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Site effects of the 2002 Molise earthquake, Italy: Analysis of strong motion, ambient noise, and synthetic data from 2D modelling in San Giuliano di Puglia

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Abstract. On October 31st and November 1st 2002, the Basso Molise area (Southern Italy) was struck by two earthquakes of moderate magnitude ($M_L = 5.4$ and 5.3). The epicentral area showed a high level of damage, attributable both to the high vulnerability of existing buildings and to site effects caused by the geological and geomorphological settings. Specifically, the intensity inside the town of San Giuliano di Puglia was two degrees higher than in neighbouring towns. Also, within San Giuliano di Puglia, the damage varied notably. The site response in the city was initially evaluated from horizontal-to-vertical spectral ratios (HVSr) from a limited number of strong motion recordings of the most severe aftershocks. Several microtremor measurements were also available. Both data sets indicated the simultaneous presence of two amplification peaks: one around 6 Hz, attributed in previous studies to the strong, shallow impedance contrast among landfill/clay and calcarenites, and one at 2 Hz related to the first S-wave arrivals and predominant seen only on one receiver component. Further studies performed on weak-motion recordings also showed strong amplification on the vertical receiver component, thus indicating an underestimation of the amplification by the HVSr technique. Additionally, a 2D-model of the geology of the sub-surface was developed, reproducing the flower-shaped structure generated during the late orogenic transpressive regime. The numerical (finite-difference hybrid) simulation reproduced the two peaks of the observed data at slightly higher frequencies. The model also confirmed that the borders of the flower structure define a boundary between amplification levels, with higher amplification inside.

Key words: Molise earthquake, seismic damage, site amplification, spectral ratio, 2D modelling

1. Introduction

On October 31st and November 1st 2002, the Basso Molise area (Southern Italy) was struck by two earthquakes of moderate magnitude ($M_L = 5.4$ and 5.3). After these 2002 Molise earthquakes, seismological research groups (Mucciarelli *et al.*, 2003; Cara *et al.*, 2005) focused their attention on the epicentral area (Figure 1), in particular on the village of San Giuliano di Puglia (SGP). The studies focused on this village not only because the intensity exceeded that observed in the neighbouring villages (Colletorto, Santa Croce di Magliano, and Bonefro) by two degrees, but also because of the very diversified pattern of damage observed inside the municipality. However, as clearly explained in different reports about damage and vulnerability in SGP (e. g. Dolce *et al.*, 2004), the zones with higher level of damage did not show a higher level of vulnerability. Therefore, site effects were suspected to be responsible for the observed phenomenon.

The principal data set for analysing site effects is composed of eight strong motion recordings from the short-term aftershocks (Table 1) with M_L ranging between 3.2 and 4.2. Several microtremor measurements were also completed. The site amplification was evaluated using a non-reference technique (e.g. Bard, 1995), namely the horizontal-to-vertical spectral ratio (HVSr) method, which can be applied to earthquake data and to ambient noise. Many authors (e.g. Lachet *et al.*, 1996) agree that HVSr, when applied to earthquake data, provides a reliable estimate of the site response. Nevertheless, this technique sometimes seems to underestimate the absolute level of amplification with respect to that inferred by a reference site method (RSM; Borchardt, 1970). In the last years, the HVSr method applied to microtremors (Nakamura, 1989) has been extensively investigated (e. g. Parolai *et al.*, 2004a and b). The main results of these studies confirm that this technique gives a reliable estimate of the fundamental resonance frequency of the soft deposits. Nevertheless, it fails to provide

information about higher harmonics, while the amplification factors obtained are generally lower than those estimated by other techniques.

Additionally, synthetic seismograms were simulated along a profile crossing the village. The model is based on a detailed geological and structural investigation that allowed to define the occurrence of a NNW-SSE trending flower-shaped structure along the ridge SGP is built upon. The simulations were conducted using a 2D hybrid modelling approach (Richwalski *et al.*, 2006). HVSr were calculated using the same method as for the real data; additionally spectral ratios were computed by the RSM.

