EUROPEAN COMMISSION
JOINT RESEARCH CENTRE

Institute for the Protection and Security of the Citizen
European Laboratory for Structural Assessment (ELSA)
I-21020 Ispra (VA), Italy

The Molise (Italy) earthquakes of 31 October and 1 November 2002: Report and analysis from a field mission

E. Mola, G. Tsionis, F. Taucer, A. Pinto

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ABSTRACT

This report presents the evidence collected during the field mission by means of an extensive photographic documentation. Moreover, an introduction regarding the historical seismicity of the region and an estimation of the main seismological features of the earthquake is presented. Finally, the behaviour of different categories of buildings, from masonry ones to reinforced concrete, roadways and lifelines, is analysed and discussed and an overview of the management of the emergency is summarized.

1 INTRODUCTION

On 31 October and 1 November 2002, two strong earthquakes took place in the Italian region of Molise. The magnitude and intensity of the two events, the major ones of a seismic sequence lasting about fourteen days, were remarkable: the magnitude was estimated in the range of 5.4-5.8 and the intensity reached VIII – IX MCS (Mercalli Scale) values in the most damaged towns of the area. Among them, all located in the northern part of the province of Campobasso, the one that paid the heaviest tribute to the earthquakes was the small town of San Giuliano di Puglia, located at about 5 km from the epicentres of the two major earthquakes. In fact, the collapse of the primary school of the town, due to the first event of 31 October, caused the death of 26 young children, while no casualties were experienced in all the other towns.

The importance of the event, the extent of the damage suffered by the building stock and the need to investigate the performance of buildings and structures to the earthquake called for a field mission by the ELSA Laboratory Earthquake Engineering staff. The mission, a two-day field trip in the epicentral area, took place on 14 and 15 November 2002, when the effects of the earthquake and its consequences on the environment and the people were still evident.

The aim of the present field report is to carry out a thorough overview of the most significant aspects of the event, referring to the evidence collected during the field trip, to the documentation collected in preparation for the mission and to the information gathered through exchanges with international experts met on the field.

In Chapter 2 the seismological framework of the event is traced, referring to the historical seismicity of the area and to its tectonic configuration; a description of the two events is then carried out. In Chapter 3 a more detailed description of the human environment of the affected area is given; the distribution of the damage is presented in relation to the local amplification effects due to topographic or stratigraphic conditions. In Chapter 4 a detailed description of the damage experienced by the different categories of structures present in the area is carried out; masonry buildings, reinforced concrete buildings, churches and bridges and viaducts are considered; a photographic documentation gives a vivid representation of the effects of the earthquake. Chapter 5 is devoted to the management of the emergency situation caused by the earthquakes, in particular data on the homeless, the casualties, the inspected structures and other relevant statistics related to the Molise events are given. Finally, in Chapter 6 the conclusions drawn from the field mission are presented.

2 SEISMOLOGY AND GEOLOGICAL ASPECTS

2.1 Geology and tectonics

The Mediterranean basin area has a quite complex tectonic configuration. In this relatively small area, in fact, different kinds of seismogenetic zones can be found. Some of them are characterized by compressive tectonic movements leading to subduction (the Alps and the Hellenic Arch), while some others are characterized by elongation and sliding.

The seismic activity in the Italian Peninsula is mainly caused by the converging movements of the African and the Eurasiatic plates, resulting in high seismicity, both from frequency and intensity points of view. The events that take place in Italy are possibly correlated with those of the Eastern coasts of the Adriatic Sea.

The Apennine area shows a mostly diverging tectonic activity, with some areas on the eastern side characterized by compressive stresses. This shows a complex activity that is possibly due to the rotation of the Atlantic micro-plate, added to a marked disomogeneity at the crustal level. For this reason, the seismicity in Italy is quite high, as can be observed in Figure 2.1, where a map of the events with $M \leq 4$ in the Mediterranean area is represented. In Italy such events are present almost everywhere [Pondrelli et al., 2002].

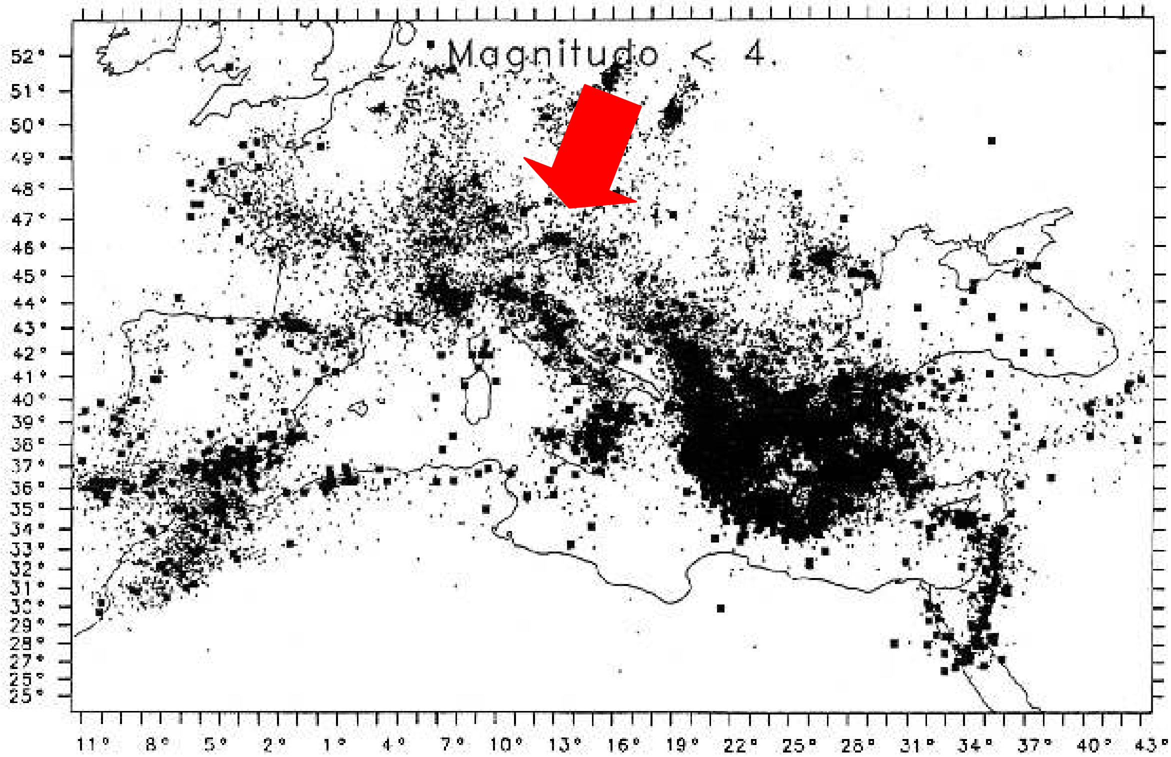

Figure 2.1. Map of events with $M \leq 4$ for the Mediterranean area [Pondrelli et al., 2002]

Figure 2.2 shows a map of events with $M > 4$, where it can be seen that stronger earthquakes are also quite common, (in the map the squares represent events with $5 \leq M \leq 6$, the circles represent events with $4 \leq M < 5$ and the triangles represent those with $M >$

6) [Pondrelli et al., 2002]. In particular, the most critical areas are found in the Apennine mountains, where in the last 30 years most of the major events have taken place; many of them with M > 5, reaching M = 6 for the Irpinia earthquake of 1980. The regions of Calabria, Molise and the lower part of the Tirrenean Sea exhibit a frequent seismic activity, with M > 5 and medium-to-large source depths.

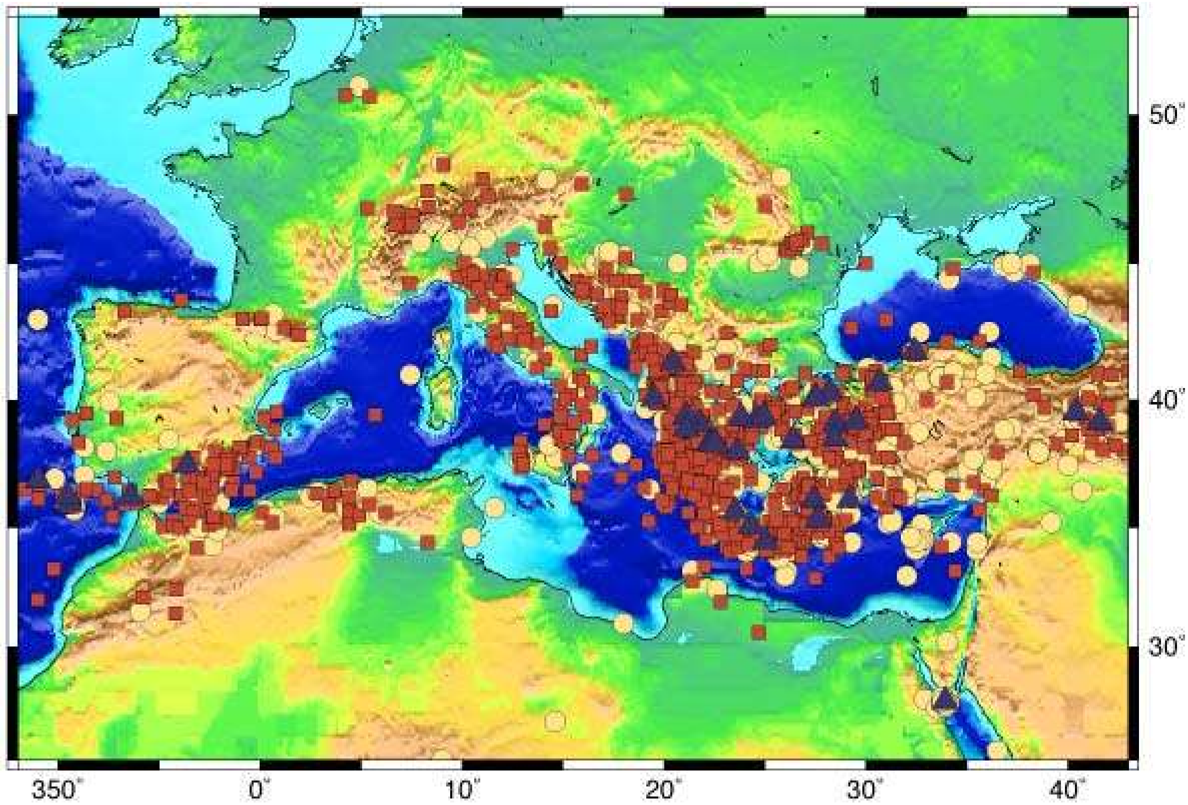

Figure 2.2. Map of events with M > 4 for the Mediterranean area [Pondrelli et al., 2002]

The Italian institutions devoted to the study of geophysics and vulcanology, together with those active on the classification and study of earthquakes and their effects on the protection of the citizens have joined forces to classify the country into different seismicity classes, to edit vulnerability maps and to produce maps reporting the historical seismic activity. In particular, the most important institutions involved in this task are the National Institute of Geophysics and Vulcanology (INGV), the National Group for the Defence against Earthquakes (GNDT) and the National Seismic Service (SSN).

In 1999 a map representing the seismic hazard, with a probability of exceedence of 10% in 50 years, was edited by GNDT and SSN. The area of Campobasso is shown in the map of Figure 2.3. It can be observed that the maximum expected peak ground acceleration (PGA) value for the area is less than 0.15 - 0.20 g.

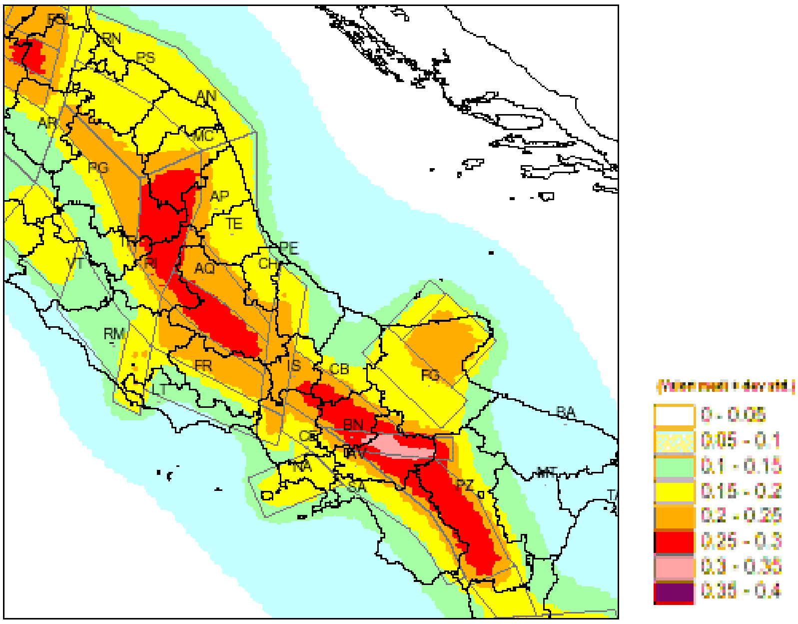

Figure 2.3. 1999 Seismic hazard map for Central and South-Eastern Italy [Albarello et al., 1999]

This fact, though, apparently contrasts the predictions reported in the map of maximum observed intensities for the last millennium, edited in 1996 by ING, GNDT and SSN, which assigned a maximum intensity of IX MS to the area, due to the Gargano sequence of events of 1627. The maps for the whole country and for Molise are shown in Figure 2.4. This clearly points out that the correlation between PGA and damage strongly depends on the type of structures commonly present in the affected areas. Therefore, the correlation between magnitude and intensity must be established on a local basis. In the case of the 2002 earthquakes high level of damage was observed in most of the towns, even if the magnitude of the earthquakes was relatively small.

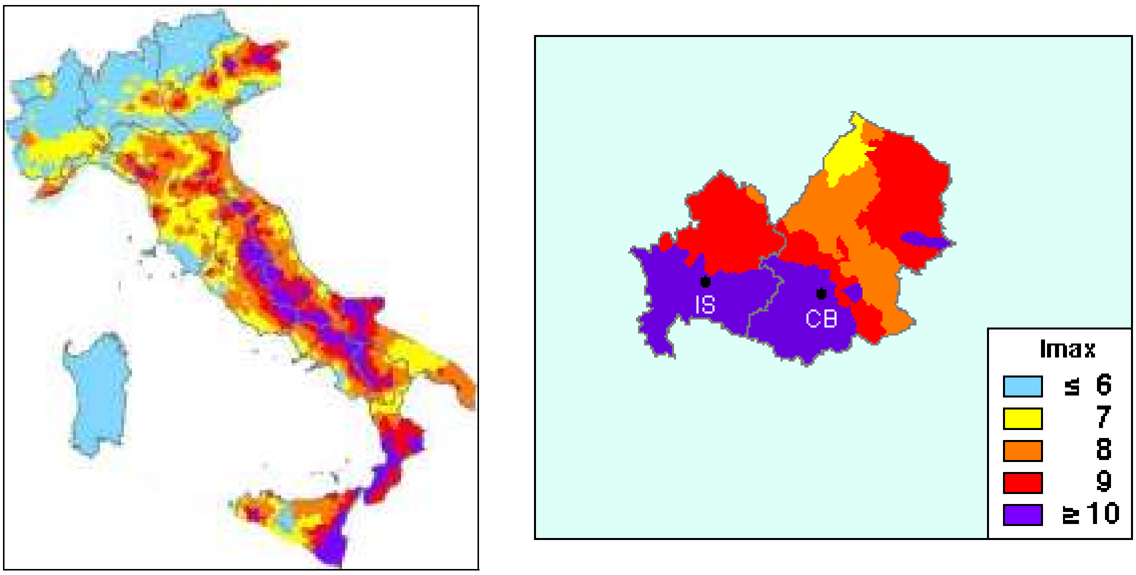

Figure 2.4. Map of maximum observed intensities during the last millennium for Italy and Molise [Molin et al., 1996]

Even though the area hit by the earthquake is near seismically active zones and had experienced some serious damage from earthquakes far back in time, at present it is not classified as hazardous, so that no special provisions for earthquake resistance of buildings in the area were enforced by the Italian Law. In fact, the municipalities involved in the earthquake were not considered subject to seismic hazard in the Italian Seismic Law N.64 of 1974 and its updates. Only the towns of Ururi and Rotello were included in the II category of seismicity in 1981 (there are three categories: I, II, and III, from the least to the most active). This fact clearly points out that the current Italian seismic hazard maps are based on outdated information and that classification methodologies strongly need to be upgraded and perfected. In Figure 2.5a the current seismic zonation of the affected area is shown, whereas in Figure 2.5b a proposal for a new classification conceived by INGV, GNDT and SSN is represented.

