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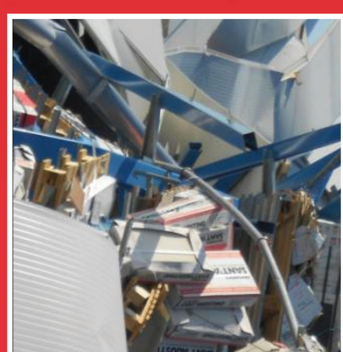
Emilia Earthquake of May 20, 2012 in Northern Italy: Rebuilding a Community Resilient to Multiple Hazards

by

Gian Paolo Cimellaro, Marco Chiriatti, Andrei M. Reinhorn and Lucia Tirca



Technical Report MCEER-13-0006

June 30, 2013

This research was conducted at the University at Buffalo, State University of New York, and the Politecnico di Torino in Italy. It was sponsored by the National Science Foundation and the European Community's Seventh Framework Programme (Marie Curie International Reintegration Actions – FP7/2007-2013 under the Integrated European Disaster Community Resilience Project).

NOTICE

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Gian Paolo Cimellaro[1], Marco Chiriatti[2], Andrei M. Reinhorn[3],
and Lucia Tirca[4]

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ICRED—Integrated European Disaster Community Resilience)

1 Assistant Professor, Department of Structural, Building & Geotechnical Engineering (DISEG) Politecnico di Torino, Italy
2. Graduate Research Assistant, Department of Structural, Building & Geotechnical Engineering (DISEG) Politecnico di Torino, Italy
3. Clifford C. Furnas Eminent Professor, Department of Civil, Structural & Environmental Engineering, University at Buffalo, State University of New York
4. Assistant Professor, Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Canada

MCEER
University at Buffalo, State University of New York
212 Ketter Hall, Buffalo, NY 14260
E-mail: *mceer@buffalo.edu*; WWW Site: *http://mceer.buffalo.edu*

ABSTRACT

A series of important seismic events occurred in Italy in the Po Valley, beginning on Sunday morning, May 20, 2012. This report describes the types and causes of damage resulting from the earthquake and the associated social and economic impact.

Funded by the National Science Foundation, a multidisciplinary team of investigators from the Multidisciplinary Center for Earthquake Engineering Research (MCEER), headquartered at the University at Buffalo, together with a team from the Politecnico di Torino in Italy, conducted post-disaster field reconnaissance to examine the impact of the earthquake on physical engineered systems and the response and recovery efforts that followed. By collecting information, the Politecnico di Torino together with MCEER is seeking to develop engineering design strategies and organizational strategies that will make the Emilia region more resilient against future earthquakes and any extreme event in general. The report presents the findings from the field reconnaissance mission and contributes to the development of a better understanding of how to cost-effectively enhance the resilience of a community against future extreme events (Bruneau et al., 2003; Cimellaro et al., 2009)

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ACKNOWLEDGEMENTS

The work in this report is sponsored by MCEER (formerly the Multidisciplinary Center for Earthquake Engineering Research), and by the European Community's Seventh Framework Programme - Marie Curie International Reintegration Actions - FP7/2007-2013 under the Grant Agreement n° PIRG06-GA-2009-256316 of the project ICRED - *Integrated European Disaster Community Resilience*. Any opinions, findings and conclusions or recommendations expressed in this report are those of the author(s) and do not necessarily reflect those of the Multidisciplinary Center for Earthquake Engineering Research (MCEER), the National Science Foundation (NSF), the State of New York (NYS) or the University at Buffalo.

MCEER Reconnaissance Team:

- Andrei M. Reinhorn (structural engineer)
- Gian Paolo Cimellaro (structural engineer)
- Marco Chiriatti (M.S. student)
- Luci Tirca (earthquake engineer)
- Fabrizio Bunino (surveyor)
- Vittorio Giraud (geologist)

The MCEER reconnaissance team arrived in the earthquake-affected area on May 25, 2012, four days after the event, to survey damage, interview experts, and collect data. The team presented preliminary findings at a seminar in Buffalo.