1.1 DAMAGE AND VULNERABILITY

SGP showed a markedly variable distribution of damage. Mucciarelli *et al.* (2003) and Baranello *et al.* (2003) therefore divided SGP in three zones (Figure 2):

- *zone 1* - historical centre on the hilltop to the South, moderate level of damage
- *zone 2* - masonry and reinforced concrete (RC) buildings dating from mainly after the 1940s along the main street (Corso Vittorio Emanuele), strong damage
- *zone 3* - mainly RC buildings dating from after the 1970s on the hill to the North, low level of damage.

Detailed vulnerability studies (Dolce *et al.*, 2004) pointed out that the overall vulnerability in SGP was the same with respect to the three neighbouring, almost undamaged villages. Moreover, inside SGP there was no vulnerability variation able to explain the observed damage enhancement in the central part of the town.

1.2 GEOLOGICAL SETTING

The studied area is located in the external sector of the Southern Apennines, a typical thrust-and-fold belt characterized by a prevailing NW-SE structural trend and a NE-vergence of the major contractional features. Indeed, in this sector of the orogenic belt two main thrust sheets can be recognized. The western one can be correlated to the “Unità tettonica del Fortore” while the eastern one corresponds to the “Unità Dauna” (Dazzaro *et al.*, 1988). The western tectonic unit overlaps the eastern one, and the eastern tectonic unit overlaps the Bradanic deposits through an E-NE verging thrust. Nevertheless, like all orogens, this sector has also been affected by polyphase tectonics showing the superposition of compressional and transcurrent events (Caputo, 1998). As a consequence, within the epicentral area, the structural setting is mainly represented by NNW-SSE sub-vertical strike-slip faults, which show a typical, small-scale positive “flower” geometry. In particular, the bedrock, on which the older part of SGP is built, is bordered on both sides by these kind of structures.

From a morphological point of view, SGP is built on a NNW-SSE trending ridge rising from nearby gentle slopes and large valleys. The ridge was formed by topographic inversion as a consequence of differential erosion of contrasting lithologies as emphasised by detailed geological investigations. Based on the survey by A. Strollo (2003) that involved four municipalities of the epicentral area, three major sedimentary units have been identified. Unit 1 consists mainly of calcarenites alternating with thin marly layers; Unit 2 comprises clays with argillaceous silty layers. Both of these units can be traced to the “Formazione del Flysch di Faeto” (calcarenites and limestones alternating with marly layers; Burdigalian-lower Tortonian) and to the “Formazione delle Marne Argillose del Toppo Capuana” (clay and clayey marls grey-blue, layered with rare sandy layers; Tortonian), respectively, with both deposited in the “Unità Dauna” described by Crostella *et al.* (1964). Unit 3, located in the central sector of SGP, consists of landfill, debris and weathered clay cover. This unit is always superimposed on Unit 2 (Figure 3).

The bedrock on which the village stands consists of calcarenites alternating with marly layers, while on both sides of the ridge argillaceous and silty layers predominate. A further consequence of this lithological distribution is the diffuse superficial creeping (landslides, see Figure 3), and the numerous mud- and debris-flows that occur in the area.

2. Data collection and processing

In the immediate aftermath of the 2002 Molise earthquakes, the QUEST group (Quick Earthquake Survey Team, <http://www.ingv.it/quest>) collected macroseismic data, installed an accelerometer station, and performed microtremor measurements. The dataset used in this study is composed of eight strong motion recordings and twenty-five microtremor measurements (Figure 2). The strong motion data were recorded at 100 samples per second using a Kinematics K2 accelerometric station. The instrument has a dynamic range of 114 dB and a natural frequency of 50 Hz. It was installed in the backyard of a collapsed school (Unit 3: landfill material, debris and weathered clay cover) on November 3rd and moved to the Palasport site (Unit 2: clays with argillaceous silty layers) on November 5th. The noise samples were taken using sometimes a compact ISMES BNA V2 unit, composed of a Lennartz 3D-Lite tridirectional sensor (1 Hz natural frequency) and connected to a 24-bit digital acquisition PRAXS-10 unit and a Pentium 1 personal computer, and sometimes using a Tromino digital tromometer. Both sensors have identical characteristics on all three axes, hence when working with spectral ratios, it is possible to consider a reasonable range of frequencies below the fundamental frequency, as demonstrated in Giampiccolo *et al.* (2001).