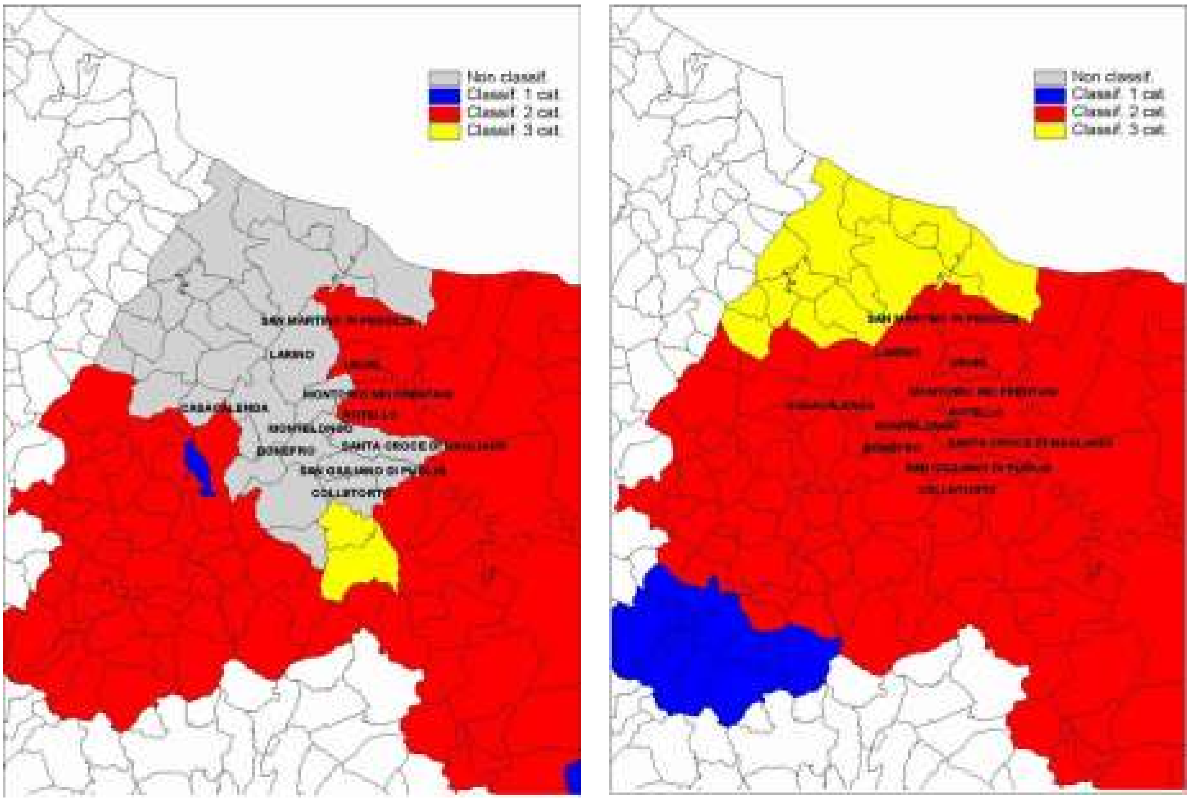

Figure 2.5. Current [INGV, 2002] (a) and proposed [Gavarini et al., 1998] (b) seismic classification of the Molise region

2.2 Historic seismicity

The earthquakes that affected Molise in October and November 2002 took place in an area where no other events of the same energy level have taken place in the last 1000 years. Nevertheless, the area is surrounded by centres of significant seismic activity. The latter correspond to the seismogenetic structures of Gargano (60-100 km at East), San Severo (30-40 km at East), Foggiano (50-80 km at South-East), Beneventano-Irpinia (40-80 km at South) and the Bojano basin (40-50 km at West). All these faults have generated earthquakes of high magnitude (M = 6.5 - 7) and have damaged the eastern part of Molise.

The strongest earthquakes that have been recorded in the area are:

- The Apennine seismic sequence of 1456, which caused great damage in the small town of Casacalenda;
- The Gargano seismic sequence of 1627, which caused VIII and IX MCS level damage in Termoli and Campomarino;
- The Matese earthquake of 1805, causing VI MCS damage in Larino;

Scarce information seems to suggest a medieval earthquake that hit central Molise in 1125, causing VIII MCS damage in Larino.

In Figure 2.6 the historical events are represented as red squares, with the related magnitude, together with seismogenetetic sources and tectonic configuration of the area. The red stars represent the epicentres of the seismic sequence of October and November 2002.

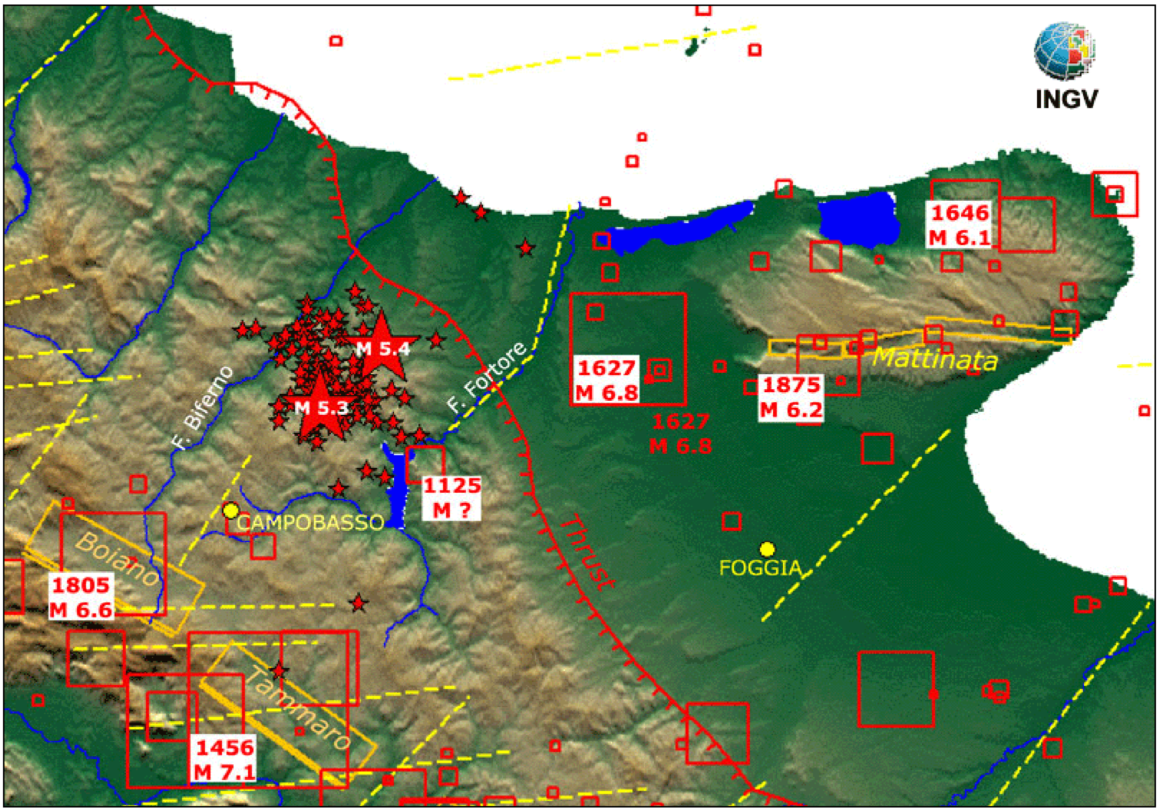

Figure 2.6. Historical earthquakes, 2002 events and tectonic configuration of the area [INGV, 2002]

The maximum local intensity in San Giuliano di Puglia seems to have been reached on the occasion of the 12 May 1456 earthquake, which is the most important seismic event of Central-Southern Italy in the last millennium. The event is characterized by three epicentral areas, one of them being the Bojano basin, at about 40 km from San Giuliano di Puglia. The value of intensity in San Giuliano, MCS VIII-IX, results from the macroseismic field of the earthquake. The data used for the calculation correspond to the localities of Casacalenda (IX), Castellino sul Biferno (IX), Montecorvino (IX), Limosano (IX) and Lucera (VIII). Historical records from the earthquake of 1456 indicate damage of the San Giuliano Martire church. The more recent earthquakes of 21 August 1962 and 23 November 1980 also caused damage to San Giuliano di Puglia, with intensities in the order of VI MCS. Other earthquakes that have caused possible damage to San Giuliano di Puglia are reported in Table 2.1.

Table 2.1. Intensities of historical earthquakes in San Giuliano [Galli & Molin, 2002]

date	epicentral area	M_s	distance (km)	MCS
5/12/1456	Bojano		48	8.5
30/7/1627	Capitanata		32	7.5
1/1657	Gargano		34	5.0
5/6/1688	Beneventano		56	6.5
20/3/1731	Capitanata		80	7.0
20/2/1743	Canale d'Otranto			4.5
26/7/1805	Bojano		46	6.5
22/11/1821	Medio Adriatico			5.0
14/8/1851	Monte Vulture		101	5.5
6/12/1875	Gargano		59	5.0
10/9/1881	Chietino		83	4.0
26/12/1885	Monti del Sannio		29	4.0
8/12/1889	Gargano			5.0
25/3/1894	Capitanata		36	3.0
9/8/1895	Medio Adriatico			5.0
7/6/1910	Irpinia	5.9	95	5.0
4/10/1910	Monti del Sannio	5.2	25	5.5
13/1/1915	Fucino	7	124	5.0
26/9/1937	Irpinia	6.7	78	5.0
26/9/1933	Maiella	5.5	77	4.0
21/8/1962	Beneventano-Irpinia	6.2	62	6.0
23/11/1980	Irpinia	6.9	97	6.0
7/5/1984	Lazio-Molise	5.5	76	4.5

2.3 Description of the earthquakes of 31 October and 1 November 2002

The two earthquakes of 31 October and 1 November are the major events of a sequence that started on 31 October and lasted more than two weeks. The events related to this sequence are presented in Figure 2.7. The sequence started at 01:25 am with a series of events ranging in magnitude between 2.6 and 3.5.

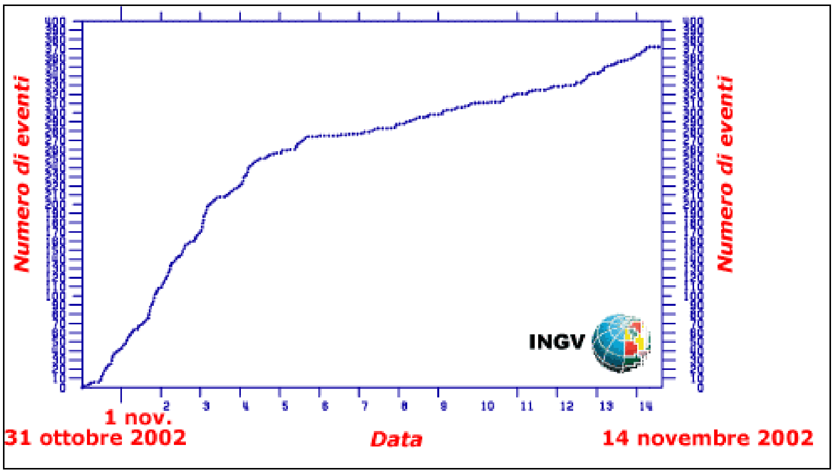

Figure 2.7. Number of events vs. date plot for the seismic sequence from 31/10/2002 to 14/11/2002 [INGV, 2002]

The earthquake of 31 October 2002 struck at 11:32 am local time. It was a superficial earthquake (focal depth = 10 km) of magnitude M_L = 5.4 (SSN) with the epicentre approximately 5 km North-West of San Giuliano di Puglia. Estimates of the magnitude and depth vary according to different sources (Table 2.2). The different definitions of earthquake magnitude are explained in Annex A. The epicentre of the earthquake was located by INGV by means of the so-called 'master event' technique, particularly useful when the net of seismograph is quite large and can possibly affect the precision of the prediction.

Table 2.2. Magnitude, depth and location of the 31/10/2002 seismic event

Source	M_W	M_b	M_S	M_L	Depth (km)	Longitude	Latitude
USGS	5.9/5.7	5.3	5.6	5.9	10	41.8 N	14.9 E
SED				5.9		41.7 N	14.9 E
SSN				5.4		41.8 N	14.9 E

In Figure 2.8 is shown the location of the epicentre with respect to the small town of San Giuliano di Puglia, the most damaged by the earthquake. The other towns seriously damaged by the event were Bonefro, also in a 5 km radius from the epicentre, and Ripabottoni, Castellino sul Biferno, Casacalenda, Colletorto, and Santa Croce di Magliano, all in a 10-12 km radius from the epicentre.

Preliminary moment-tensor solutions carried out by the United States Geological Survey (USGS) imply that the shock occurred as the result of movement on a strike-slip fault. According to initial studies, the fault would have been either a North-South, left-lateral fault or an East-West, right-lateral fault. Some geologists have hypothesized that a major component of the relative motion between the African plate and Eurasian plate is accommodated on a North-South, left-lateral boundary that passes near the epicentre of the earthquake [USGS, 2002]. The boundary is thought to accommodate a slip rate of 5 - 10 mm/year. However, many earthquakes in Italy derive from crustal movements that are not directly related to this mechanism, so that further studies need to be carried out to obtain a more precise description of the origin of the event.

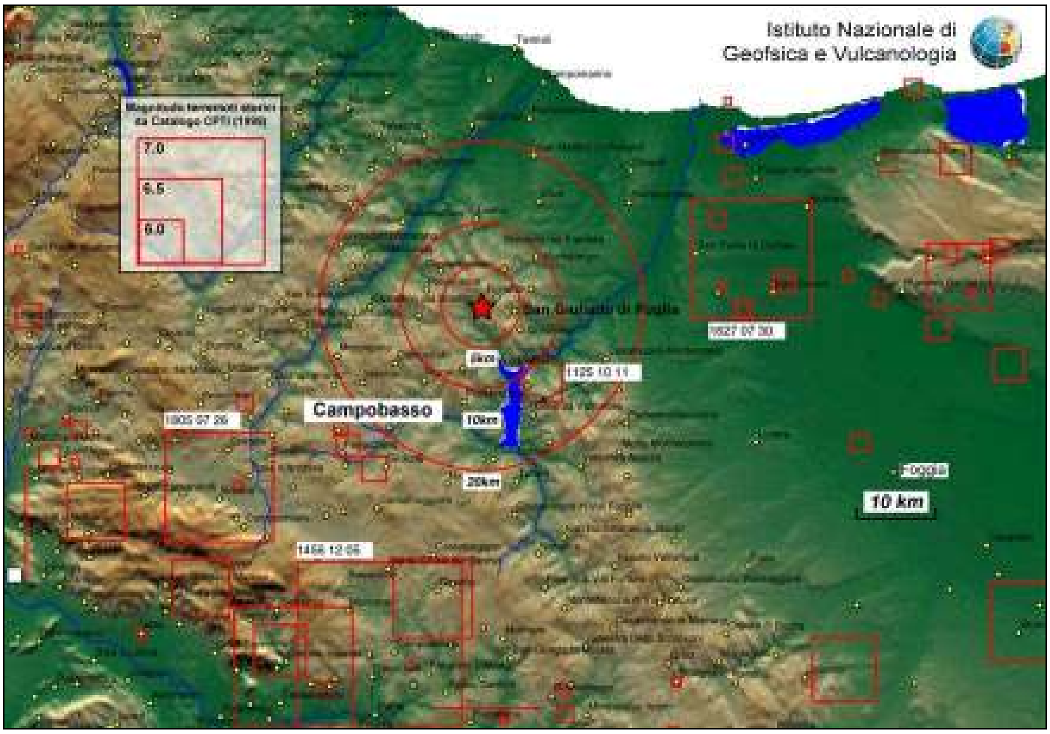

Figure 2.8. Epicentre of the earthquake of 31/10/2002 [INGV, 2002]

In Figure 2.9 the 'beach ball' representation of the source mechanism for the earthquake is given, together with the slip, dip and strike data. This solution was performed by INGV-Harvard European-Mediterranean Regional Centroid-Moment Tensors Project.

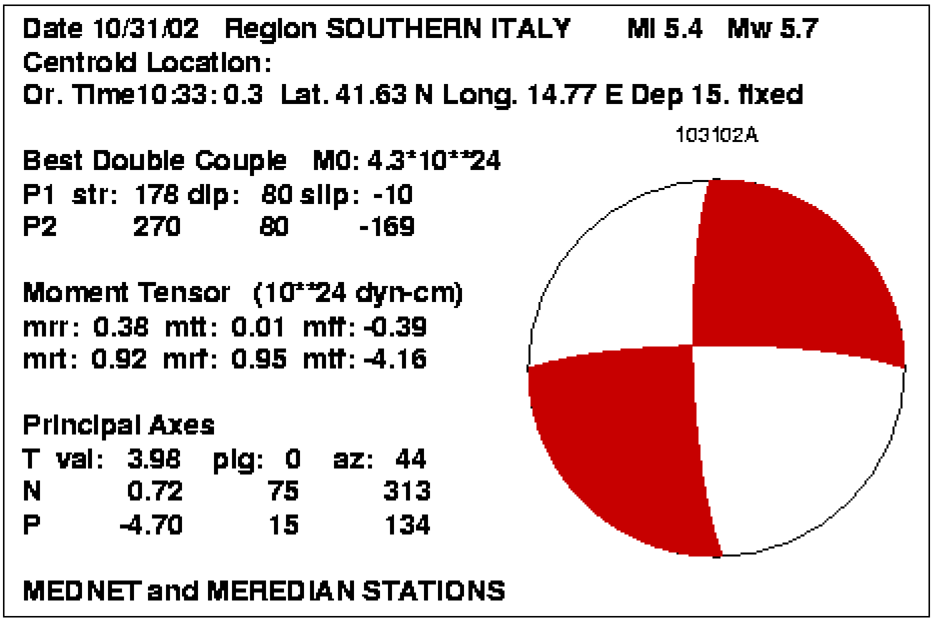

Figure 2.9 Moment tensor solution for the earthquake of 31/10/2002 [INGV, 2002]

The second major event took place on 1 November 2002 at 4:08 pm, with magnitude of M_L = 5.3 according to INGV and M_w = 5.8 according to USGS. It must be noted that a difference in the magnitude values given by INGV and USGS exists both in the case of the first and of the second event (Table 2.3) (See ANNEX A for the definitions of M_w, M_b, M_S and M_L. The epicentre of the second earthquake was located with the same technique and was located at about 12 km South-West of the epicentre of the first event.