We gratefully acknowledge the following Institutions and sources for their contributions:

- Piedmont Region
- Civil Protection – Piedmont Region
- University at Buffalo, State University of New York
- Civil Protection regione Emilia (Dott. Pignone)
- INGV

Field reconnaissance team: from left, Cimellaro, Bunino, Giraud

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SECTION 1
INTRODUCTION

1.1 Characteristics of the Earthquakes

A series of important seismic events occurred in Italy in the Po Valley, beginning on Sunday morning, May 20, 2012. The events began at 04:03:53 local time (02:03:53 UTC) with a strong earthquake with a magnitude of M_w 5.9. The epicenter was located in Finale Emilia (44°50'N 11°17'E) in the province of Modena. On Tuesday, May 29, at 09:00:03 local time (07:00:03 UTC), another strong earthquake with a magnitude of M_w 5.8 occurred in the same seismic region as the previous event (44°85'N 11°09'E) and this time, it was felt throughout northern Italy. The earthquake was followed by three major aftershocks that same day: one at 12:55 local time with a magnitude of M_w 5.4, and two more at 13:00 local time with magnitudes of M_w 4.9 and 5.2. These aftershocks were followed by a swarm with variable magnitudes. Figure 1 indicates the geographic location of the epicenters in the Po Valley.

Temporal analysis of the seismic swarm shows a shift to the west of the epicenters after the first phase of the sequence.

All of these earthquakes had a devastating effect on the towns near the epicenter, resulting in 27 fatalities (22 from the collapses, 3 from heart attack or sudden illness, and 2 from injuries). The collapse of industrial structures was the major contributor to life hazard, as most people were working when the second earthquake struck.

The town centers most affected by earthquakes were: Alberone, Camurano (Meddola), Canaletto, Finale Emilia, Galeazza, Mirandola, San Felice sul Panaro, and San Carlo (INGV). In these places, overturning of objects inside houses was observed.

Many low-rise unreinforced masonry structures, which are the most vulnerable buildings, suffered major damage that made them unfit for use. Some monuments were also damaged, resulting in huge losses to the region's historical heritage. Chimneys frequently fell from the rooftops of residential buildings, but, in general, new buildings were not damaged, while many abandoned houses in the countryside collapsed.

The affected area is a seismogenic area next to the regions of the Apennines, classified at level 3 on the reference scale of earthquake risk. The complex system of faults that branches off in the low plains of Emilia is the dorsal of Ferrara, which connects to the west with that of Mirandola.

The African plate pushes northward to the Po Valley, where the crustal rocks deform and absorb deformation energy until the system becomes unstable and creates mechanical waves. The earthquake activated a seismogenic zone which released energy through earthquake in an area which is classified in Italy as one of low seismicity.

Figure 1-1 Location of the epicenter of the M_w 5.9 earthquake in Emilia, Italy

1.2 Seismic Sequence and Characteristics of Foreshocks and Aftershocks

The main earthquake of May 20 was preceded by a first event with a magnitude of M_w 4.1 in the same place at 01:13 local time on Saturday, May 19. The strong earthquake of 4:03 local time began a long seismic sequence, which continued in the following weeks with more than 2,200 aftershocks, seven of which had magnitudes of M_w >5 (Table 1-1). The map of the epicenters of seismic events that have occurred since May 20, 2012 in the region is shown in Figure 1 2.

Table 1-1 Main Earthquakes

Table of earthquakes with M_w >5 (updated on July 13, 2012)						
date	UTC (local time)	latitude	longitude	depth	magnitude	source
20/05/2012	02:03:52 (04:03:52)	44.889	11.228	6.3	5.9	iside.rm.ingv.it
20/05/2012	02:07:31 (04:07:31)	44.863	11.370	5.0	5.1	iside.rm.ingv.it
20/05/2012	13:18:02 (15:18:02)	44.831	11.490	4.7	5.1	iside.rm.ingv.it
29/05/2012	07:00:03 (09:00:03)	44.851	11.086	10.2	5.8	iside.rm.ingv.it
29/05/2012	10:55:57 (12:55:57)	44.888	11.008	6.8	5.3	iside.rm.ingv.it
29/05/2012	11:00:25 (13:00:25)	44.879	10.947	5.4	5.2	iside.rm.ingv.it
03/05/2012	19:20:43 (21:20:43)	44.899	10.943	9.2	5.1	iside.rm.ingv.it