Table 1 shows the list of recorded earthquakes. An example of the recordings at the school site is given in Figure 4. There exists a large difference between the three components: the EW component, almost perpendicular to the ridge elongation, is larger than the NS and much larger than the UP component. In order to investigate the site response, the HVSR on windows of 3 and 12 seconds was calculated, each one starting at least half a second before the S-wave arrival for each event. Time histories were first corrected for base line and anomalous trends and each window was then cosine tapered (5%) and Fourier transformed. The spectral amplitudes were smoothed using the Konno and Ohmachi (1998) window ($b = 20$). Before calculating the HVSR the spectral ratio between signal and noise was calculated to evaluate the quality of the signal. Therefore, 10 seconds of the signal containing the S-wave arrival and 10 seconds of pre-event noise were taken. At the school site, this ratio is higher than three for each time series between 0.2 and 20 Hz.

3. Strong motion data

The average HVSR ratio of the seven recorded aftershocks at the site of the collapsed school was calculated. Figure 5 shows the results together with the HVSR from the single recording of the Palasport site. Compared to the Palasport site, the school site shows a higher level of amplification and this amplification is significant at around 2Hz in particular on the EW component. The Palasport site shows similar amplification for both horizontal components. Furthermore, HVSR amplifications obtained with the NS-component at the school site show less variation if different analysis window lengths are used than the results obtained with the EW-component. A smaller (secondary) peak at 6 Hz is observed on all records.

To better understand whether the amplification at around 2 Hz is correlated with the S-wave arrival, the variability of HVSR was investigated when different parts of the signal are analyzed. Therefore, the HVSR was calculated for each event with a moving window of three seconds width and with half a second overlap, starting before the S-wave arrival and ending in

the coda (Figure 6). Given the difference between the two horizontal components (Figure 5) the spectral ratios for the EW and the NS component were calculated separately. Figure 6 shows for event #3 (Table 1) the results for the conspicuous EW component. The level of HVSR remains stable for the amplification around 6 Hz, but the peak at 2 Hz is clearly related to the S-wave arrival in the first moving window. Similar results were obtained for event #2. The smaller events, however, do not show this time-dependent effect. Moreover, when taking the average of all small events, the peak at 2 Hz has lost its significance completely (compare Figures 5 and 7).

To evaluate the duration of this amplification for the two strongest aftershocks, the total Arias Intensity (AI) was calculated, as well as the AI over a narrow frequency band (similarly to Cara *et al.*, 2005). It is here used to better identify which part of the signal contributes significantly to the amplification and to the extension of signal duration. In Figure 8 the results are shown for the total and filtered AI for event #2 (results for event #3 are similar), which was the strongest aftershock. The highest values of total AI are obtained for the EW component (top). When analyzing the AI in narrow frequency bands (bottom) it is seen that the curves belonging to frequencies around 2 Hz increase quickly and reach the highest values. In contrast, the AIs filtered beyond 4.5 Hz show a gradual increase. This increase starts nearly one second after the steep increase for the frequency band around 2 Hz, and their maximum values remain lower than those of the AIs filtered around 2 Hz. In contrast, the AI for the smaller events show a similar increase over time for both horizontal components (e.g. event #7, Figure 9).