Table 2.3. Magnitude, depth and location of the 1/11/2002 seismic event

Source	M_W	M_b	M_S	M_L	Depth (km)	Longitude	Latitude
USGS	5.8/5.7	5.5	5.6		10	41.8 N	14.9 E
SED				5.9		41.5 N	15.0 E
SSN				5.3		41.7 N	14.9 E

In Figure 2.10 the location of the two epicentres is given, together with those of the historical earthquakes in the area. The towns of Castellino sul Biferno and Provvidenti were in the 5 km radius from the second epicentre, whereas Ripabottoni, Colletorto, Bonefro and San Giuliano di Puglia were in the 10 km radius.

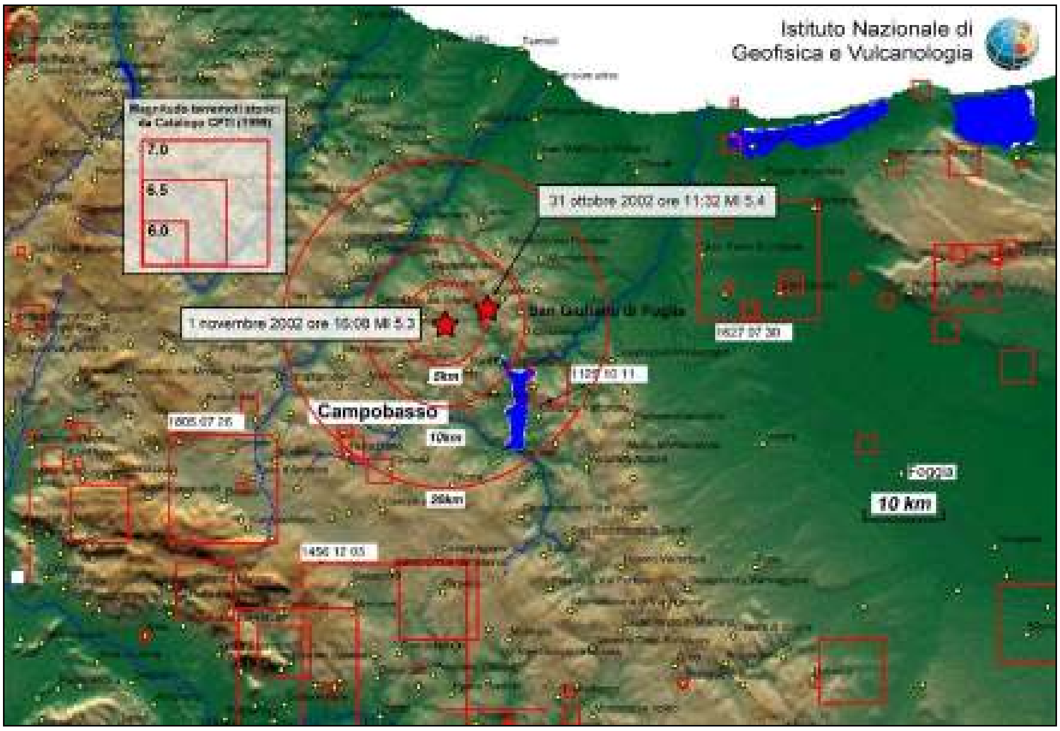

Figure 2.10 Epicentre of the earthquake of 1/11/2002 [INGV, 2002]

In Figure 2.11 the moment tensor solution for the second earthquake reported by INGV-Harvard European-Mediterranean Regional Centroid-Moment Tensors Project is presented. It can be seen that also in this case the prevailing movement is of the strike-slip type, with a secondary normal (thrust) component.

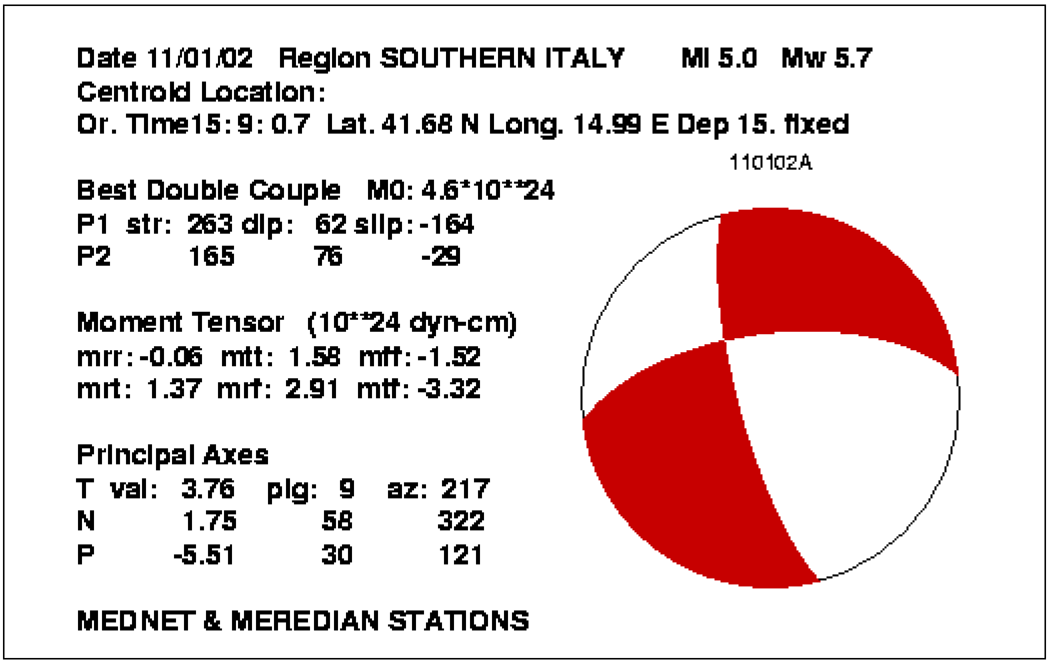

Figure 2.11 Moment tensor solution for the earthquake of 1/11/2002 [INGV, 2002]

The other events recorded in the area were all characterized by smaller magnitudes, with a remarkable occurrence of events with 3 ≤ M ≤ 4 and a few events with M > 4, as shown in Figure 2.12. The total number of recorded events between 31 October and 14 November was 402. It is important to note that the effects of the two major earthquakes and of the most significant follow-ups may have increased the cumulative damage to the building stock and consequently made it more difficult to classify the macroseismic intensity of the single events.

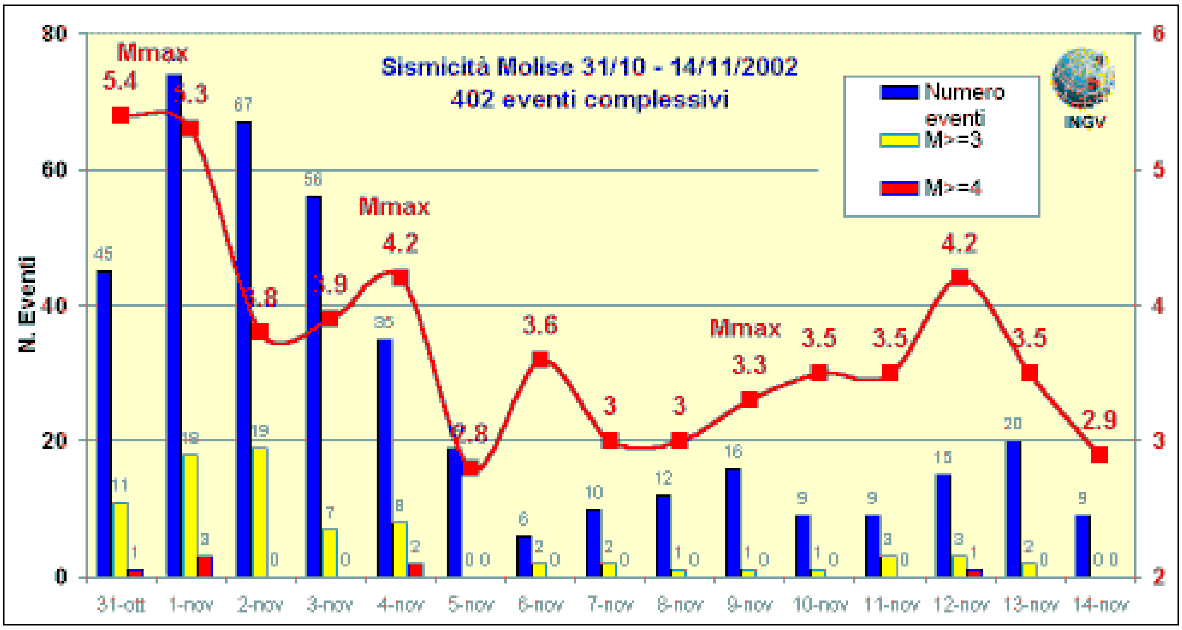

Figure 2.12 Histogram of the number of events per magnitude group for the period 31/10/2002 to 14/11/2002 [INGV, 2002]

2.4 Strong motion records

Since the affected area was classified as a low seismicity zone, there were only a few seismometers within a short distance from the epicentre. However, a large number of stations in Molise and the neighbouring regions measured the seismic motion. They belong to the fixed National Accelerometric Network of Italy and are located in Lesina (LSN), Sannicandro Gargano (SNN), San Severo (SSV), Castiglione Messer Marino (CMM), San Marco dei Cavoti (SCV), Chieti (CHIE), Avezzano (AVZ), Ortucchio (RTU), Norcia (NOR) and Assergi Gran Sasso (ASSE). The first three stations are analogical, while the remaining ones are all digital. The location of the fixed stations is presented in Figure 2.13. The accelerometric instruments in Italy are usually located in the small structures that house the transformers of electric power, away from large structures. Therefore, the recordings correspond to free-field conditions. Nevertheless, no information on the soil conditions at the site of each instrument was available.

Figure 2.13. Fixed accelerometric network in the region [SSN, 2002]

After the second earthquake, a number of mobile instruments was installed in the locations of Castellino sul Biferno (CAST), Casacalenda (CASA), Santa Croce di Magliano (SCRO), Larino (LARI), San Martino in Pensilis (SMAP), Sant Elia a Pianisi (SELI) and Casalnuovo a Monterotaro (CAMO). All the mobile instruments were digital. The location of the mobile accelerometers is shown in Figure 2.14.

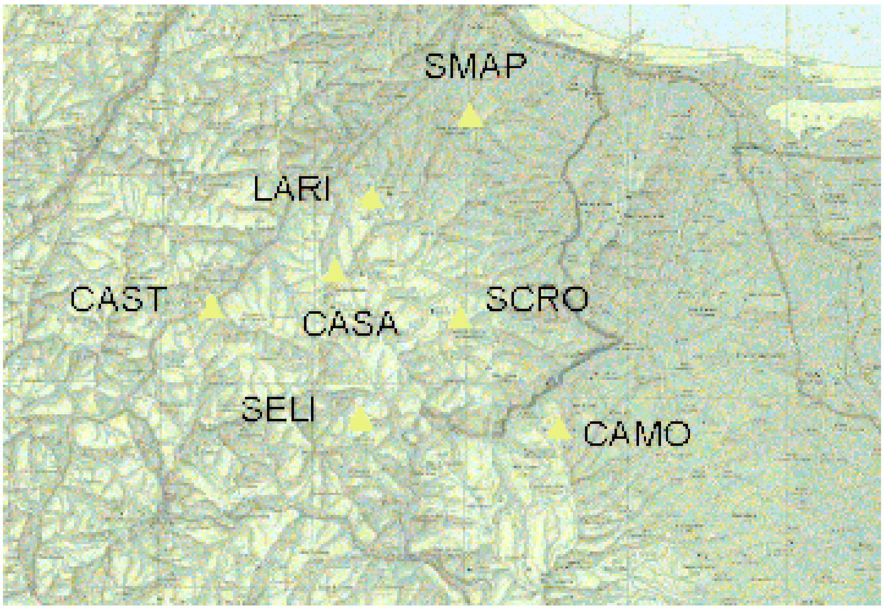

Figure 2.14. Mobile accelerometric network [SSN, 2002]

The highest value of acceleration, PGA = 0.067 g, for the earthquake of 31 October 2002 was measured at the station of Lesina, located at 36 km North-East of the epicentre. Similar values were recorded at the San Marco dei Cavoti station, which is located at almost the same distance, East of the epicentre. The ground motion recordings at the stations of Castiglione Messer Marino and San Marco dei Cavoti are shown in Figure 2.15. The duration of the significant part of the strong ground motion was less than 20 sec. The East-West component was stronger than the North-South one, indicating that the former was the direction of the seismogenetic source. It should be noted that the amplitude of the vertical component was comparable to that of the horizontal components. The limited available information does not permit a comparison in terms of frequency content.

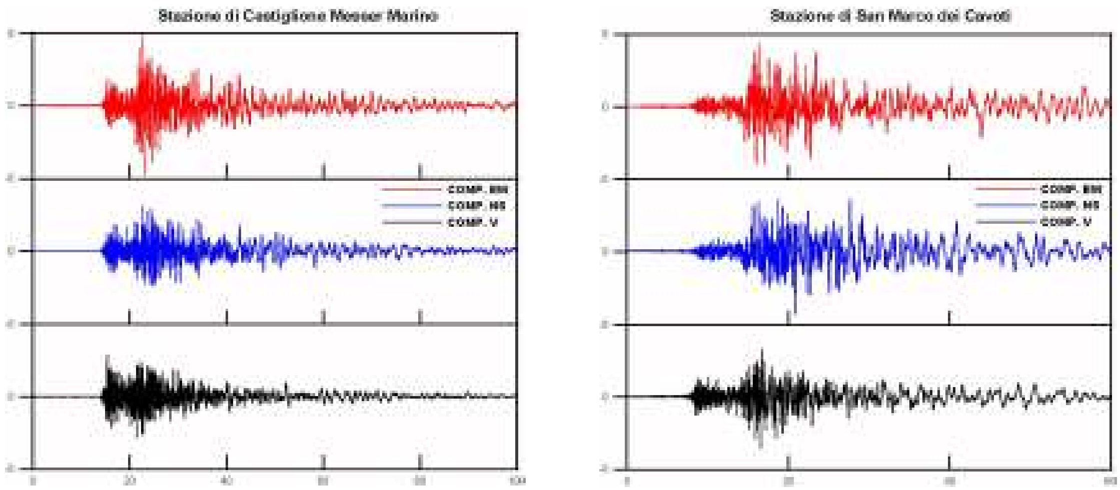

Figure 2.15. Accelerograms of the earthquake of 31/10/2002, Castiglione Messer Marino and San Marco dei Cavoti stations [SSN, 2002]

The highest value of acceleration, PGA = 0.008 g, for the earthquake of 1 November 2002 was measured at the station of Chieti, located at 83 km North-West of the epicentre. Similar values were recorded at the Castiglione Messer Marino station, which is located at 55 km South-West of the epicentre. The ground motion recordings are shown in Figure 2.16. The duration of the significant part of the strong ground motion was about 20 sec. In both stations, the amplitudes of the horizontal and vertical components are similar. At the Chieti station the two horizontal components are of the same order, while at the Castiglione Messer Marino station, the East-West component present higher values. The different shape of the accelerograms recorded in the two sites implies some effect of the conditions of the soil between the stations and the epicentre.

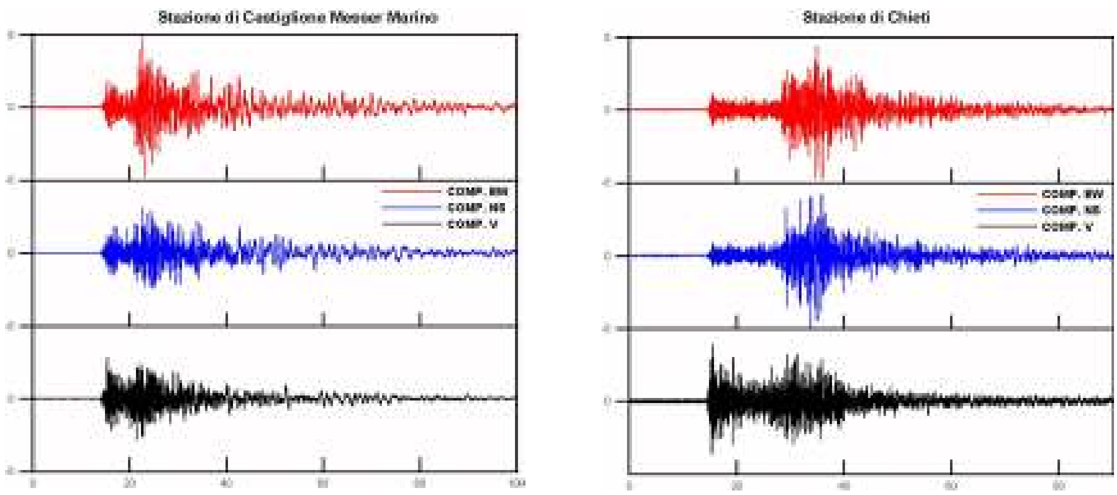

Figure 2.16. Accelerograms of the earthquake of 1/11/2002, Castiglione Messer Marino and Chieti stations [SSN, 2002]

The small values of ground acceleration that where recorded for both events, can be attributed to the medium magnitude and small focal depth of the earthquakes. Indeed, for such cases, the seismic motion is attenuated within a small distance from the epicentre. It is interesting to notice that, for the second earthquake event, the values recorded in the Chieti station were similar to those measured in the Castiglione Messer Marino station, although the first station was located at twice the distance of the second station from the epicentre. This could be due to the different soil properties between the epicentre and the two stations.