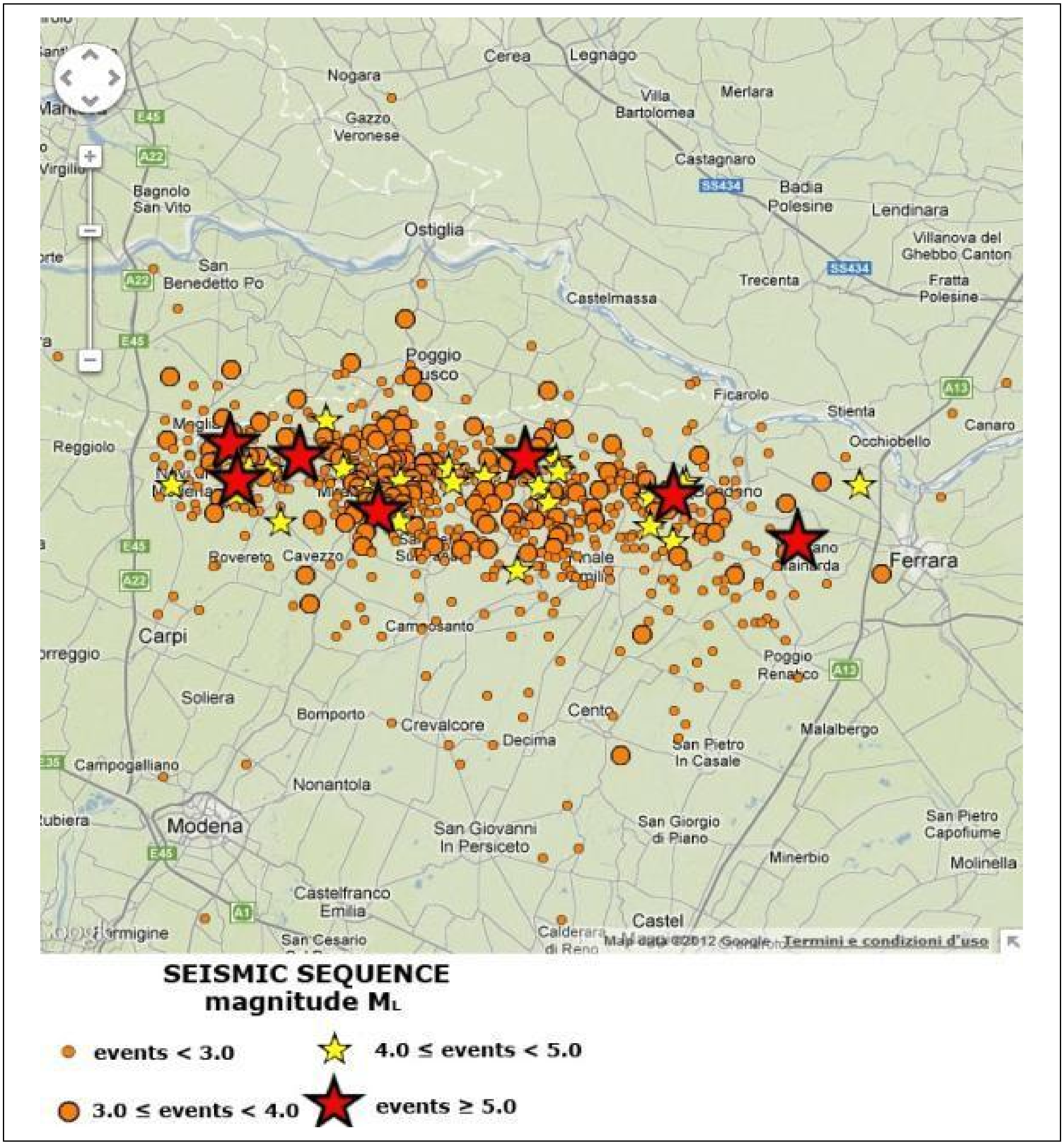


Figure 1-2 Map illustrating the epicenters of seismic events that have occurred since May 20, 2012 in the region hit by the earthquake (INGV 2012)

All these events were recorded and analyzed by the recording station network RAN (rete accelerometrica nazionale) that monitors the entire Italian territory. The nearest stations that recorded the event are shown in Figure 1-3.