4. Ambient noise data

13 noise measurements were conducted in SGP at sites with differing level of damage. Additionally, noise was measured at 12 sites along a profile oriented SW-NE crossing the ridge, to investigate if the variation of the spectral ratio shapes is consistent with the surveyed geological heterogeneity. At each site at least five time series of 60 seconds duration (sampled at 125 samples per second) were recorded. Albarello (2001) showed that this procedure enables significant results, although Picozzi *et al.* (2005) showed that more stable results (regarding the amplitude of the maximum peak of the HVSR) are obtained with a larger number of windows. To calculate the HVSR the same processing already described for the strong motion data was applied. The final HVSR for each site was obtained by averaging the HVSR of the individual recordings. Figure 2 shows typical results for the different zones and the landslide area. In zone 1 (#6, #7) no amplification occurs. In zone 3 (#1, #8) amplification reaches up to 3, but no distinct peaks are visible, while in zone 2 (#2 - #5, #9), where the damage was strongest, values above 3 can be found and the peaks (often 2) are more distinct than in the other zones. On the landslides (#10 - #13), amplification reaches up to 4 with a clear peak around 4 Hz and another (less distinct) at lower frequencies.

HVSR of noise was also compared to that obtained from earthquakes at two sites close to the school site. Figure 10 shows as an example the HVSR of noise at points #1 (zone 3) and #2 (zone 2) with the average HVSR from aftershock data recorded by the strong motion station. Apart from the peak at 2 Hz, amplification levels are comparable.

On the basis of the results previously shown, the amplification at 2 Hz was interpreted to be related to the arrival of strong S-waves. Therefore, this effect appears to be strongly directional, since it affects mainly one receiver component. It was tested whether the directionality of the amplification around 2 Hz is also present in the HVSR of noise. HVSR was calculated while rotating the horizontal components in steps of 20°. Figure 11 shows a comparison between HVSR for a site located on the ridge (Figure 11 left, site is #14i in Figure 2) and one outside (Figure 11 right, site is #14o in Figure 2). The site outside the ridge

shows a stable HVSR when rotating the components, while the site on the ridge shows two maximum values of HVSR (around 2.5 and 4 Hz) in the direction perpendicular to the extension of the ridge.

5. Modelling

A number of geological surveys were performed after the 2002 Molise earthquakes and several geological models for both deep and upper geological structures were proposed. Furthermore, one of the DPC-INGV Italian national projects is focused on this area with the specific task of obtaining a coherent geological model (e.g., Giaccio et al., 2004; Silvestri et al., 2006a; Silvestri et al., 2006b). With no final geological model at disposal, it was decided to rely on a simple geological model of the area for the numerical modelling. A hybrid 2D finite difference (FD) modelling (Richwalski et al., 2006) was carried out for that purpose that combines the approaches of Zahradnik and Moczo (1996) and Wang (1999). The program separately computes synthetic seismograms for the transversal and the vertical/radial components. The model is based on the geological SW-NE section through SGP (partly shown in Figure 3) and two velocity profiles from Mucciarelli *et al.* (2003). The two velocity profiles down to 30m, one on the ridge and another near the Palasport site, were obtained according to the technique described by Louie (2001). Topography could not be included in the model, and the crustal model is based on the standard 1-D model for the Italian area used by the National Institute of Geophysics and Volcanology. The final model is shown in Figure 12. Values close to in the mean-time published values for focal mechanism and depth of the main shock ($4.0 \cdot 10^{17}$ Nm, strike 260° , dip 80° , slip -165° and depth: 18 km; see e.g. Vallée and Di Luccio, 2005) were used. Seismograms were calculated every 37.5 m along the profile and analysed using the same technique as for the earthquake recordings. RSM was also calculated for the radial and vertical components, using a trace located on the bedrock in the SW as the reference (Figure 12). For all ratios, the two horizontal components were averaged. Figure 13 shows that HVSR (Figure 13a) and RSM H/H (Figure 13b) differ inside the flower structure as well as outside, except for the first peak inside the structure (at 3 Hz). The non-existence of the RSM H/H peak outside the structure at 6-8 Hz in HVSR can be partly explained by the amplification of the vertical component, visible in the same frequency range in the RSM V/V sub-figure (Figure 13d).