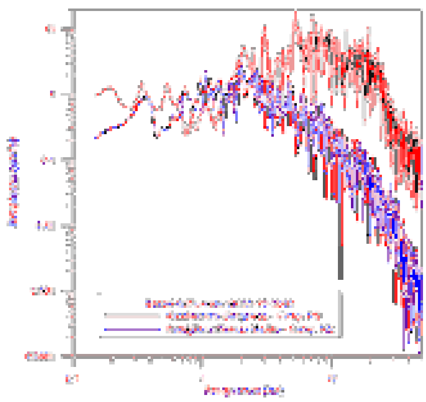

Figure 2.17. Velocity spectra of the seismic event of 31/10/2002 [SSN, 2002]

Figure 2.17 shows the velocity response spectra for 5% critical damping obtained from the acceleration records from Sannicandro Garganico (analogical instrument) and Castiglione Messer Marino (digital instrument). A difference in the frequency and amplitude for the maximum amplification is observed in the recordings at the two sites. The period corresponding to the maximum amplification is about 0.2 sec and 0.5 sec for the Sannicandro Garganico and Castiglione Messer Marino stations, respectively. These values are close to the natural periods of stiff structures, such as masonry buildings with one or two storeys. In fact, the buildings that belong to this structural type were the most heavily damaged, while multi-storey reinforced-concrete frame structures, which have higher natural periods, were not significantly affected by the earthquakes.

Table 2.4. Measured peak ground accelerations [SSN, 2002]

station (see Figures 2.13 and 2.14) *mobile stations	31/10/02 M = 5.4		1/11/02 M = 5.3		4/11/02 M = 4.2	
	distance (km)	PGA (g)	distance (km)	PGA (g)	distance (km)	PGA (g)
LSN - Lesina	36	0.067				
SNN - Sannicandro G.	53	0.043				
SSV – S. Severo	37	0.062				
CMM - Castiglione Messer Marino	43	0.008	55	0.007	50	0.002
SCV – S. Marco dei Cavoti	50	0.007	68	0.005	86	0.001
CHIE - Chieti	92	0.007	83	0.008		
AVZ - Avezzano	128	0.007	136	0.004		
RTU - Ortucchio	110	0.004	124	0.003		
NOR - Norcia	191	0.002	186	0.002		
ASSE - Assergi Gran Sasso	138	0.001	140	0.001		
CAST - Castellino del Biferno*					77	0.015
CASA – Casacalenda*					38	0.015
SCRO – S. Croce di Magliano*					34	0.007
LARI – Larino*					74	0.007
SMAP – S. Martino in Pensilis*					23	0.006
SELI - S. Elia a Pianisi*					42	0.004
CAMO -Casalnuovo a Monterotaro*					40	0.003

A summary of the peak ground accelerations measured at different locations of the fixed and mobile accelerometric network is given in Table 2.4. The values of PGA recorded at different stations suggest directivity of the seismic source for both main events. For the earthquake of 31 October 2002 the values of PGA are higher at the East of the epicentre, compared to the values measured at the West of the epicentre. On the contrary, for the event of 1 November 2002, the values are higher at the West of the epicentre. This observation suggests a seismogenetic structure with East-West orientation.

2.5 Attenuation of the seismic motion

As stated in before, there are no records of the main earthquakes in the zone of the most affected towns. However, it is possible to estimate average peak ground accelerations from empirical relations. For Europe, a general expression has been proposed that gives the property of interest (e.g. PGA) as a function of the epicentral distance for a given magnitude [Ambraseys et al., 1996]

$$\log(Y) = C_1 + C_2\,M + C_4\,\log(R^2 + h^2)^{0.5} + C_A\,S_A + C_S\,S_S + \sigma\,P \qquad (1)$$

Based on a statistic study of Italian earthquakes a modified expression has been proposed [Sabetta & Pugliese, 1996]. The expression takes the form

$$\log_{10}(Y) = a + b\,M + c\,\log_{10}(R^2 + h^2)^{0.5} + e_1\,S_1 + e_2\,S_2 + \sigma\,P \qquad (2)$$

where Y is the acceleration or the velocity, M is the magnitude, R is the epicentral distance (in km), σ is the standard deviation of the logarithm of Y and h is a depth (in km) that takes into consideration the parameters that limit the motion near the source. $S_1 = 1$ for sites where the soil consists of shallow alluvium deposits and $S_1 = 0$ elsewhere, $S_2 = 1$ for deep alluvium deposits and $S_2 = 0$ elsewhere. The values of the regression coefficients are presented in Table 2.5. The expression should be used for distances less than 100 km and for magnitudes between 4.6 and 6.8.

Table 2.5. Coefficients of Eq.(2) for horizontal and vertical peak ground acceleration [Sabetta & Pugliese, 1996]

	a	b	c	e_1	e_2	h	σ
horizontal PGA	-1.845	0.363	-1	0.195	0.	5.0	0.190
vertical PGA	-2.637	0.443	-1	0.209	0.	4.1	0.195

A similar expression, based on recorded data from Greece, has been proposed [Theodoulidis & Papazachos, 1992]. The attenuation relation takes the form

$$\ln(Y) = C_1 + C_2\,M + C_3\,\ln(R + R_o) + C_4\,S + \sigma_{\ln Y}\,P \qquad (3)$$

where Y is the acceleration, velocity or displacement, M is the earthquake magnitude (M_s), R is the epicentral distance (in km), $\sigma_{\ln Y}$ is the residuals root mean square (RMS), R_o is a depth (in km) used to take into consideration the conditions near the seismic source and P is zero for 50 percentile and one for 84 percentile levels of non-exceedence. S is a parameter depending on the soil, which assumes the values S = 1 for rock soils and S = 0 for alluvium deposits. The values of the coefficients C_1, C_2, C_3 and C_4 are reported in Table 2.6.

Table 2.6. Coefficients of Eq.(3) for horizontal and vertical peak ground acceleration and horizontal peak ground displacement [Theodoulidis & Papazachos, 1992]

	C_1	C_2	C_3	C_4	R_o	$\sigma_{\ln Y}$
horizontal PGA	3.88	1.12	-1.65	0.41	15	0.71
horizontal PGV	-0.79	1.41	-1.62	-0.22	10	0.80
horizontal PGD	-5.92	2.08	-1.85	-0.97	5	1.23

The empirical Eqs.(2) and (3) have been used for the estimation of the PGA and peak ground displacement (PGD) for the earthquakes of 31 October, 1 and 4 November, 2002. The soil was considered as alluvium deposit ($S_1 = 1$, $S_2 = 0$, $S = 0$). The results are plotted in Figure 2.18 for the earthquake of 31 October 2002. The full circles correspond to the recorded values (see Table 2.4) and the squares correspond to the values calculated for the four sites of interest, namely: San Giuliano di Puglia (SGP), Santa Croce di Magliano (SCM), Ripabottoni (RIP) and Castellino sul Biferno (CDB).

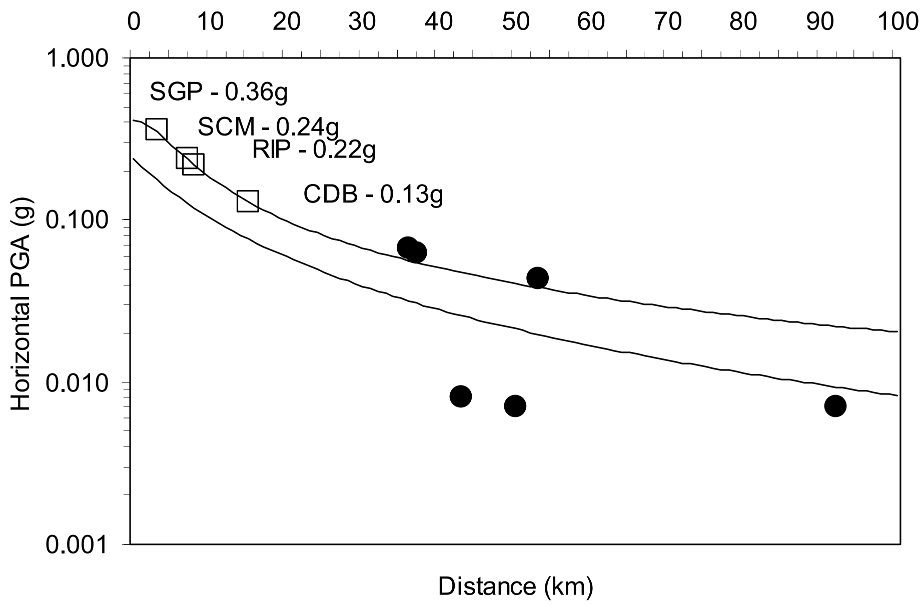

Figure 2.18. Attenuation relations for the M = 5.4 earthquake of 31/10/2002

Considering the earthquake of 31 October, the values calculated according to Eq.(2) are in good agreement with the values recorded East of the epicentre, where heavier damage was reported. For the 1 and 4 November events, both empirical expressions overestimate the site response. Nevertheless, a preliminary estimation of the PGA, according to Eq.(2), and PGD, according to Eq.(3), in the four sites is attempted for the earthquakes of 31 October and 1 November 2002. The resulting values are summarised in Table 2.7.

Table 2.7. Estimated values of PGA and PGD

site	31/10/02		1/11/02	
	PGA (g) Eq.(5)	PGD (cm) Eq.(6)	PGA (g) Eq.(5)	PGD (cm) Eq.(6)
San Giuliano di Puglia	0.36	4.8	0.17	1.1
Ripabottoni	0.22	1.8	0.34	4.1
Santa Croce di Magliano	0.24	2.0	0.14	0.8
Castellino sul Biferno	0.13	0.8	0.27	2.3

Figure 2.19 collects the uniform hazard response spectra referred to some major towns at the central Adriatic coasts on rocky sites, for a period of return T = 475 years, calculated using 14 sampled periods in the range of 0.1 - 2.0 s. The constant acceleration plateau for Pescara, near the epicentral region, corresponds to a PGA in the order of 0.4 g for a period range from T_1 = 0.1 sec to T_2 = 0.3 sec. The value of PGA is in good agreement with the values computed according to the attenuation relations of Eq.(2). The period range is typical of low-rise masonry structures, mostly damaged during the earthquake.

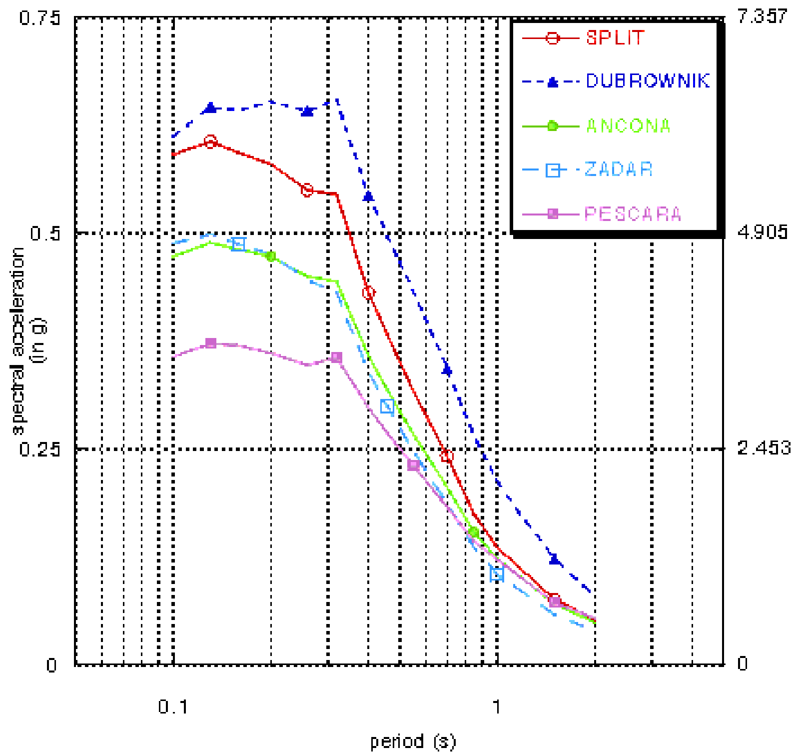

Figure 4.15. Uniform hazard spectra for major towns along the Adriatic coast [Slejko et al., 1999]

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3 DESCRIPTION OF THE AFFECTED AREA AND DAMAGE DISTRIBUTION

3.1 General

3.1.1 Population

The affected area is part of the Molise region and is mostly rural. The Molise region has a population of 327210 (last population census of 1997), about the same as those living in a medium-size city. The Region is the second smallest in Italy with a surface of 4438 km^2 and a density of population of 74 inhabitants per km^2 [SIAR, 2002]. The population of Molise is mostly composed of elderly people with 20.6% of the inhabitants older than 65 years, which to a certain extent made it more difficult to cope with the problems posed by the post-emergency interventions, given the reluctance of older people to leave their traditional dwellings and the worse psychological damage caused to them by such sudden moving.

Figure 3.1 Municipalities in a 50 km radius from the epicentre [SSN, 2002]

Molise has only two provinces, Campobasso and Isernia, and a total of 136 municipalities. All the towns struck by the earthquakes are in the province of Campobasso. In Figure 3.1 all the municipalities in a radius of 50 km from the epicentre are represented; in Figure 3.2 a close view of the location of the most heavily damaged towns is given.

Figure 3.2. Most damaged Municipalities around the epicentre [SSN, 2002]

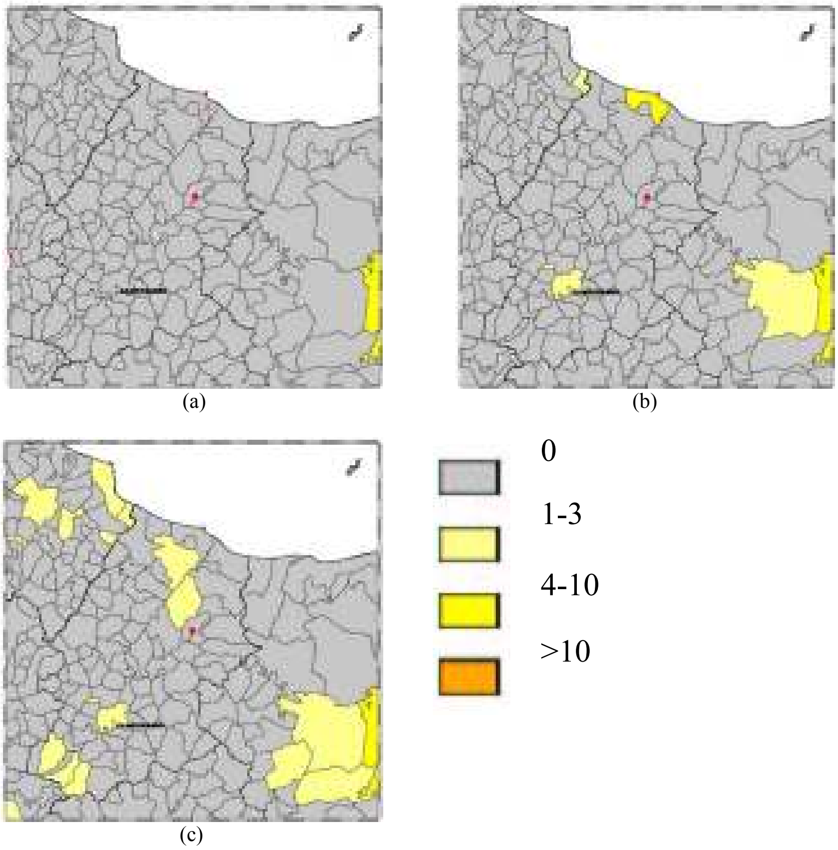


Figure 3.3. Number of industries at high (a), medium (b) and low (c) earthquake risk in the affected and neighbouring areas [SSN, 2002]

3.1.2 Economy

The economy in Molise is mostly based on agriculture, with a low presence of industries. The most recent data obtained by the Italian Institute for Demographic Statistics (ISTA) yielded 34100 farms and 17132 industries counting 44146 employees: the ratio of industries to farms is about 0.5. In Figure 3.3 a map giving the distribution of industries at high, medium and low earthquake risk in the area is presented.

The agricultural tradition of Molise is very strong and still healthy at present, with many products of the Region exported and appreciated worldwide; the main products are olive oil, wine, corn and hand-made pasta. Breeding is also a traditionally widespread activity in Molise, with products such as milk and traditional hand-made cheeses; fishing and production of tinned fish and meat represent growing industries in the coastal areas.

3.1.3 Topography

The topography of the region is quite peculiar and varied. Mountains cover a remarkable portion of the territory: more than half of the region, 55.3%, is mountainous, with the Matese mountains at the heart of the affected area, while 44.7 % of the surface of the region is flat. The valleys of the region have been excavated by numerous small rivers; among them the biggest and most important is the river Biferno, which runs right through the area affected by the earthquakes.