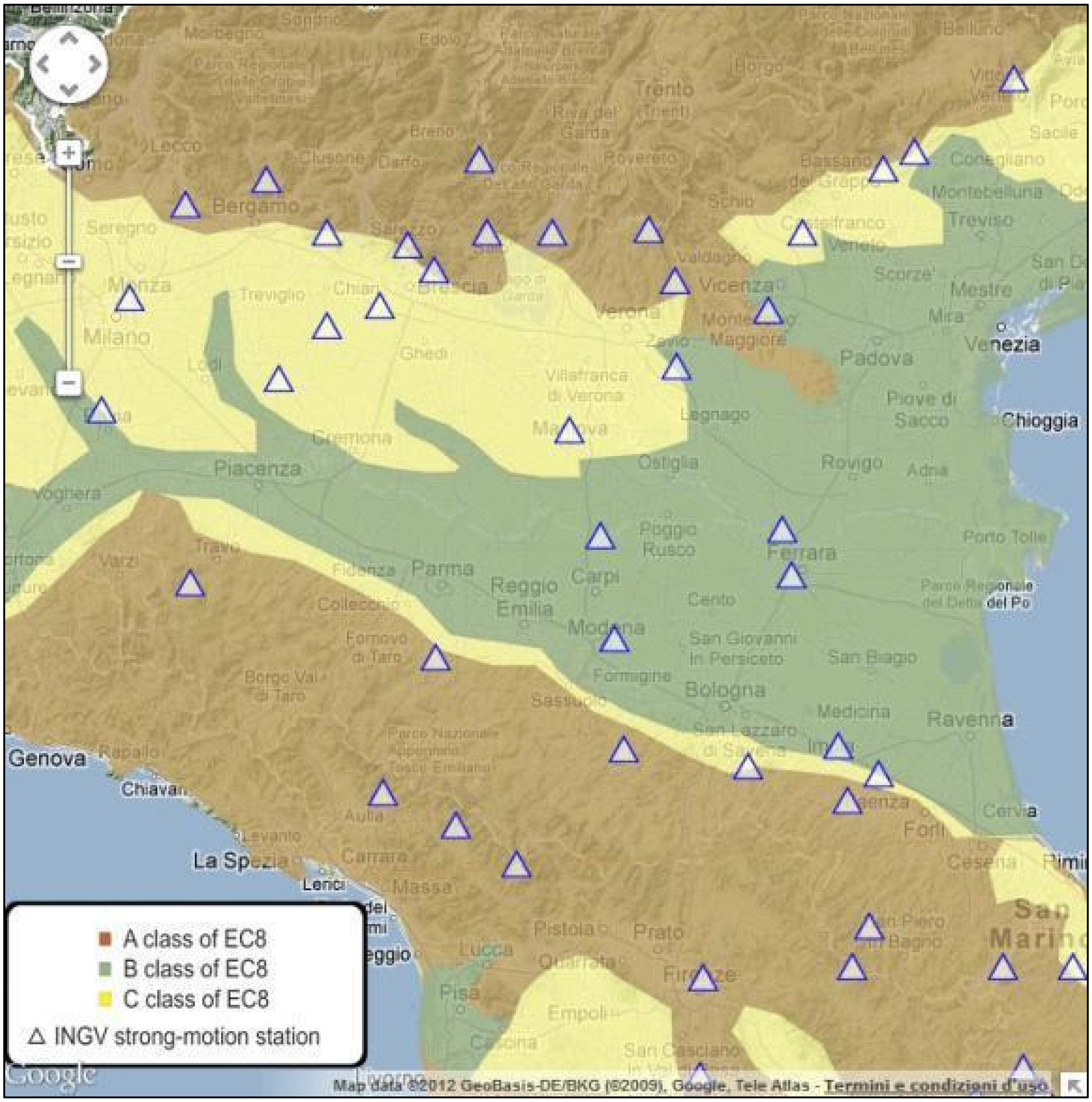


Figure 1-3 Recording station network (INGV 2012)

In order to understand the mechanism that generated the earthquake, focal solutions were calculated. The focal solution, in fact, helps to indicate the three geometric parameters that generated the earthquake: strike, dip, and slip (Figure 1-4). In Figure 1-5, focal mechanisms are represented through colored balls called beach ball diagrams. These spheres are the projection, on a horizontal plane, of the lower half of an imaginary sphere called the focal sphere, which contains the hypocenter of the earthquake. Two lines divide the sphere into white and colored areas--the areas of compression are colored while the tensional ones are left white. One of the lines represents the fault that generated the earthquake; the other is the plane orthogonal. The focal mechanism and magnitude have been calculated for the main earthquakes in the Po Valley and the results are shown in Figure 1-5.