The results obtained from synthetic data analysis show partial agreement with the observations made along the section SW-NE across the ridge (Figure 13c). In fact, while HVSR of the synthetic data indicates that the amplified zone is at the centre of the ridge (in accordance with HVSR of noise, AI, and damage distribution), a shift of the highest amplification peak towards higher frequencies (3 instead of 2 Hz) occurs (Figure 13e). Note that the highest values of measured HVSR (Figure 13c) coincide with areas where immediately after the main-shocks a re-activation of old landslides occurred, which are located on both side of the ridge (see Figure 3). In these areas, on the basis of the geological survey, clay deposits with thicknesses reaching up to 150 m were assumed to be present (<http://www.ingv.it/emergeo/terremoto-molise.html>). These landslides had not been included in the model adding to the differences between modelled and measured data.

6. Conclusions

Discriminating different contributions to the site effects surveyed in San Giuliano di Puglia, especially in the area around the collapsed school, was the aim of this study. Therefore, the HVSR technique was applied both to earthquake and to microtremor recordings. AI for earthquakes was calculated and 2D hybrid modelling was carried out.

From the analysis of the earthquake data it was observed that significant site amplification occurs at the collapsed school site, mainly on the EW component at a frequency of around 2 Hz. The amplification around 2 Hz is strongly dependent on azimuth and might be caused by a 2D effect. This effect is determined by the geological structure on which SGP, and specifically the school site, is located. Additionally, site amplification was also found on both horizontal components near 6 Hz. The amplification around 6 Hz is essentially caused by a 1D effect.

The computation of AI for different frequency bands enabled the differentiation of the observed amplifications according to their time of occurrence and their importance in the respective frequency bands. Moreover, HVSR obtained from noise recordings at two sites near the school also showed amplifications, although they were smaller than those estimated from earthquake recordings.

The observed dependence on azimuth, which was confirmed by rotating the horizontal components, apparently contradicts previous studies, e.g., Cara *et al.* (2005). However, they only used small-magnitude events. In fact, if AI is calculated only for the smaller events of the data set at hand, it is impossible to identify differences between the results obtained for the two horizontal components separately. Moreover, calculating an average HVSR of the recorded events after removing the two events exceeding magnitude 4 yields results in good agreement with Cara *et al.* (2005). In particular, the strong peak around 2 Hz on the EW-component disappears. Therefore, although the data set at hand is limited, these results seem to indicate that differences in the site response, especially in the occurrence of a 2D effect, might be related to the size of the event.

Synthetic data were calculated in order to validate a possible model of the structure that might be responsible for the ground-motion amplification in SGP. HVSR and RSM spectral ratios both for the horizontal and for the vertical components were computed. In particular, the RSM results for the vertical components showed significant amplifications. This result agrees with other studies performed on weak and strong-motion recordings in SGP (Dolce *et al.*, 2004). This amplification might be responsible for the underestimation of the site response amplitude over certain frequency bands when the HVSR technique is applied. The analysis of the synthetic data showed that with the considered simplified structure, at least some gross features of the amplification pattern can be explained. Therefore, a more detailed model of the geological structure of the area (also considering topography) needs to be considered. Based on newly acquired data, this will be undertaken during studies within the ongoing DPC-INGV Italian projects.

In conclusion, it is important to note that in SGP a superposition of many site effects might occur in the event of an earthquake. The main one is strongly dependent on azimuth and affects the EW direction. This strong amplification is directly correlated with the arrival of the S-phase and also shows a long duration. Since it occurs at frequencies close to that of many buildings in SGP, increased damage is possible.

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List of abbreviations:

AI - Arias Intensity

HVSR - horizontal-to-vertical spectral ratio

RSM - reference site method

SGP - San Giuliano di Puglia

FD – finite difference

Table 1: List of strongest aftershocks of the Molise 2002 earthquakes recorded at SGP (<http://www.ingv.it/~roma/reti/rms/terremoti/italia/molise/repliche.html>).