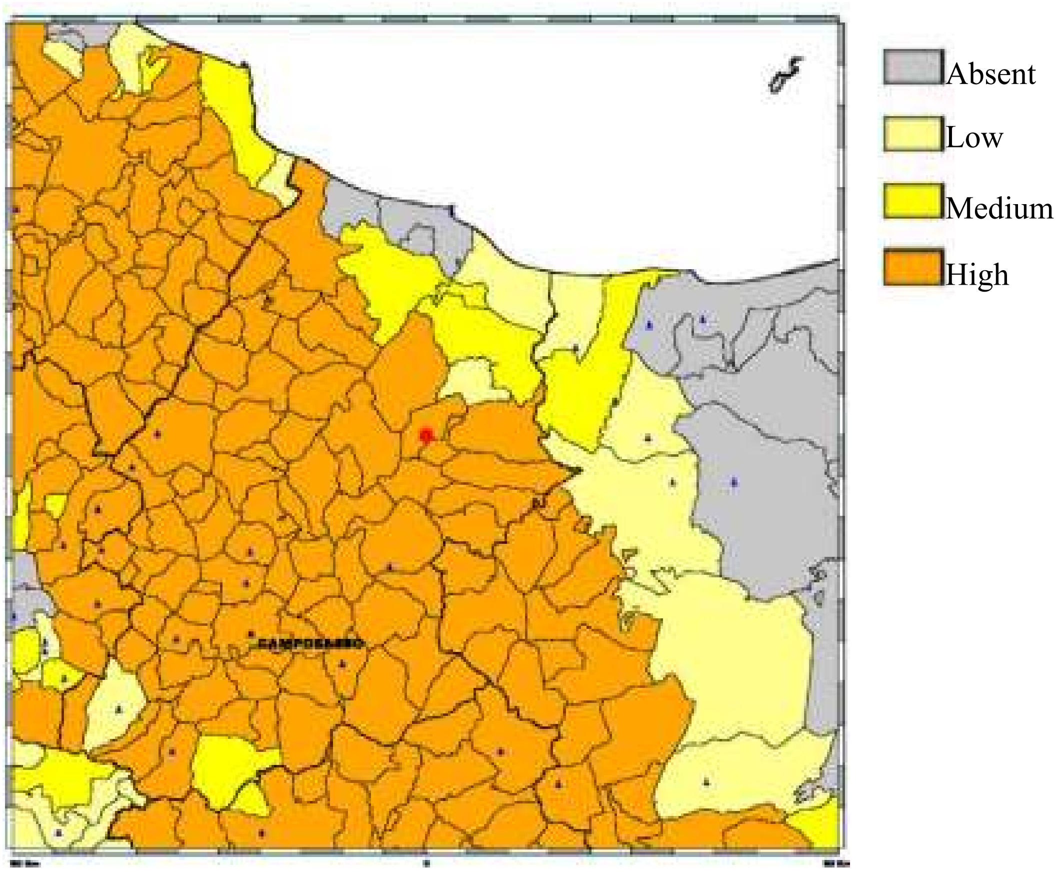


Figure 3.4 Landslide and slope instability hazard zones [SSN, 2002]

The mountainous nature of the territory, together with its geological stratification and the presence of centres of earthquake activity and superficial ruptures (some known faults are at a distance of about 40-50 km from the epicentres of the recent earthquakes), makes the area prone to landslides and instability of slopes. In Figure 3.4 a map of the area divided into different levels of landslide risk is presented.

The mountains have been of great importance for the inhabitants throughout the centuries, during which they have turned to their mountains for shelter and defence during wars and invasions. For this reason, most of the historical centres (present in every town, however small they may be) were built in elevated areas, cliffs and steep slopes from which a complete view of the valleys below allowed a ready defence from invaders, while the difficult-to-reach location discouraged the enemies.

The historical sites, some of them of Roman origin, some other funded in Medieval times, evolved into the small towns of today, which of course required in most cases extensions of the inhabited areas. This posed quite difficult problems in those towns that were originally built on the top of sections of steep topography, because no further houses could be built in the vicinity without being exposed to the danger of landslides and slope instability. Moreover, in those towns where less steep slopes and a more favourable topographic situation allowed easier extensions of the inhabited areas, human interventions such as fillings and land movements were necessary.

Figure 3.5. Bird’s-eye view of Castellino sul Biferno

In some cases, the human modification to the natural topography of the area did not have a large impact on the global configuration of the towns, evident in towns such as Castellino sul Biferno or San Giuliano di Puglia, which are all characterized by a still very irregular topography in terms of elevation. Figures 3.5 and 3.6 show a view of Castellino sul Biferno, a typical example of a town located on top of a steep cliff, and a closer view of its older buildings, respectively.

Figure 3.6. The older buildings in Castellino sul Biferno

Figures 3.7 and 3.8 show two views of San Giuliano, the town where the irregular topography, the difference between the older and newer zones and the human intervention along the main street are evident.

Figure 3.7. Bird's-eye view of San Giuliano di Puglia

Figure 3.8. The main street in San Giuliano di Puglia

In fact, two different factors contributed to draw the local distribution of damage in towns like San Giuliano: the first one is the topographic situation, characterized by cliffs in which the seismic waves were focalised due to the phenomenon of reflection. The second one is a stratigraphic factor, meaning that the human land fills, non cohesive sand, and the characteristics of the soil in the lower areas, mainly younger cohesive clay, are characterized by amplification factors much higher than those pertaining to the rock cliffs where the most ancient parts of the towns were built. In general, in San Giuliano the most heavily damaged areas were the lower ones and where the statigraphic conditions played a predominant role [Galli & Molin, 2002].

3.2 Local ground conditions in San Giuliano di Puglia

The local ground conditions of San Giuliano di Puglia are described in the geologic map of Figure 3.9. Soil type 1 consists of limestone and calcareous marl, while soil type 2 consists of clayey marl and clay. Soil type 3, talus, originates from the first two soil types. Finally, anthropic refillings are present along the main street of San Giuliano di Puglia.

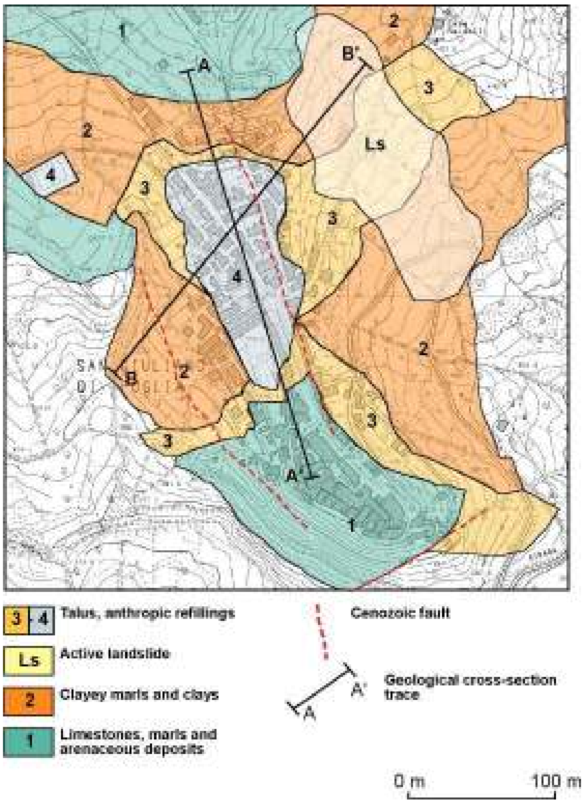


Figure 3.9. Geological characteristics of the San Giuliano area [SSN, 2002]

Two sections, A-A' and B-B' describe the geology of San Giuliano di Puglia, as shown in Figure 3.10. The presence of two faults with NNW-SSE orientation along section A-A' is evident from the geological map.

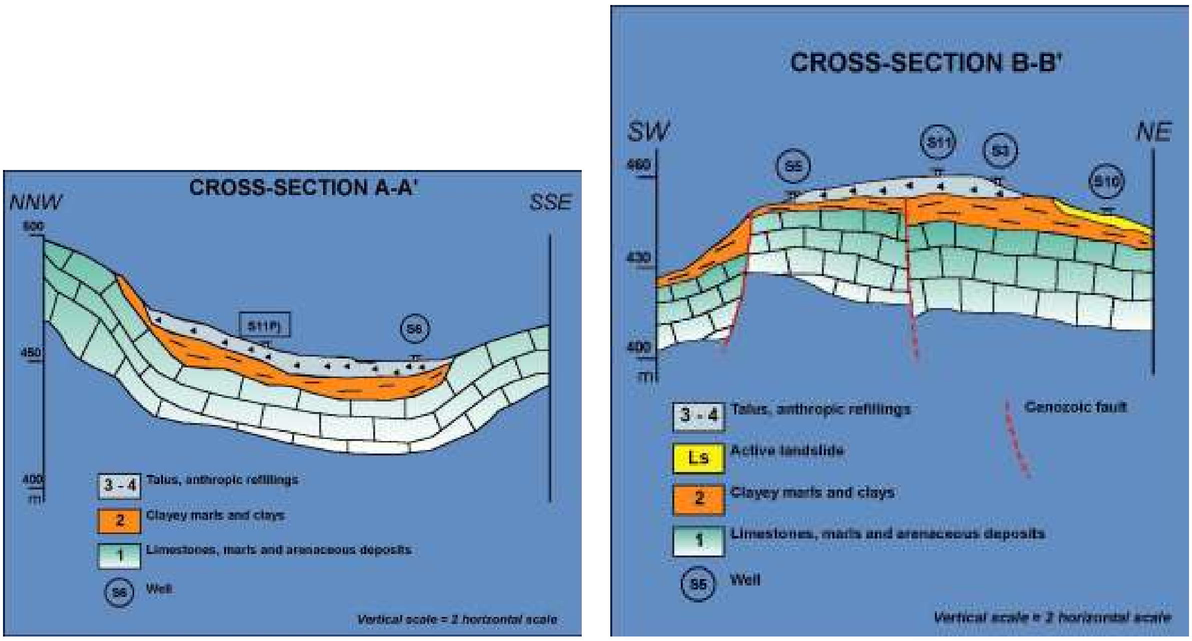


Figure 3.10. Geological characteristics of the San Giuliano di Puglia area: cross-sections A-A' and B-B' [SSN, 2002]

Based on the reported soil properties, the fundamental period of vibration of the soil, T_o, can be estimated using the expression

$$T_o = 4H / c \qquad (4)$$

where H is the depth of the soil stratum and c the velocity of shear wave propagation. The values of T_o range from 0.04 sec for the sites with shallow clay deposits to 0.19 sec for the sites with deeper clay deposits. The above values suggest that the shorter periods of the input motion are more amplified. These periods correspond to stiff structures.

Considering the amplification of the input motion due to topographic effects, a simple model suggests the approximation of ridge-valley topography with a triangular wedge structure [Faccioli, 1991]. The amplification of the input motion, v/v_o, can be estimated using the simple expression

$$v / v_o = 360 / \varphi \qquad (5)$$

where φ is the angle (in degrees) between the slopes of the hill or valley. Obviously, this expression yields amplification of the motion for a hill and de-amplification for a valley, while accurately represents the effect of the elastic half-space, i.e. $v/v_o = 2$ for $\varphi = 180^o$. For the topographies shown in Figure 3.10, the angles can be estimated as $\varphi_1 = 196^o$ for the valley and $\varphi_2 = 167^o$ for the hill. Following Eq.(5), the amplitude of the motion is approximately $(v/v_o)_1 = 1.8$ and $(v/v_o)_2 = 2.2$. Finally, dividing by the amplitude at the surface of the half-space, the amplification factors for the hill and the valley are respectively 1.1 and 0.9. These values indicate a minor effect of the local topography for this specific site.

3.3 Distribution of damage

Figure 3.11 represents the distribution of the macroseismic intensities for the area, together with the isoseismal lines. The most heavily damaged towns are located in an elliptic area oriented in the East-West direction and centred on San Giuliano di Puglia. This seems to agree with the solutions for the stress tensor of the earthquake, indicating a strike-slip movement of the fault in the same direction.

However, the attribution of a level of damage to each town was not easy, because of the wide variety of situations observed in each single town, due to local effects, together with the cumulative effects, at least of the two major events. In general, the effect of the earthquake of 1 November was to increase by half degree the MCS classification due to the earthquake of 31 October, especially in those areas previously classified midway between two grades (for example, areas classified as VII MCS, where classified as VI-VII MCS before the 31 October earthquake).

The highest macroseismic intensities observed were in San Giuliano, where VIII and IX MCS damage was reported [Galli & Bosi, 2002.]. These values correspond to partial and total collapse of structures, of which the worst example is given by the primary school of the town, which totally collapsed, killing 26 children and a teacher.

It must be noted that the heavy damage observed in the town was all located in the clayey part, along the upper main street, in particular where a change of slope was present (at the location of the collapsed school).

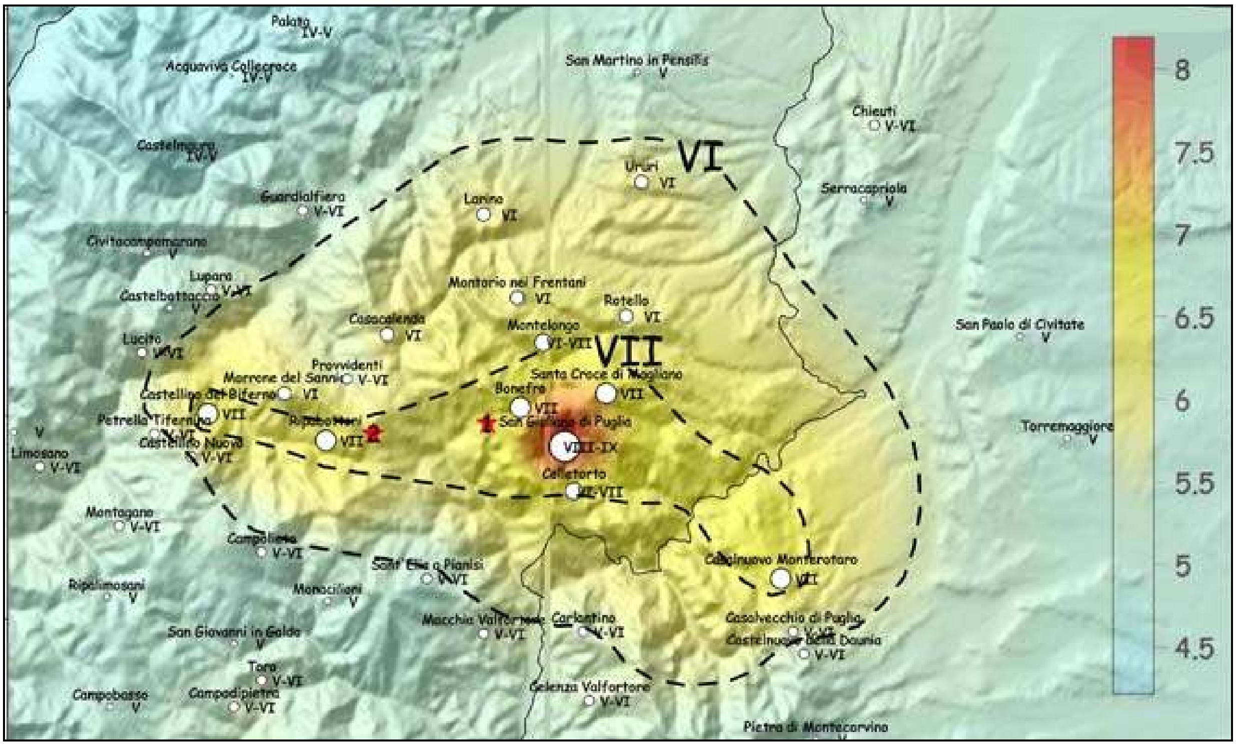


Figure 3.11. Interpolated distribution of MCS intensities in the epicentral area [Galli & Bosi, 2002]

Figure 3.12 View of Morrone del Sannio

Other towns, such as Ripabottoni, about 15 km from San Giuliano, and experienced some partial collapses, but, especially in the latter case, the collapsed structures were old non-engineered masonry houses. In Castellino sul Biferno, the heaviest damage seems to be due to slope instability phenomena.

Other towns, such as Morrone del Sannio, did not experience any major damage. This latter small town is located right above Ripabottoni, so that to a certain extent, damage was expected. However, contrary to the predictions, even the old masonry buildings did not collapse, neither did they show the cracks, holes and partial collapse observed elsewhere. This fact is in good agreement with the topography of the area. Morrone del Sannio is built on the top of a hill overlooking Ripabottoni. The soil of the town, most probably rock, did not produce amplification due to stratigraphic effects, so that the observed intensity was much less than that of the lower towns. Figure 3.12 shows a view of Morrone del Sannio. The close up of a reinforced concrete (RC) water tank located in the upper part of the town, shown in Figure 3.13, shows that it did not suffer any significant damage.

Figure 3.13. Reinforced concrete water tank in Morrone del Sannio

A more detailed discussion of the local site effects in San Giuliano can be found in Chapter 3.2, whereas a survey of the damage in relation with the features of the local building stock will be carried out in the following paragraph.

3.4 Building stock

The buildings of the area are generally small housing units with one or two storeys, rarely three. Most of them are masonry buildings with structural walls and wooden simply supported slabs. Masonry is also the material of old historical buildings, present in each town and mostly represented by churches of architectural and historical value that sadly developed extensive damage in most towns.

In general the quality of masonry buildings was not good, even for the restored ones, where very often traces of additions, super-elevations and more generally not very thoughtful interventions were observed. The same quality of materials and of construction techniques could be observed in historical buildings.

The only beneficial structural component noted in some of the masonry structures was that of steel ‘chains’, i.e. ties passing through the slabs and anchored to the façades of the buildings. These ties have a positive effect of increasing the global stiffness, generating a ‘rigid-box’ behaviour of the structure, thus preventing the collapse and separation of the façades and the loss of support of the slabs. Unfortunately, this kind of structural elements was only present in a minor part of the masonry buildings. Figure 3.14 shows an example of a tied house, located in Ripabottoni, in front of an old building whose façade was almost completely separated from the lateral walls; on the contrary this building experienced the earthquake suffering only minor damage.

Figure 3.14. Tied masonry structure in Ripabottoni

There are also a number of ‘composite’ structures, where the structural walls are made of masonry but also RC columns or beams are present. In these structures, observed for example in San Giuliano, heavy damage was observed and very often loss of support of the slabs caused their collapse.

The newer buildings are represented by RC structures, generally not designed to provide basic earthquake resistance and built with poor materials and low quality. Nevertheless, most of the RC structures exhibited a better behaviour than the masonry ones and did not cause risk for the inhabitants, neither will they pose particular problems for the repairing phase. Some damage to RC structures was observed in San Giuliano di Puglia, where a RC frame structure exhibited some cracks and damage to the columns and the non-structural walls. A major cause of damage was the presence of a soft-story, resulting from a ground floor with no infills, which caused a concentration of deformation demand, leading to the development of a storey mechanism. A more detailed analysis of this peculiar case is performed in the following. All the other RC houses in the town of San Giuliano di Puglia did not show significant damage; only the infills of some houses that were still under construction were demolished to decrease the risk of local instability and accidents. In the town of Bonefro, a group of multistorey RC frame structures were reported to have suffered significant damage.