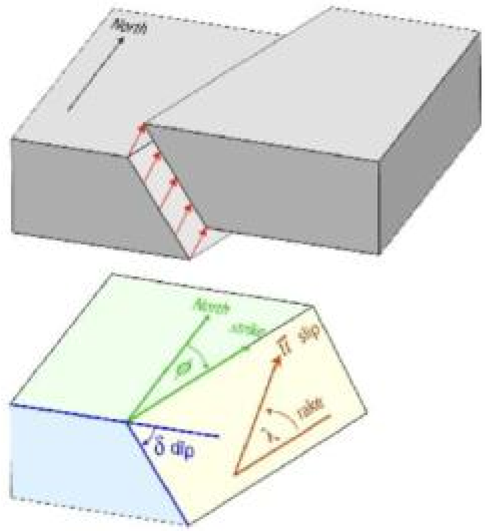


Figure 1-4 Focal solution scheme

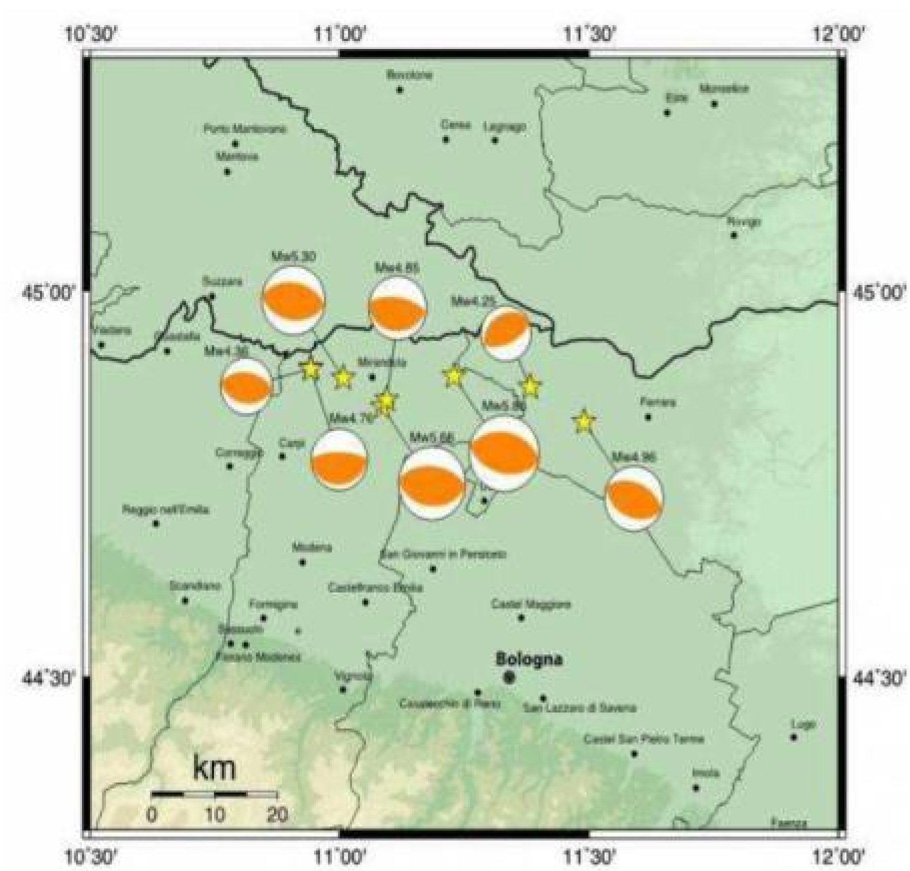


Figure 1-5 Map illustrating the location and focal solution of earthquakes with $M_w > 4$ (INGV 2012)

In Figure 1-5, the yellow stars indicate the epicenters of earthquakes and the beach ball plot represents the focal mechanisms. The position of the white zone in every plot suggests a compression movement in the north-south direction. All previous earthquakes have occurred on fault planes oriented east-west.

These results suggest that the mechanism of the earthquakes that struck Emilia is represented by the pattern in Figure 1-6 and the orientation of this mechanism is consistent with the movement of a reverse fault positioned beneath the Po Valley.

