	12 km^2

Table 3: Earthquake scenarios. Source areas are estimated assuming a stress drop of 200 bars.

The following computations for the urban area of Catania have been carried out for three different earthquake scenarios (see also Table 3). The first scenario regards the 11 January 1693 event with an epicentral distance of about 35 km. The second scenario corresponds to the Santa Lucia earthquake on 13 December 1990, which happened at a distance of approximately 30 km. We refer to this case as "Santa Lucia". In the third scenario we consider the case of a "local" earthquake with modest magnitude. This hypothetical event is referred to as "local M=5.5". Its source parameters are the same as estimated for the Santa Lucia earthquake, but it is supposed to be situated closer to the city of Catania, at a distance of 12 km. The focal depth of all three earthquakes has been fixed to 15 km.

5 Results

In order to represent the distribution of seismic loading across the urban area of Catania we have chosen three parameters: (i) the peak ground acceleration as inferred form the synthetic seismograms, (ii) the value of the synthetic 5% pseudo-acceleration response spectra taken at 1 Hz, and (iii) the value of the synthetic 5% pseudo-acceleration spectra taken at 5 Hz. Following the EC 8 (or the US Uniform Building Code) a natural frequency of 1 Hz can be expected for buildings 25 to 50 m high, whereas 5 Hz corresponds to one or two-story buildings. Note that both in the US Building Code and in the EC 8 the standard spectra reach their highest value at frequencies around 5 Hz.

The distribution of the synthetic strong ground motion parameters reveals the importance of the subsurface geology. In particular the high frequency radiation shows a strong dependence on the geotechnical parameters of the uppermost layers. In Figure 1 we present the distribution of the simulated pseudo-accelerations at 5 Hz for the 11 January 1693, M=7 earthquake. The worst situation is encountered in the old downtown, where weak material crops out at the surface. On the other hand strong ground motion is expected be considerably lower in areas with thick lava flows.

Figure 1: Distribution of the values of the synthetic 5% pseudo-acceleration spectra taken at 5 Hz in the urban area of Catania. Higher values correspond to the darker zones.

The distribution of strong ground motion in the urban area of Catania can be understood considering the results obtained for three selected typical sites (see Table 4). The main feature of the site "Old Downtown" are the two surface layers with a shear-wave velocity of 100 m/s and 400 m/s, respectively. The site "Barriera" is a typical example for zones where lava flows are present at the surface, whereas "Campus" can be regarded as example with intermediate site conditions.

Site	Thickness	c	Density	Q
Old	5 m	100 m/s	1700 kg/m^3	10
Downtown	5 m	400 m/s	1700 kg/m^3	20
Campus	20 m	300 m/s	1700 kg/m^3	15
"Barriera"	22 m	1000 m/s	2000 kg/m^3	30

Table 4: Subsurface geology of three typical selected sites of Catania. Note that the site "Old Downtown" is characterized by two thin surface layers.

The synthetic strong ground motion parameters obtained for the three sites and the three earthquake scenarios are given in Table 5. In all scenarios the site "Old Downtown" yields the highest values, i.e., represents the most unfavorable conditions, whereas "Barriera" turns out as the most favorable out of the three sites. The site "Campus" represents an intermediate situation, particularly with respect to the strong ground motion parameters A_{max} and R5, which are sensitive to high frequency radiation.

Event/Site	*Old Downtown*			*Campus*			*"Barriera"*		
	A_{max}	*R1*	*R5*	A_{max}	*R1*	*R5*	A_{max}	*R1*	*R5*
1693 M=7	1.8	2.0	6.5	1.1	1.8	3.2	0.9	1.8	2.3
"Santa Lucia"	0.8	0.7	2.8	0.5	0.8	1.2	0.3	0.4	0.6
Local M=5.5	3.3	3.0	11.5	1.9	3.2	4.0	1.0	1.7	2.5

Table 5: Ground motion parameters for the three earthquake scenarios as obtained for typical sites. A_{max} is the average peak ground acceleration, whereas R1 and R5 are the average pseudo-accelerations at 1 Hz and 5 Hz, respectively. All values are in m/s^2.

Following our results (cf. Table 5) the hypothetical scenario with the local earthquake of modest magnitude appears to be the most critical one. This is somewhat surprising since the earthquake of 11 January 1693 is the largest one occurred in the region, and one commonly refers to it for hazard evaluation. Indeed, the intensity quoted at Catania for this event is X-XI, whereas the epicentral intensity for the event of 13 December 1990 is I_0=VIII. The discrepancy may be explained to some part by the difficulties to compare intensities of historic earthquakes with recent ones. Modern buildings differ significantly from older ones with respect to their structure and material make up, and the average site conditions may have changed throughout the historical development of the city.

A further problem arises from the difficulties to link macroseismic intensities to strong ground motion parameters in a simple way. It is well known that peak ground acceleration, taken as the only measure, is not sufficient for the explanation of earthquake damages and neither are values taken from response spectra even though these numbers have a decisive role in most common seismic regulations (as EC 8, US Uniform Building Code, etc.). Various parameters have been suggested which account for the duration of strong ground motion, one of these is given by the expression[22]

$$\int a(t)^2 dt$$

Indeed, using this parameter in our earthquake scenarios and for our three typical sites (see Table 6) the 11 January 1693 earthquake becomes the most dominant one at least at "Barriera" and "Campus", whereas at "Old Downtown" the local event remains the most dangerous one. Note that with respect to this parameter the three sites differ with a factor of more than 10 for the local event with modest magnitude whereas the scatter is significantly lower for the large M=7 earthquake.

Event/Site	*Old Downtown*	*Campus*	*"Barriera"*
1693 M=7	1.95	0.86	0.41
"Santa Lucia"	0.15	0.02	0.05
1990 M=5.5	2.65	0.80	0.23

Table 6: Signal energy (m^2/s^3) for the three earthquake scenarios and for the selected sites reported in Table 4.

6 Acknowledgements

This work has been performed by grants CNR, contract nr. 97.00532.PF54. The simulation of the synthetic accelerograms and response spectra were carried out with WINSIMUL 1.0 ©.

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