3.5 Comparison with the effects of the 1997 Umbria-Marche earthquake

The greatest seismic activity in Central Italy in the last few years took place in the regions of Umbria and Marche in 1997. It is thus useful to compare the most remarkable features of that earthquake, in terms of magnitude, intensity, damage distribution and site effects, with those of the Molise earthquake to detect similarities or differences related to the source mechanisms, the topographic characteristics and the building stock and vulnerability of the two areas.

The so-called Umbria-Marche seismic sequence started on the 4 September 1997 and lasted for about a fortnight; the major event occurred on 26 September, with magnitude of 5.5 and MCS intensity of VIII. Figure 3.15 presents the epicentral area of the earthquake and the most damaged towns [CGP, 2002.].

In the 1997 earthquakes, considerable MCS intensities were observed in areas that had not been severely damaged by historical earthquakes in the past, with large differences of the damage experienced in adjacent areas; these features are altogether similar to those of the Molise earthquake.

One of the most important variations in the observed MCS intensity was in the small town of Cesi, where in the higher areas (Cesi Vila) intensities of VI-VII MCS were detected, whereas in the lower ones (Cesi), a higher intensity of IX MCS was observed. Figure 3.16 shows the local amplification effects measured in two parts of the town, clearly pointing out the much higher amplification at the lower locations. The amplification factors have been computed based on microtremor data collected during the first three weeks after the main earthquake and using the Nakamura technique [Mucciarelli & Monachesi, 1998].

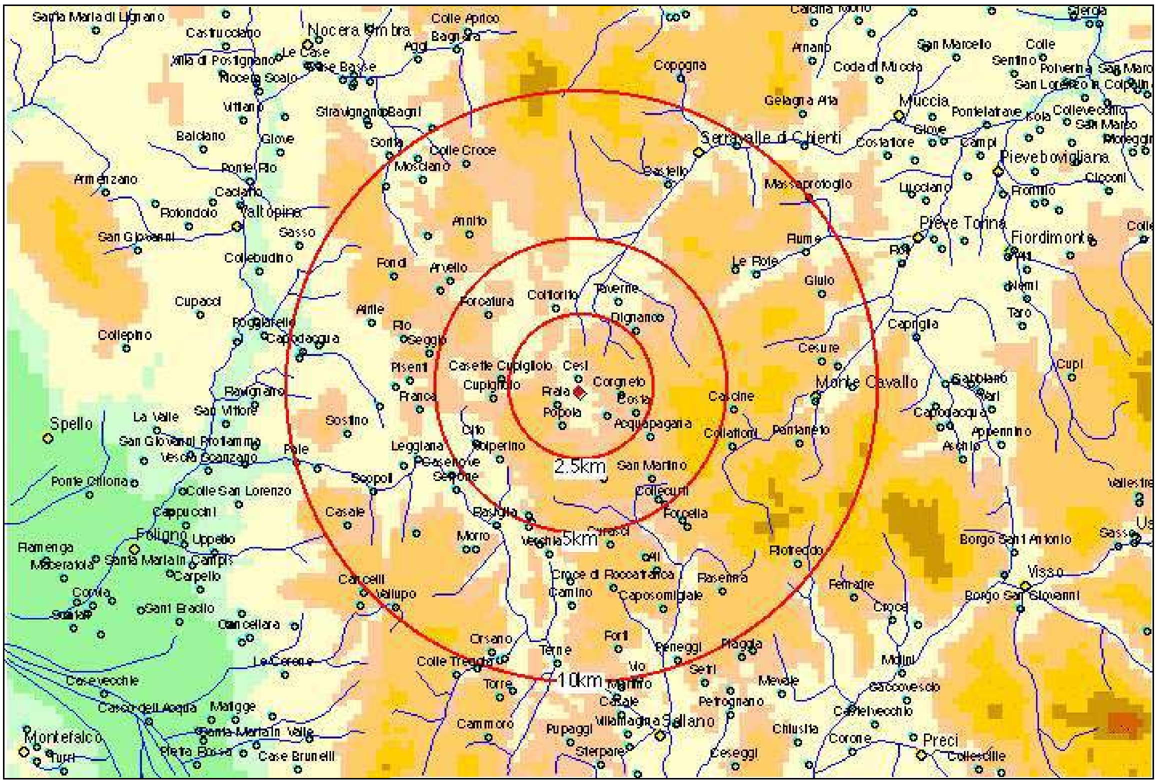


Figure 3.15. Epicentral area of the 1997 Umbria Marche earthquake [CGP, 2002]

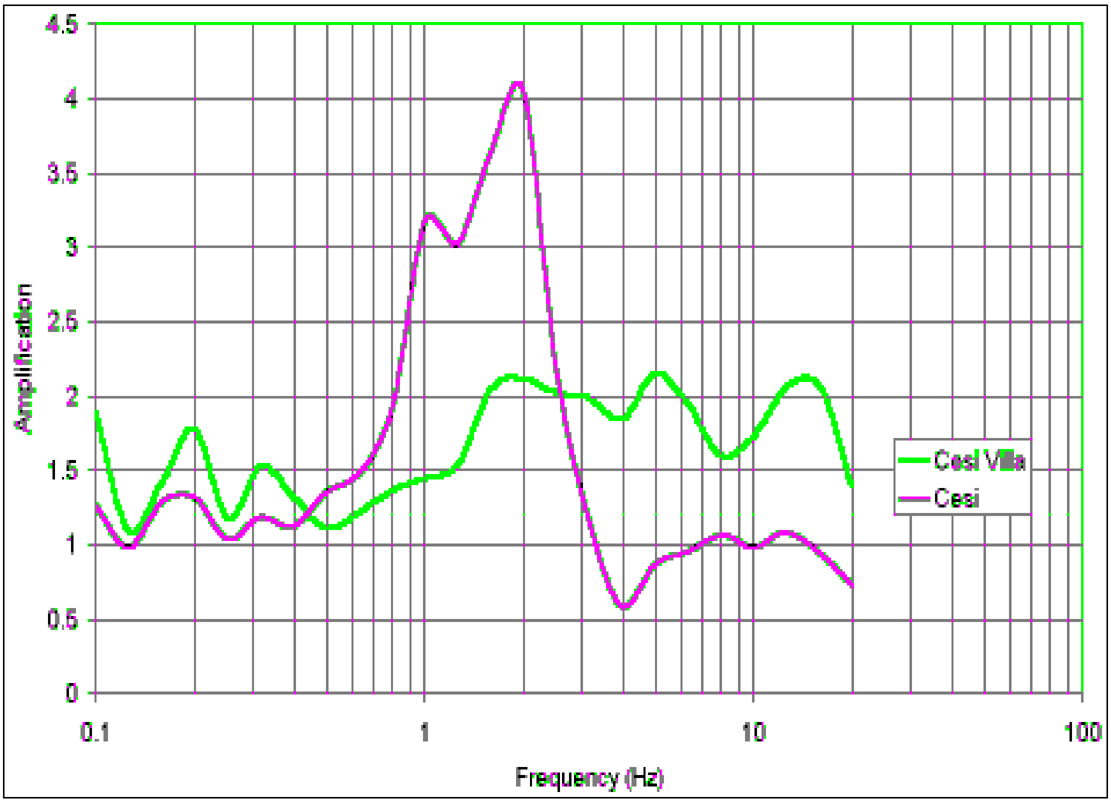


Figure 3.16. Local soil amplification effects in the town of Cesi [Mucciarelli et al., 2002]

Figure 3.17 presents the distribution of the observed MCS intensities for the two major events of September 1997 and for the greatest of the aftershocks of October 1997, which reached a magnitude of 5.4. It can be observed that towns whit the same level of observed damage were located equidistantly from the epicentre in Colfiorito. This damage pattern is different from that observed in Molise (Figure 3.11), owing to the fault mechanisms inherently different in the two cases.

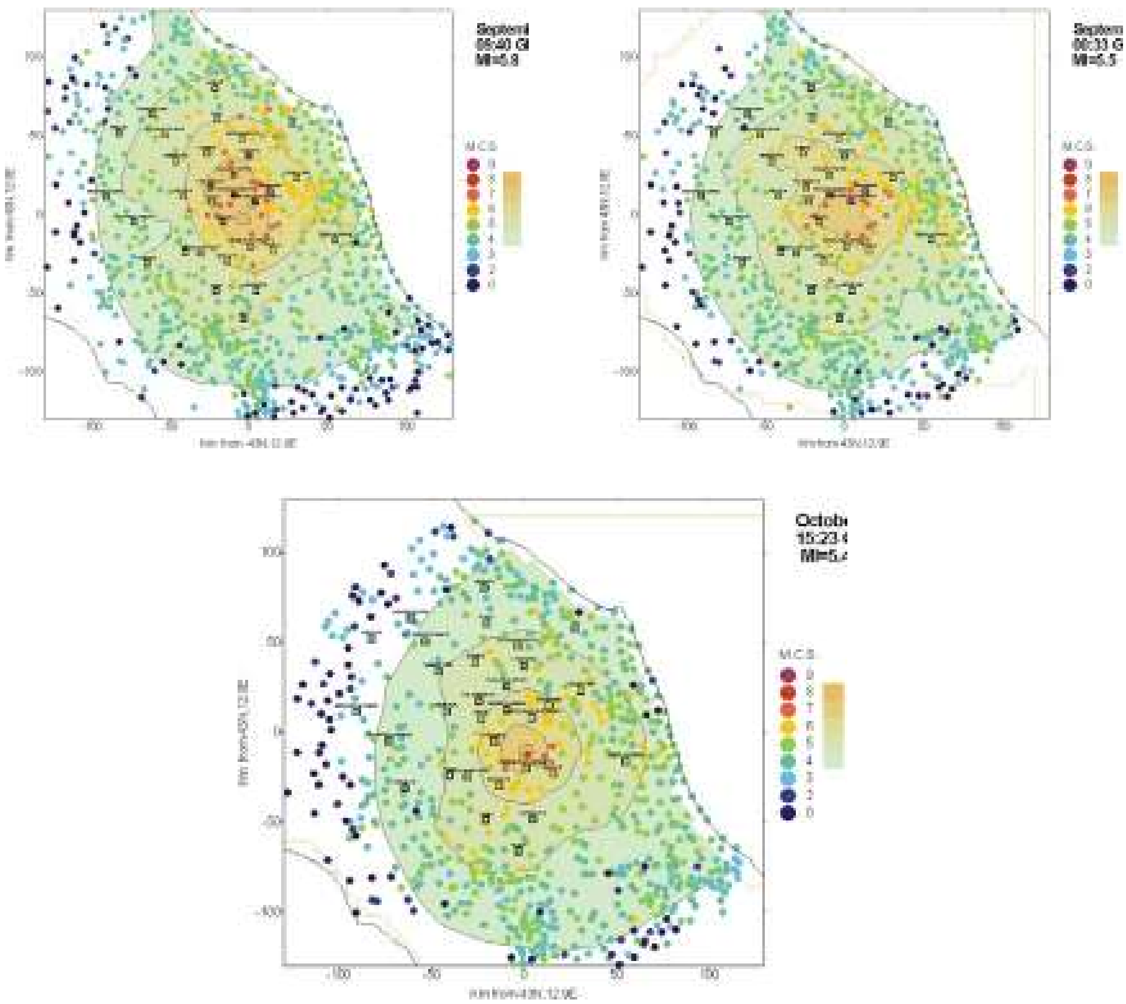


Figure 3.17. Distribution of the MCS intensities for the two major events of September 1997 and for the greatest aftershocks of October 1997 [Ekström et al., 1998]

The Umbria-Marche earthquakes were in fact characterized by normal fault mechanisms, with a NE-SW tension axis, with a presumed fault plane dipping towards the South-West. Only few events had a different faulting geometry, indicating instead right-lateral strike-slip faulting on a plane oriented approximately East-West, or left-lateral faulting on a plane oriented North-South. Figure 3.18 shows the Centroid Moment Tensor Solutions for the two main events in the ‘beach ball’ representation, which can be compared with that for the Molise earthquake presented in Chapter 2.

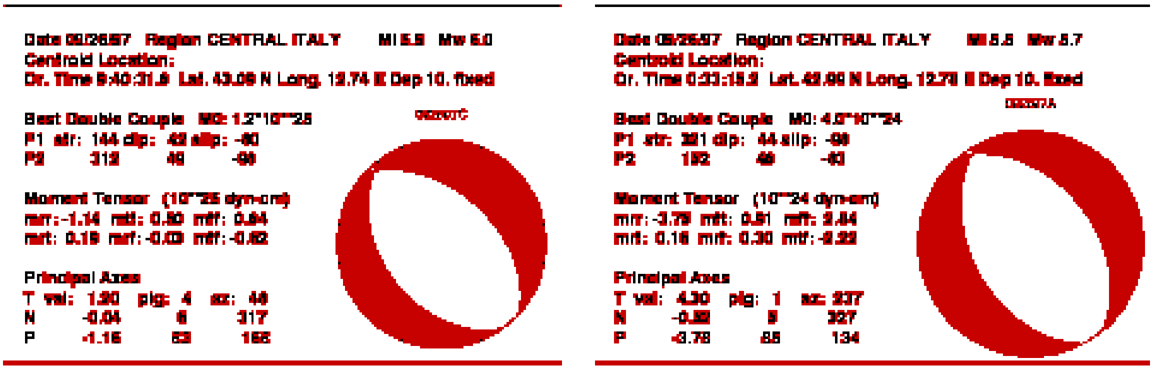
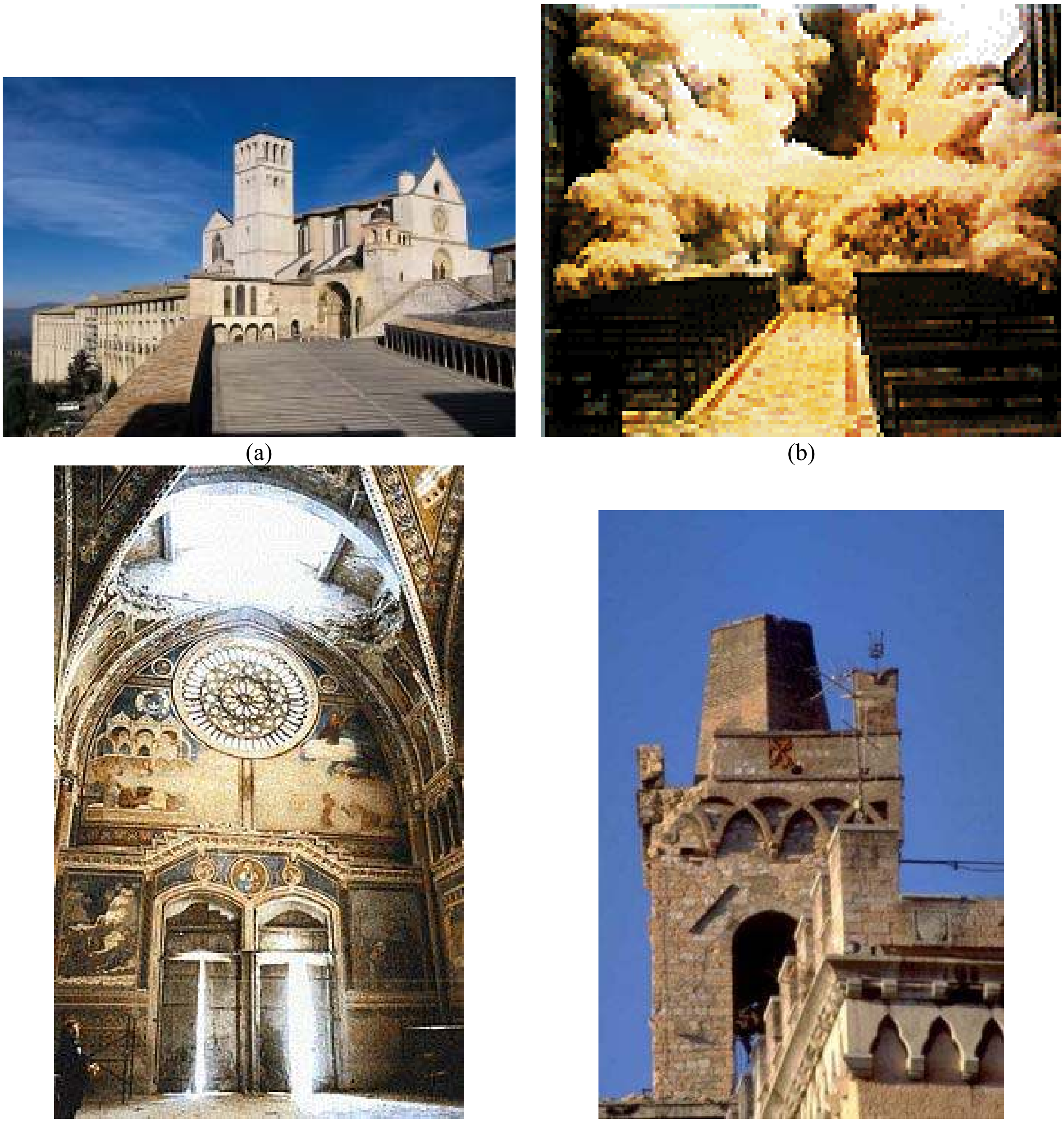


Figure 3.18. CMT solutions for the two main events of September 1997 [USGS, 2002]

Figure 3.19. Damage of new and old masonry buildings in the Umbria-Marche earthquake [Primitaly, 2002]

As for the building stock present in the 1997 epicentral area, it must be noted that it was similar to that of Molise: the most widespread type of structures were small masonry ones, with a large number of historical or old buildings. For this reason, the distribution of damage was also strongly influenced by the intrinsic vulnerability of many of the buildings. In Figure 3.19 three examples of damage to masonry buildings can be observed.