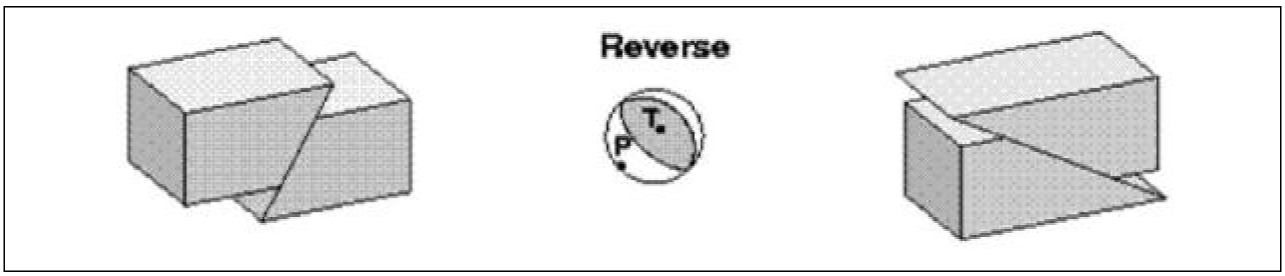


Figure 1-6 Reverse fault mechanism

Thanks to the collaboration between ASI (Agenzia Spaziale Italiana), CNR-IREA (Consiglio Nazionale delle Ricerche-Istituto per il Rilevamento Elettromagnetico dell'Ambiente) and INGV (Istituto Nazionale di Geofisica e Vulcanologia) to provide support for civil protection, radar images were acquired by the Italian constellation COSMO-SkyMed. Using these radar images made it possible to measure the ground deformation of the zone affected by the earthquakes. The technique used to make these types of analyses is called differential interferometry, or DInSAR. Two radar images were used, one captured before and a second one immediately after the earthquake. An interferogram can then be made from these images; that is, a displacement map of the soil in terms of phase differences between the signals of the two radar images. The succession of colors indicates a shift of the land surface of about 1.5 cm.

Figure 1-7 represents the interferogram from the dates May 27 and June 4. It shows some concentric fringes that indicate a displacement of the soil due to the movement in the depth of a seismogenic fault. This deformation is continuous in the space and is in agreement with the fact that the fault line displaces the earth's crust in depth but does not reach the earth's surface.

A shift of about 12 cm of the soil corresponding to the main rupture plane dipping to the south is shown in Figure 1-8. This lifting has the shape of a spoon with a smaller gradient to the east. A lowering of the ground in the zone of Finale Emilia is also apparent; however, it has a lower intensity that can be explained by the phenomena of surface movements of the water in the subsoil.

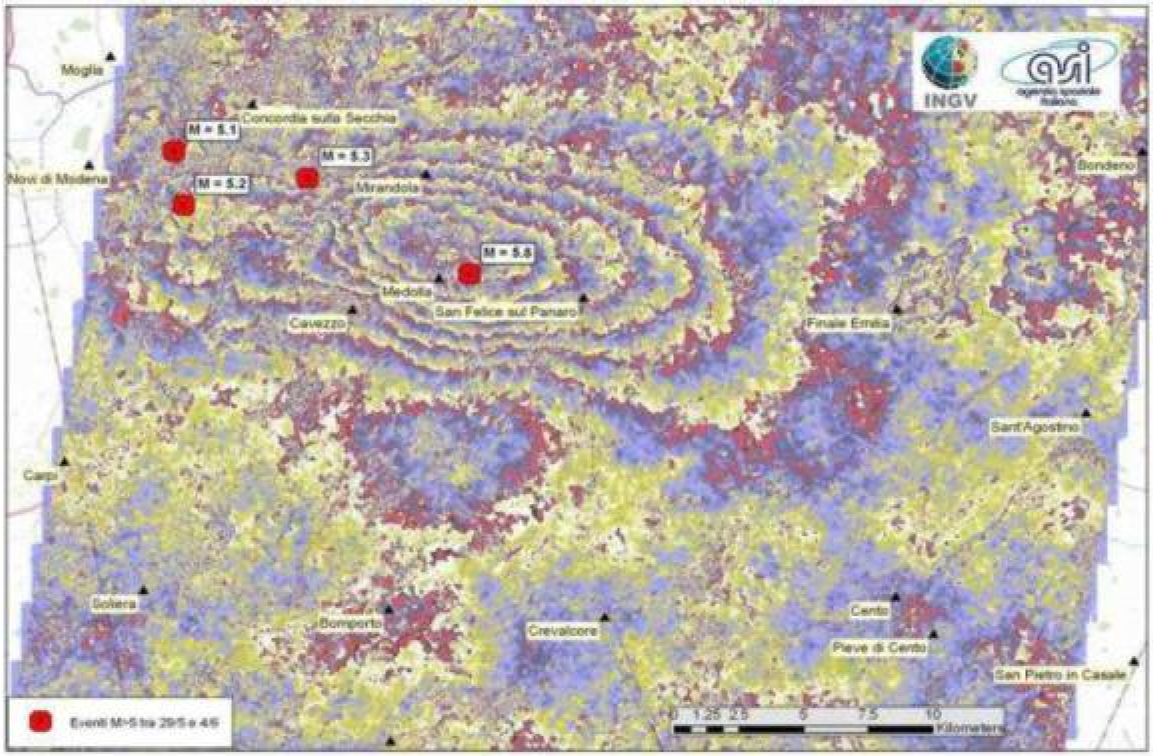


Figure 1-7 Interferogram from May 27 and June 4 (INGV 2012)