Event number	Site	Date	Hour	Local magnitude	Epicentral distance [km]	PGA [g]
1	Palasport	6 Nov. 2002	00:10	3.6	17.9	0.0270
2	School	4 Nov. 2002	01:35	4.2	14.9	0.0312
3	School	4 Nov. 2002	04:26	4.1	9.5	0.0064
4	School	4 Nov. 2002	04:49	3.5	9.3	0.0034
6	School	4 Nov. 2002	10:28	3.5	14.0	0.0068
7	School	4 Nov. 2002	12:11	3.2	13.6	0.0046
8	School	4 Nov. 2002	15:31	3.5	4.5	0.0048
9	School	4 Nov. 2002	19:45	3.3	12.7	0.0048

Table 2: Physical parameters for 2D FD model (Figure 12)

Unit	Vp [km/s]	Vs [km/s]	ρ [g/cm ³]	Q
clays	0.600	0.300	1.8	20
clays and sandstones	1.600	0.800	2.2	50
calcarenites 2	3.118	1.800	2.3	100
calcarenites	3.464	2.000	2.5	100
calcarenites and marls 2	3.984	2.300	2.4	100
calcarenites and marls	4.330	2.500	2.6	100

Figures captions

- Figure 1: Map of the area. Intensity is given in MSC scale (modified after Mucciarelli *et al.*, 2003)
- Figure 2: Map of San Giuliano di Puglia with the damage zonation of Mucciarelli *et al.* (2003). Shown are the locations of 13 out of 25 sites used for microtremor measurements (black stars) and the results from HVSR analysis, as well as the location of the two accelerometric stations (black triangles) and the two sites where noise measurements were analysed for azimuthal dependence (white stars).
- Figure 3: Geological map of SGP and surrounding area (1:10000) derived from the geological survey by A. Strollo (2003). Two cross-sections along and perpendicular to the ridge structure are shown as insets.
- Figure 4: Accelerogram of the strongest aftershock (#2 in Table 1) recorded in the backyard of the collapsed school; the NS, UP, and EW (from top to bottom) components are shown with the two windows (3 and 12 s) used for HVSR indicated.
- Figure 5: Average HVSR (white line) of strong motions (± 1 stand. dev., dark grey bars) recorded at the school site and HVSR of the event recorded at the Palasport site (grey line). Shown are results for data windows of 3 (left) and 12 s (right) of EW on UP component (top) and NS on UP component (bottom).
- Figure 6: An example of HVSR analysis on event # 3 recorded at school site (see Table 1) using a moving window of three seconds in width. Shown is the ratio between EW and UP component.
- Figure 7: Average HVSR (white line; ± 1 stand. dev., dark grey bars) for all events, except the two strongest (#2 and #3 in Table 1).
- Figure 8: AI of event #2 (see Table 1). Top: UP component (grey), NS (dark grey) and EW (black); bottom: AI for different frequency bands for only the EW component of event #2.
- Figure 9: Same as Figure 8 (top) for event #7 (Table 1).
- Figure 10: Comparison between average HVSR (white line; ± 1 stand. dev., dark grey bars) of events recorded at the school site, and two HVSR of microtremor recordings near the collapsed school; EW on UP component (top) and NS on UP component (bottom). Grey line is station 1 and the dark grey dashed line is station 2 (Figure 2).
- Figure 11: HVSR for rotating the horizontal components in steps of 20° . Left: HVSR of station 14i (on the ridge); right: HVSR of station 14o (outside the ridge).
- Figure 12: The 2D FD model used for synthetic seismogram calculations. Physical parameters for the different units are shown in Table 2. The seismogram icon indicates the position of the reference station.
- Figure 13: The spectral ratios: HVSR (a), RSM H/H (b), RSM V/V (d) applied to synthetic data, and HVSR (c) applied to noise recordings. The dotted lines indicate the limits of the flower structure on which the village is located. Comparison between real and synthetic HVSR for selected seismogram (e).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13