(a) (b) (c) (d)

Figure 3.20. General view of the Basilica of San Francesco di Assisi (a), damage at the vaults (b, c) and damage at the bell towers (d) [Moveaboutitaly, Primitaly, Villaschiatti, 2002]

Finally, it must be noted that the damage to churches and historical buildings was remarkable in both earthquakes. In fact, in the Molise sequence many churches of great value experienced failures of vaults, arches or façades and in general ancient bell-towers developed cracks and damage mainly in the upper parts. In the Umbria-Marche seismic sequence, great damage was inflicted to invaluable masterpieces of Italian sacred architecture, above all the Basilica of San Francesco in Assisi, which experienced, among other damage, the complete failure of the vault. Figure 3.18 shows examples of this type of damage.

Apart from the Basilica, the construction of historical buildings in Umbria-Marche was of better quality, because many of them had been retrofitted with ties. Had not been that the case, the damage to churches and historical buildings would have been much higher for the Umbria – Marche earthquake events. The higher quality of construction of historical buildings, mainly in the region of Umbria, owes to its importance as a Papal state and its proximity to Rome. More recently, tourism has played an important role for the renovation of historical structures, a situation that has clearly not benefited the Molise region.

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4 PERFORMANCE OF BUILDING STRUCTURES

4.1 Non-engineered buildings

4.1.1 Non-engineered masonry buildings

Many masonry buildings (2~3 storeys) existing in the older parts of the towns affected by the earthquakes were poor quality masonry structures, which suffered heavy damages or partial collapse. In general, these structures were present in the historical centres of the towns and were mostly inaccessible to the reconnaissance team for detailed inspection, since no minimum safety conditions could be guaranteed. Some of these buildings were also found in the zones outside of the old part of the towns, as shown in Figure 4.1.

There are several aspects that are worth mentioning, concerning the poor performance of these non-engineered masonry structures, namely: a) poor quality of the masonry bearing walls, b) absence of ties, c) recent interventions replacing the existing light-weight roofs with heavier materials and in some cases the addition of new storeys, and d) lack of maintenance.

In what concerns the quality of the bearing walls, mostly made of rubble stone or tufo blocks, it was observed that stones were small in size and the lime mortar was coarse. The bearing walls were sometimes externally plastered or had a façade made of good quality stone tiles (see Figures 4.1c and 4.1d). However, the connection between these tiles and the rubble stone was inefficient and did not provide any contribution to the strength of the main walls; this is evident in Figures 4.1c and 4.1d.

The absence of ties was also common, but due to the very poor quality of masonry walls, their effectiveness would have been doubtful, unless many ('micro') and well distributed ties had been used. In fact, as shown in Figure 4.1d of a building in San Giuliano di Puglia, ties were present at the roof floor (one is visible in the picture; the other in the left-end side was identified during the field mission) but they were almost ineffective due to the poor quality of the masonry walls.

Other factors that may have contributed to severe damage and collapse of these structures are the addition of new storeys, and/or replacement of the original timber roofs with concrete roof slabs, as shown in Figure 4.1a (concrete roof slab and original timber floors) and Figure 4.1b (addition of a new storey and concrete roof-slab).

Figure 4.1. Damage to non-engineered masonry buildings in San Giuliano di Puglia

Figure 4.2 shows some pictures of the oldest buildings in Castellino sul Biferno (Figures 4.2a and 4.2b) and Ripabottoni (Figures 4.2c and 4.2d) were the poor quality of masonry and more specifically, the lack of maintenance is evident. The impression is that most of these buildings were abandoned or were used as storage, including animal keeping.

(a) (b)

(c) (d)

Figure 4.2. Damage to non-engineered masonry buildings in Castellino sul Biferno and Ripabottoni

4.1.2 Churches

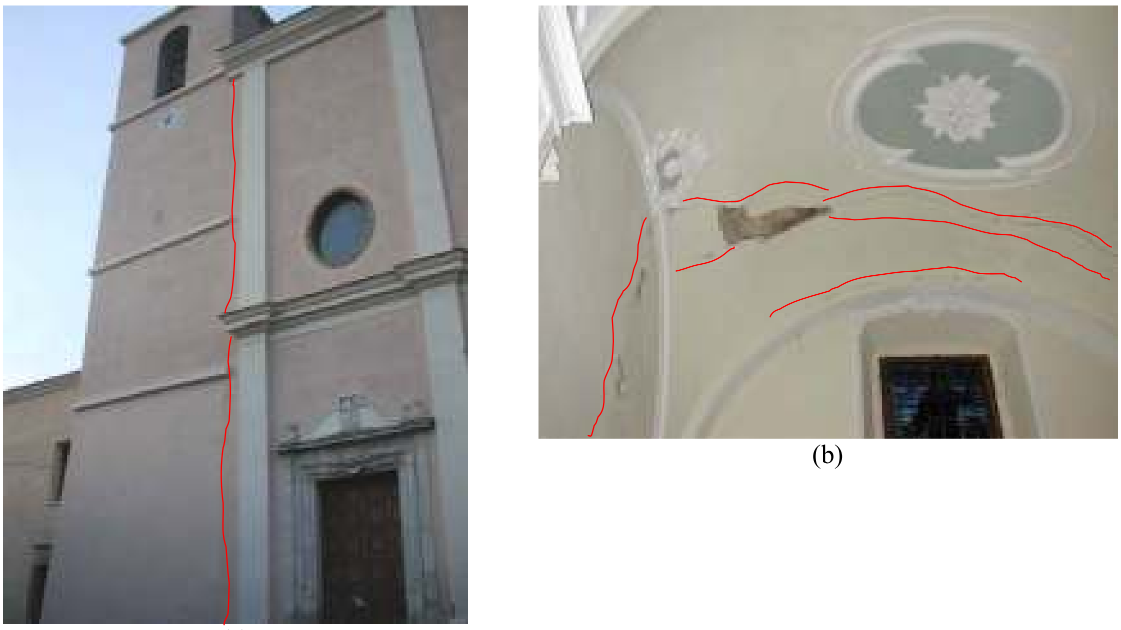
Most churches were seriously damaged. In fact, in towns without evident damage reported in family housing, the churches suffered heavy damage: collapse of bell towers and vaults, serious damage to arches and separation of the external main walls. It is noted that the quality of masonry did not seem to be of much better quality than that used in normal housing. There is an important aspect to highlight: ties were almost completely absent in the large churches of Molise. In other non-seismic regions, such as in Lombardy, ties are commonly used to prevent cracking from differential settlement. As a result, the opening of the main walls that resulted from the absence of any restraint lead to the loss of the support to arches and vaults.

The church of Castellino sul Biferno is situated in the old part of the town, on top of a steep hill. The old part was extremely damaged and access was not allowed. The church, shown in Figure 4.3, presented damage at the top of the façade and separation of the lateral and central naves. Hammering of the roof caused partial collapse of the external part of the walls. The spire of the bell cell was extensively cracked. Overturning of the end wall of the apse was also observed.

Figure 4.3. Church in Castellino sul Biferno

The bell tower of the San Giacomo church in Santa Croce di Magliano partially collapsed (Figure 4.4). A small dome was present on top of the bell tower; half of this dome collapsed and the remaining part was demolished after the earthquake for safety reasons. Figure 4.4 also highlights the beneficial effect of tie rods. The lower part of the bell tower, where metallic rods were present in both directions and at different heights, was protected against overturning and shows no significant damage. On the contrary, the upper part, where no tie rods were present, collapsed. Significant damage was also reported at the interior of the church, where access was not granted.

Figure 4.4. Partial collapse of the bell tower of the San Giacomo church in Santa Croce di Magliano



(a) (b)

Figure 4.5. Chiesa Madre in Santa Croce di Magliano, separation of the bell tower (a) and damage of the arches and vaults (b)

The Chiesa Madre in Santa Croce di Magliano was seriously damaged, and at the time of the inspection, volunteers were evacuating the religious works of art from the church. A vertical crack between the façade and the bell tower (see Figure 4.5a) indicates separation of the two macroelements, but no other damage was observed from the outside. However, inside the church significant damage was observed, namely: cracking of the triumphal arch, wide cracks at the vaults of the nave and separation of the vaults from the arches (Figure 4.5).

Figure 4.6. Old church in Ripabottoni, separation of the façade and overturning of spire

Both churches of Ripabottoni were seriously damaged. The façade of the old church was separated from the lateral walls and the cusp was separated from the rest of the façade (Figure 4.6). More serious damage was observed at the interior of the church. The vault of the apse partially collapsed (Figure 4.7a) and extended cracking was observed in the apse. The dome was seriously cracked, but a collapse mechanism did not fully develop, possibly thanks to the beneficial effect of the tie rods at the base. The vaults of the nave were also cracked and separated from the adjacent walls (Figure 4.7b).

(a) (b)

Figure 4.7. Old church in Ripabottoni, partial collapse of the dome (a) and damage of the arches and vaults (b)


(a)


(b)

Figure 4.8. New church in Ripabottoni, façade (a) and bell tower (b)

The new church of Ripabottoni is situated at a short distance from the old one and suffered similar damage. No significant damage was observed at the façade and the bell tower, but scaffolding was installed for protection of the façade against overturning (Figure 4.8). At the interior, the vaults of the transept presented diagonal cracks that continued above the arches (Figure 4.9a). The pillars showed vertical cracks at all faces (Figure 4.9b), while the triumphal arch presented extensive wide cracks.


(a)


(b)

Figure 4.9. New church in Ripabottoni, damage of the vaults (a) and the pillars (b)

From past earthquakes it has been observed, that the seismic response of churches may be described according to recurrent phenomenology, traceable to damage modes and collapse mechanisms of its different parts, called macroelements, which show independent structural behaviour. Typical examples of a macroelement are the façade, the bell tower, the apse and the transepts. The main kinematic mechanisms of collapse in the different macroelements have been summarised in a limited number of damage mechanisms. The damage mechanisms are: overturning, shear mechanism and damage at the top of the façade, transversal vibration of the nave, damage of the triumphal arch, damage at the vaults of the nave, hammering of the roof covering, damage of the dome, overturning of the apse, damage at the vaults in the presbytery or the apse, overturning of end walls, lack of continuity in walls, shear failure of the walls, damage of the bell tower and the bell cell and overturning of projections or spires [Lagomarsino, 1998].

An index was proposed for the damage assessment of churches. The damage index, i_d, is a number between 0 and 1, which measures the average level of damage to the church and is defined as

$$i_d = \frac{1}{3N}\sum_{k=1}^{16} d_k \qquad (6)$$

where d_k (from 0 to 3) is the damage reported in the k-th mechanism and N is the total number of mechanisms that can be potentially activated in the church ($N \leq 16$). Damage is classified as no damage ($d_k = 0$), light damage ($d_k = 1$), fully developed mechanism ($d_k = 2$) and severe damage - near collapse ($d_k = 3$).

Table 4.1. summarizes the damage index for the churches that were investigated. The damage index is calculated on the basis of limited data, particularly for the church of Castellino sul Biferno and of San Giacomo in Santa Croce di Magliano: $d_k = 0$ (no damage) was assigned to the mechanisms for which no data were available, e.g. because access to the interior of the churches was not allowed, and their contribution to i_d was not considered. The damage index for all churches assumes high values, indicating significant damage, in agreement with the observations. These values verify the high vulnerability of this kind of structures, which are part of the cultural and historical heritage.

Table 4.1. Damage assessment of churches

	i_d
Church of Castellino sul Biferno	0.7
San Giacomo in Santa Croce	1.0
Chiesa Madre in Santa Croce	0.9
Old church in Ripabottoni	0.7
New church in Ripabottoni	0.9

4.2 Engineered buildings

4.2.1 Plain masonry buildings with RC floors

Load bearing masonry buildings with RC floors represent an important part of the building stock in the most affected towns. In San Giuliano di Puglia, these buildings were constructed along the main street and show an extremely high percentage of openings in the ground floor. As a result, they suffered heavy damages and possibly should be demolished.

Typical examples of masonry buildings with RC slabs in San Giuliano di Puglia are presented in Figure 4.10, confirming the large percentage of openings in the ground floor. Furthermore, all the pictures show severely damaged buildings in the extremity of building blocks, a phenomenon that has been commonly observed in previous earthquakes.

These buildings represent typical cases of engineered structures, which could have been designed for improved earthquake resistance if the zone had been qualified as seismic zone. Anyway as-built seismic resistance is not sufficient for the case of low-moderate seismicity.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 4.10. Damage to engineered plain masonry buildings with RC floors in San Giuliano di Puglia

Apart from the lack of appropriate layout and resistance for seismic performance, there is an aspect to be underlined and concerns the quality of construction materials and the execution of construction works. The general impression is that the more recent engineered masonry buildings suffer from low quality of materials, namely mortars and a somewhat random arrangement of the brickwork.

4.2.2 RC structures

Reinforced concrete structures represent only a very small part of the housing/building stock of the small towns affected by the earthquake. For example, in San Giuliano di Puglia, only a few RC houses constructed recently exist in the upper part of the town and no-damage (see Figure 4.11b) or minor non-structural damage was identified in these RC structures (houses and buildings).

It is however pointed out that some damage to RC structures, specifically to infill panels, was identified in a few buildings in San Giuliano di Puglia, Bonefro, Colletorto and Santa Croce di Magliano. These buildings generally show particular features such as open ground floor or extremely irregular configurations. As shown in Figure 4.11a, a building in the upper part of San Giuliano di Puglia, without infill walls in the ground floor (just above the garages) suffered some structural and severe non-structural damage at the ground floor. The set of buildings shown in Figure 4.11b are located in the same area, 100 meters from the building in Figure 4.11a and did not suffer any damage.

(a)

(b)

(c)

(d)

Figure 4.11. Reinforced concrete structures in San Giuliano di Puglia

Another building in San Giuliano di Puglia, in the most affected area of the town, shown in Figure 4.11c, shows extremely severe damage in the ground floor, where the relative area of openings (windows and doors) is quite high.

The structure shown in Figure 4.11d is the gymnasium, adjacent to the collapsed school of San Giuliano di Puglia. It is a simple RC structure with a long infill brick-wall in the West side, which suffered crushing of the infills in the upper-left corner and provoked shear failure of the left column in the joint region. In fact, it was reported that the long brick-wall was reinforced recently with a horizontal RC beam (visible in Figure 4.11d), which inhibited failure of the wall itself and allowed for development of a larger compression strut and consequently for higher shear forces transmitted in the wall-column interface.

(a)

(b)

(c)

(d)

Figure 4.12. Reinforced concrete building in Pozzo di Terra – Bonefro [Giannini et al., 2002]

Severe damage to a set of RC buildings was reported in Bonefro (Figure 4.12) [Giannini et al., 2002]. The building also presents an irregular configuration in plan with a partially-open ground-storey. Furthermore, there are two aspects to underline, namely: the long and thin infill panels (double wall fully disconnected) which can buckle prematurely, and the poor reinforcement and detailing of the RC columns (see Figure 4.12b). This structure represents a typical RC building of the 60's.

4.3 Evaluation of ground accelerations in San Giuliano di Puglia

In the absence of acceleration records, it is proposed to estimate the ground shaking intensity from the effects observed on simple structures. It is however underlined that such an exercise requires several assumptions, which should be confirmed in order to increase the confidence on the obtained results.

(a) (b) (c) (d)

Figure 4.13. Reinforced concrete building in San Giuliano di Puglia, South view (a), East view (b), damage of infills (c) and damage at the base of a column (d)

The structure shown in Figure 4.13 is a four-storey brick-infilled RC building with an almost completely open storey (construction not yet finished). In fact, in the open storey only a few bays were infilled and these infill panels suffered severe damage. In what concerns the RC structure, only slight damage was identified at the base of the columns of the open-storey, see Figure 4.13d. Damage consisted of slight crushing/spalling at the base of the columns, spalling of concrete in the column-joint region of the external columns, caused essentially by buckling of the longitudinal external rebars (detailing in this region is certainly very poor). No cracks remained opened and no residual drift was evident. Comparison between these damages with damages observed in experimental tests on structures with similar detailing, see [Pinto et al., 2002], indicate that the structure may have experienced interstorey drifts in the range of 0.7 ~ 1.2 % in the most flexible direction.

The structure was simulated numerically (simplified model with columns framing into the adjacent beams and the mass of the upper part uniformly distributed in the floor), assuming the plan and elevation layout shown in Figures 4.13a and 4.13b and considering the following conditions: a) beams do exist in the North-South (longitudinal) direction in the exterior part of each module; b) transversal beams only exist in the external bays. Furthermore, it was assumed a RC Young modulus of 25 GPa, rectangular columns with dimensions 0.35x0.35 m, longitudinal external 0.35 m deep beams, transversal external 0.25 m deep beams and 0.15 m deep internal slab-embedded beams.

Three distinct frequencies were calculated: 2.5, 2.9 and 4.2 Hz, corresponding to the transverse and longitudinal translation and the torsional vibration modes respectively. A subsequent equivalent static analysis with an applied floor force computed from the mass, a base acceleration of 0.4g (as estimated on the basis of the attenuation relations) and a spectral amplification of 2.5, leads to a storey displacement of 42 mm in the transversal direction and to a storey displacement of 6 mm in the longitudinal direction, which correspond to storey drifts of 1.4% and 0.2% respectively.