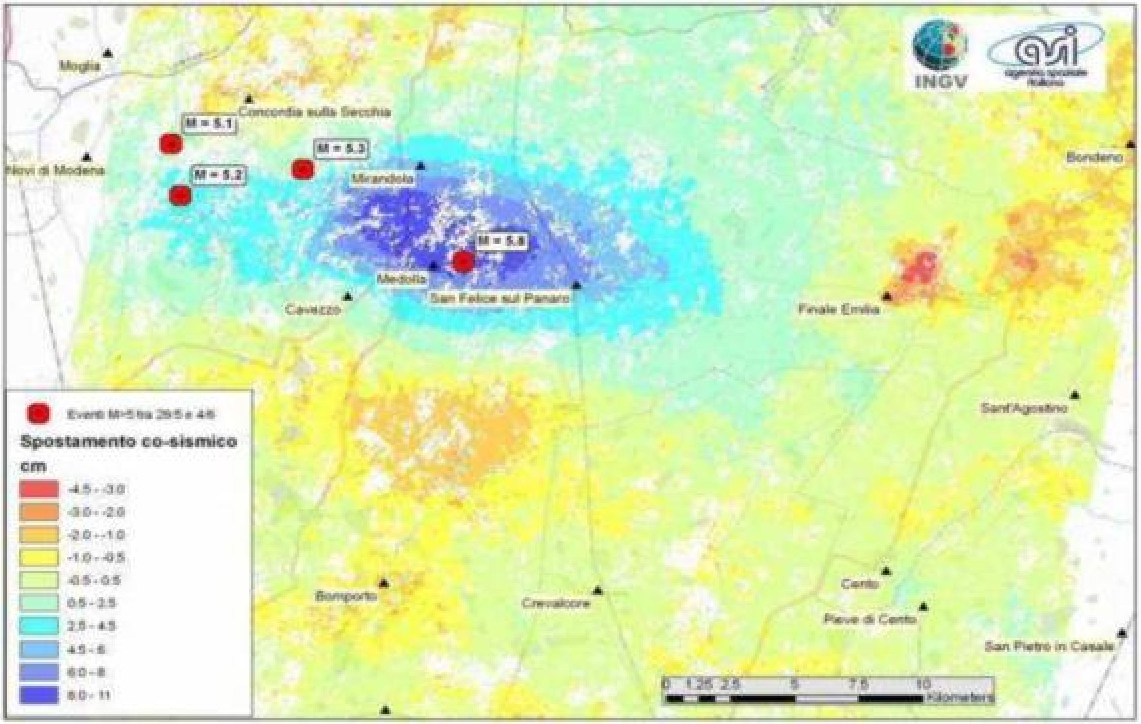


Figure 1-8 Displacement map of the soil (INGV 2012)

1.3 History of the Po Valley

The Po Valley is a geographical region of Southern Europe. It is included in the catchment of the River Po, including its Venetic extension. It runs from the Western Alps to the east, up to the Mediterranean. The Alps and Alpine foothills bounding the Po Valley slope along the north, west and south-west, and the south side is closed by the chain of the Apennines, which extends with an area of approximately 46,000 km^2. The presence of the Po River and its tributaries is the cause of the floodplain, with significant constraints due to glaciations and the phenomena of differential subsidence at buried synclines and anticlines.

The altitude of the valley varies from the river's origin at about 2,100 m to 4 m below sea level in the delta around Ferrara. Therefore, it can be divided into high and low plains. Also, the land and vegetation are different in the two areas.

From a historical point of view, the Etruscan domination left city names such as Parma, Ravenna, Felsina, and the ancient name of Bologna as part of their cultural heritage. After the Etruscan domination, there have been many other conquerors from the Celtic horde to the Western Roman Empire. Until the present day, a large number of cultures have left their mark on these beautiful lands. Each of them has contributed to the importance of this area. After World War II, the Padan area took the lead in the Italian economic miracle of the 1950s and 60s.

Also of significance is the contribution of the Po Valley to the production of some traditional Italian food that is widely known throughout the world. Parma, for example, is related to the production of ham, while Modena is famous for the production of balsamic vinegar using ancient methods. Two very important cheeses, Parmigiano Reggiano and Grana Padano, are produced throughout the plain.

Today, Modena is the home of Ferrari, a company known worldwide for its production of luxury cars.

1.4 Report Organization

This report contains eleven sections and a list of references. Section 1 describes the seismic sequence of the earthquake, and section 2 the tectonics and historical seismicity of the region. Section 3 analyzes the ground motion histories and presents seismic hazard analyses. Section 4 gives a general overview of observed damage, while Section 5 describes the geotechnical effects. Section 6 discusses the behavior of warehouse and industrial shed structures, while Section 7 describes the impact of the earthquake on other structures. Section 8 offers a case study of the seismic performance of Concordia, and Section 9 deals with infrastructure damage. Section 10 describes the societal impacts, and Section 11 presents the main conclusions of this report.