These storey drifts seem to be compatible with the physical damage observed in the structure. In fact, in the longitudinal direction (0.2% drift), the short infill wall shows slight diagonal cracking in the zone without openings. However, 1.4% drift in the transversal direction is slightly larger than the values corresponding to the identified damages in the columns. It is noted that the presence of the stairs, shown in Figure 4.16c, which was not taken into account in the model, should somewhat increase the lateral stiffness and reduce the transversal drift.

It is therefore concluded that the structure may have been subjected to peak ground accelerations of about 0.4g with important energy content around 2.0 ~ 2.5 Hz, which would allow to conclude that no special soil amplification developed in the upper part of the town.

4.4 Scuola Francesco Jovine of San Giuliano di Puglia

Apart from the heavy damage inflicted to the housing in San Giuliano di Puglia by the earthquake, the collapse of the school represents the most disastrous consequence. In fact, this collapse was responsible for the death of 26 children out of the 29 casualties resulting from the event.

There is no technical report available on the characteristics of the school building, as well as on the analysis of the causes of collapse. However, on the basis of information gathered from the media it is presumed that the school was designed in the 50's, constructed in the 60's and an upper storey had been recently added to the original structure. The original building was a mixed structure – reinforced concrete and masonry – and smooth round bars were used as reinforcement. The recent intervention in the building added a new storey to accommodate two new classrooms.

The field mission team made a short visit to the school site from the South-West side and confirmed that the school was reduced to rubble (see Figures 4.14b, c and d). Furthermore it was possible to identify parts of the two construction phases referred to above, namely the original RC structure where round smooth rebars were used (see Figure 4.14c) and the recently added parts where improved-bond rebars were used (see Figure 4.14d).

(a)

(b)

(c)

(d)

Figure 4.14. The collapsed school – 'Scuola Francesco Jovine' of San Giuliano Puglia: a) North view (a), South-west view (b), and details of collapsed RC members (c, d)

It is noted that according to the Italian law (Legge Sismica N.64 del 1974), in the affected zone, only the municipalities of Ururi and Rotello were classified in the seismic category II, since 1981. Therefore, no earthquake analysis was required by law for the design of the recent intervention at the school of San Giuliano.

Italian prosecutors have opened an investigation into why the school was reduced to rubble during the earthquake, wiping out the lives of most of the town's six and seven-year-old children.

4.5 References

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5 OTHER TYPES OF STRUCTURES

5.1 Dams

The most important dam in the area is the Occhito dam, located at less than 30 km from the epicentral area. The RC body of the dam did not suffer any damage, nor any landslides were evident on the side slopes of the reservoir (Figure 5.1). No interruption of the activity of the dam was reported and the field inspections did not reveal any important damage [SSN, 2002].

(a) (b)

Figure 5.1 The Occhito dam: (a) bird's-eye view and concrete body of the dam (b) [SSN, 2002]

5.2 Bridges and viaducts

As mentioned in Chapter 4, the road system in the area is made of secondary roads. The main axis is the SS Bifernina, a motorway linking the area of Campobasso with the coastal town of Termoli and with other important towns nearby. The motorway has a number of small-to-medium RC viaducts, which did not suffer any significant damage from the earthquakes.

5.3 Roads

The local roads, winding up and down the hills and crests of the mountainous area, are characterized by slow and sparse traffic. The maintenance of the road system is well organized to guarantee continuity in the use of the roads all year long, especially during the winter season.

The roads suffered only minor and localized damage during the sequence of seismic events. In the area of San Giuliano di Puglia several cracks in the road were observed (Figure 5.2). However, they were not caused by superficial faults or ruptures, but only by small land movements and localized sliding.

Sliding phenomena were also observed in the Vallepare area (Figure 5.3), most of them restricted to cut and fill areas adjacent to roads with non-cohesive and compact soil that induced relative movements.

(a) (b)

Figure 5.2. San Giuliano di Puglia: longitudinal (a) and transverse (b) cracks in the road [INGV, 2002]

(a) (b)

Figure 5.3. Roadside landslide (a) and roadside longitudinal crack (b) in the Vallepare area [INGV, 2002]

The repair interventions for this type of damage required minor efforts and short execution times.

5.4 References

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6 SOCIO-ECONOMIC EFFECTS AND MANAGEMENT OF THE DISASTER

6.1 General

The emergency situation in Molise was managed by a large number of operators representing different governative and non-governative agencies and institutions. The centres where the field authorities were concentrated were immediately established in some neuralgic structures that were identified in the most important towns of the affected area. These centres were called C.O.M.s, the acronym for 'Centro Operativo Misto', empowered with the authority to operate during the emergency crisis.

The most important C.O.M., retaining the decisional power and the majority of contacts with the external and governmental institutions, was established soon after the main earthquakes in the primary school of Larino and was later moved to the Seminar of the same town to allow the school to open after the first phases of the emergency were completed. Two other C.O.M.s were established in Casalnuovo Monterotaro and in San Giuliano di Puglia.

The functions of the Larino C.O.M. and, subordinately, of the other two C.O.M.s were:

- Assistance to Local Authorities
- Damage estimation
- Administrative support
- Transportation and road management
- Public safety
- Historical and cultural monuments preservation
- Information and public relations
- Urgent technical services and dangerous materials
- Scientific research and planning
- Public health
- Evacuation and logistics
- Volunteering coordination
- Telecommunications
- General secretariat

In other towns, centres of local authority were established, operating at the municipal level, under the authority of the C.O.M. and practically replacing the functions of the Municipalities during the emergency. These centres were called C.O.C.s, the acronym for Centro Operativo Comunale, meaning they had operational authority at municipal level. They were generally headed by the mayors of the towns where they were established. The C.O.C.s were located in: San Martino in Pensilis, Bonefro, Colletorto, Ripabottoni and Provvidenti.

Figure 6.1 Establishing the C.O.C. in Ripabottoni [CRI, 2002]

6.2 Statistics

6.2.1 Victims

The victims of the earthquakes were 29. Most of them died in the primary school ‘Jovine’ of San Giuliano di Puglia, totally collapsed following the event of 31 October 2002; the victims were 26 children aged between six and ten and one teacher. No other towns experienced casualties.

6.2.2 Emergency operations

There was a large number of operators present in the area, who were timely displaced in the region, especially if one takes into account that the Etna volcanic and seismic activity in Sicily had already called many forces to Sicily to guarantee the safety of the citizens.

Table 6.1 Operators and machinery on the field (updated on 13/12/2002) [Protezione Civile, 2002]

Institution	Number of operators		Number of machines present
	max	present	
Vigili del Fuoco	625	370	176
Aeronautica Militare	200	7	4
Esercito Italiano (EI)	300	84	44
Forze dell’Ordine (Carabinieri, Polizia di Stato, Guardia di Finanza)	400	343	124
Corpo Forestale Italiano	150	89	25
ANAS	60	4	2
Croce Rossa Italiana (CRI)	272	161	56
Marina Militare (MM)	200		
Telecom technicians	70		
Volunteers	1438	204	48
total	3715	1262	479

The institutions that were present during the management of the crisis at the peak of the emergency were: the Fire Brigade (Vigili del Fuoco), the Italian Army (Esercito Italiano), Air Force (Aeronautica Militare) and Naval Force (Marina Militare), the Police (Forze dell'Ordine, which in Italy are represented by different corps: Carabinieri, Polizia di Stato and Guardia di Finanza), the Rangers (Corpo Forestale Ialiano), the Italian Red Cross (CRI) and the road maintenance technicians (ANAS). Moreover, a great number of volunteers provided useful and very effective help in all the operational tasks. Table 6.1 shows the number of persons from each institution present during the peak of the emergency and those that were still there more than one month later (data updated at 12 December 2002). Table 6.2 shows the number of assisted people during the peak of the emergency and those still needing assistance at present.

Table 6.2. Assisted population in the most damaged towns (updated 13/12/2002) [Protezione Civile, 2002]

town	pop.	assisted pop.		beds	tents/caravans
		max	Present	max	max
San Giuliano di Puglia	1163	1163	133	850	186/103
Ripabottoni	673	673	0	640	135/1
Santa Croce di Magliano		1942	0	790	255/68
Bonefro	1832	512	80	620	235/2
Casacalenda	2490	1000	25	1534	111/8
Colletorto	2622	1500	30	1020	198/35
Larino	8118	1500	39	1020	198/35
Morrone		24	0	130	92/10
Provvidenti	170	140	27	150	18/5
Rotello		700	0	555	195/62
Castellino sul Biferno	693	673	185	526	105/62
total	19560	9827	533	7835	1728/391

The management of the disaster can be roughly divided into three phases, named after the main tasks required by each of them. The first phase, which could be defined 'Evacuation and Logistics', started right after the first earthquake events. In this phase, the inhabitants of the most damaged towns were quickly evacuated, sometimes even against their will, and shelter and food was provided to them. Tents and, in a smaller number, caravans, were provided. The biggest areas where the homeless were located were at the entrance of the towns of Ripabottoni and San Giuliano, as shown in Figure 6.2; in some cases people slept in tents in their own courtyards or small gardens.

(a) (b) (c)

Figure 6.2. Tents (a) and caravans (b) in Ripabottoni and in San Giuliano (c) [CRI, 2002]

6.2.3 Damage and economic losses

A second phase of the management of the disaster took place soon after the first one. Defined as 'Safety inspections and first interventions', as soon as the houses were freed from their inhabitants they were carefully checked and assessed as to their safety. This task was mainly carried out by the Fire Brigades and often implied the necessity to close whole areas of the towns due to the risk of collapse of buildings. The houses were assigned a mark in letters starting from A (totally safe to live in, no intervention required) to E (completely unsafe, likely to collapse, to be demolished) or F (unsafe due to external risk of collapse of adjacent structures). Table 6.3 shows the fractions of the building stock belonging to each category for the whole affected region.

Table 6.3. Results of the assessment of the building stock in the damaged area (updated 13/12/2002) [Protezione Civile, 2002]

	Class A	Class B	Class C	Class D	Class E	Class F	total
public buildings	465	100	13	23	80	5	686
private buildings	9472	1655	651	300	3062	521	15661
total	9937	1755	664	323	3142	526	16347

Besides family housing and ordinary buildings, an accurate check and assessment of the historical structures was carried out. Major damage was in fact detected in the churches or ancient palaces of many towns, many of them of monumental value. Table 6.4 shows the results of the assessment of these typologies of buildings.

Table 6.4. Results of the assessment of historical buildings in the damaged area (updated 13/12/2002) [Protezione Civile, 2002]

	Class A/B	Class C/D/E	total
churches	148	116	264
palaces	7	18	25
castles	0	3	3
towers	6	7	13
convents	6	3	9
others	4	2	6
total	171	149	320

(a) (b) (c)

Figure 6.3 Operators at work along the main street of San Giuliano di Puglia (a) [CRI, 2002], preventing the access to damaged buildings (b) and preserving statues and paintings (c) in Santa Croce di Magliano

The third phase includes the interventions needed to guarantee a minimum level of safety for the buildings that resisted the earthquakes and to allow the inhabitants to move back to their homes. The interventions, mainly represented by external wooden supports to façades, doorways and windows, were mainly carried out by volunteers using machines and construction materials provided by donors from all over Italy. Figure 6.3 and Figure 6.4 show some of these interventions.

(a)

(b)

(c)

(d)

(e)

Figure 6.4. Safety interventions: removing rubble [CRI, 2002] (a), supporting facades of masonry buildings (b, c), supporting arches (d) and supporting historical bell tower (e)

6.3 References

1. Protezione Civile, *Centro Operativo Misto*, http://www.promolise.com/com.asp; 2002.

2. CRI. http://www.cri.it/notizie/comunicati/molise/molisebase.htm, Croce Rossa Italiana; 2002.

7 CONCLUSIONS

7.1 Conclusions

Just after the two main shocks that struck the Molise region with magnitudes of 5.4 and 5.3 (estimations by SSN), the GNDT (Gruppo Nazionale per la Difesa dai Terremoti) released a communication containing the following: *'...Infine, si ricorda che questo terremoto rappresenta una manifestazione normale della geodinamica della penisola.*[1]*'* (Press release – GNDT 4-11-2002), which reflects how prone Italian regions are to such medium/low magnitude seismic events. In normal circumstances, the magnitude of these earthquakes would cause only slight, controlled damage to seismically designed constructions. However, it is known that the building stock in many Italian earthquake-prone zones mainly consists of old masonry structures very vulnerable to earthquake shaking, which result in high damage intensities also for medium magnitude earthquakes.

The issue of earthquake protection has been viewed from different perspectives in different historical periods. In the past, the attention was mainly focused on the safety of human life, however, the more recent frameworks for earthquake protection rely essentially on economic considerations, as the overriding objectives of the modern society tend to transform human issues into quantifiable units or 'numbers'. Nonetheless, the difficulties of translating into numbers the social consequences of earthquakes are largely recognized in macroeconomic terms. Moreover, the definition of quality of life integrates nowadays a necessary minimum economic standard in conjunction with appropriate security and safety levels.

The anticipated numbers concerning the Molise earthquake, estimate damage costs at 300 million Euro [IRDC, 2002], representing 0.1‰ of the Italian GDP, which is insignificant in macroeconomic terms. However, in a regional perspective, the consequences of the Molise earthquake represent an important drawback. As a matter of fact, the economic support made available by the Italian government represents only 1/6 of the estimated costs, which implies that the remaining 5/6 should be supported by the owners and the Region. In addition to this, there is the fact that the Molise region belongs to the group of the less wealthy regions, which aggravates the already existing asymmetries between regions in Italy.

There is a need to define new strategies for earthquake protection leading to the creation of safer communities in the event of an earthquake and to the definition of the roles that various groups may play [Coburn & Spence, 2002]. These groups are: individuals and community groups (e.g. Municipalities and Regions), private corporations and organizations (e.g. insurance companies), urban authorities, national governments and international aid and development organizations. The aim is firstly to create a 'safety culture' and to clearly define duties and responsibilities. This should lead to an effective mitigation of the seismic risks, avoiding the disastrous and sometimes tragic consequences of earthquakes that repeat year after year.

These new strategies should be implemented by:

[1] Finally, it is reminded that this earthquake represents a normal expression of the geodynamics of the peninsula.

- Up-dating of the seismic zonation in Europe, which must include the information and the results from the most recent studies;
- Enforcing seismic design and re-design in seismic regions and probably providing for ‘minimum seismic design’ in regions of very low to no seismicity;
- Providing for strict controls in the design and construction phases, in order to prevent substandard structures;
- Promoting and facilitating the assessment and retrofit of existing constructions and infrastructures, including research on low-cost retrofit solutions/techniques and the creation of attractive financial solutions for seismic up-grading (political/policy issues);
- Taking full-advantage of the near-future adoption/application of the Eurocodes, particularly Eurocode 8.

In addition to these strategies there are a few aspects that should be taken into consideration, namely:

- Important structures deserve special attention;
- Historical heritage must be carefully preserved: historical buildings and churches may require some intrusive interventions to achieve improved performance;
- Quality of construction (materials, workmanship, control, etc) is also very important in ‘non-seismic regions’.

These aspects are directly related to the collapse of the School in San Giuliano, the heavy damage inflicted to most of the churches in the region and to the substandard structures in the Molise rural zones.

7.2 References

1. A. Coburn & R. Spence. *Earthquake Protection* (2nd edn), John Willey & Sons, England; 2002.
2. IRDC. *Terremoto in Molise – “Danni per 300 milioni di euro”. Le stime del presidente della Regione Molise*, Newspaper Il Resto del Carlino, November 4, 2002, http://ilrestodelcarlino.quotidiano.net/art/2002/11/04/3829113; 2002.

ANNEX A - DEFINITION OF MAGNITUDE [USGS, 2002]

Magnitude is a measure of the strength of an earthquake or strain energy released by it, as determined by seismographic observations. This is a logarithmic value originally defined by Charles Richter (1935). An increase of one unit of magnitude (for example, from 4.6 to 5.6) represents a 10-fold increase in wave amplitude on a seismogram or approximately a 30-fold increase in the energy released. In other words, a magnitude 6.7 earthquake releases over 900 times (30 times 30) the energy of a 4.7 earthquake - or it takes about 900 magnitude 4.7 earthquakes to equal the energy released in a single 6.7 earthquake! There is no beginning nor end to this scale. However, rock mechanics seems to preclude earthquakes smaller than about -1 or larger than about 9.5. A magnitude -1.0 event release about 900 times less energy than a magnitude 1.0 quake. Except in special circumstances, earthquakes below magnitude 2.5 are not generally felt by humans.

Earthquake size, as measured by the Richter Scale is a well-known, but not well understood, concept. What is even less well understood is the proliferation of magnitude scales and their relation to Richter's original magnitude scale. The idea of a logarithmic earthquake magnitude scale was first developed by Charles Richter in the 1930's for measuring the size of earthquakes occurring in southern California using relatively high-frequency data from nearby seismograph stations. This magnitude scale was referred to as ML, with the L standing for local. This is what was to eventually become known as the Richter magnitude.

As more seismograph stations were installed around the world, it became apparent that the method developed by Richter was strictly valid only for certain frequency and distance ranges. In order to take advantage of the growing number of globally distributed seismograph stations, new magnitude scales that are an extension of Richter's original idea were developed. These include body-wave magnitude, m_b, and surface-wave magnitude, MS. Each is valid for a particular frequency range and type of seismic signal. In its range of validity each is equivalent to the Richter magnitude.

Because of the limitations of all three magnitude scales, M_L, m_b, and M_S, a new, more uniformly applicable extension of the magnitude scale, known as moment magnitude, or M_W, was developed. In particular, for very large earthquakes moment magnitude gives the most reliable estimate of earthquake size. New techniques that take advantage of modern telecommunications have recently been implemented, allowing reporting agencies to obtain rapid estimates of moment magnitude for significant earthquakes.

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