SECTION 2
TECTONICS AND HISTORICAL SEISMICITY

2.1 Tectonic Setting in Central Mediterranean

The convergence of the Eurasian plate at the north and the African plate at the south is the cause of a complex tectonic environment in the Central Mediterranean.

This geodynamic evolution process started in the Late Cretaceous period more than 100 million years ago. By the end of the Oligocene epoch, the Alpine orogeny had been developed as a product of continental margins along the north Adriatic Sea. The Alps and Dindarides are the result of the subduction of the stiff Adriatic micro-plate. This movement is also the cause of the uplifting of plateaus in the Balkan Peninsula, as well as in Corsica and Sardinia (Rosenbaum et al 2001).

From that time, the sinking of the oceanic seafloor of the Ionian Sea and the retreat of the subduction zone towards the southeast have been the principal geodynamic evolutions of the Central Mediterranean. In the Early Miocene era, Calabria was attached to Sardinia and the Tyrrhenian Sea was replaced by the Tethys Ocean. During the Middle Pliocene epoch, the eastward rollback of the vertical trench separated Calabria from Sardinia and by the early Pliocene epoch, the advance of the Calabrian Arc, with subduction ahead and extension behind, consumed the old sea floor. Behind it, back-arc spreading created the volcanic arc of the Eolian Islands. The northern part of the subduction zone collided with the Adriatic, creating the north segment of the Apennine Mountains. Today, the collision of the subduction zone completes the Apennines range along the length of Italy, with Calabria wedged between Sicily and Peninsular Italy.

The current geodynamic model for the Central Mediterranean is described by the juxtaposition of compression and extensional tectonic activity in the area. Compression deformation structures are present in the Adriatic Sea due to the extension of the crust of the overriding plate in Tyrrhenian Sea.

A local geodynamic model confirms that the current back-arc spreading is the principal cause of tectonics in Italy, and that thrust faults that built up the Apennines are now being reactivated as extensional normal faults.

Today, the active faults in the Italian territory are distributed on the east side of Sicily, throughout the Calabria arc and along the entire Apennine range. Also, in some Alpine sectors, active faults exist. A summary of all these faults is presented in Figure 2-1.

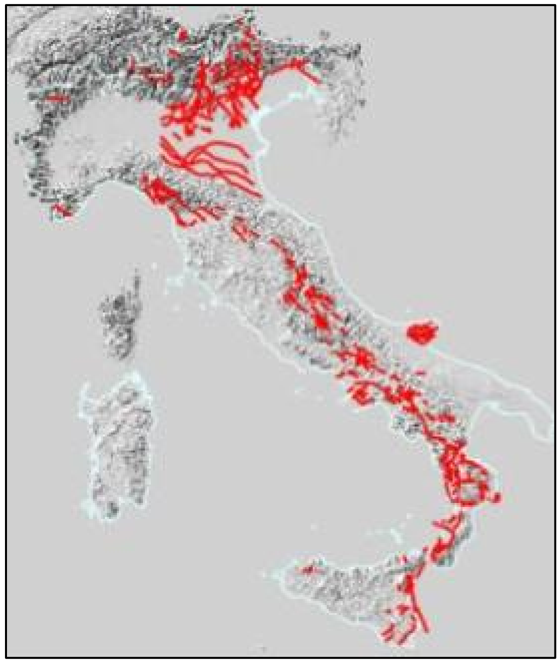


Figure 2-1 Map of the fault locations in Italy

2.2 Tectonic and Geological Setting in Emilia

In relation to the national territory, the affected area from the epicenter of the main shock can be defined as one of medium seismicity (Rossetto et al., 2012). The acceleration on the rocks corresponding to a return period of 475 years is between 0.125g and 0.15g. According to the United States Geological Survey or USGS (a scientific organization that provides information on natural hazards), the maximum acceleration recorded at 10 km from the epicenter was 0.25g, with an associated speed of about 15m/s.

In Figure 2-2, the epicenter is located on the Italian seismic hazard map, while in Figure 2-3, contour lines represent the recorded accelerations. These data were recorded by the USGS.

The ongoing seismic sequence is at the northern edge of the Apennine Mountains. This area is characterized by buried compressive tectonic structures, called the front of Ferrara, and placed below the recent sediments of the Po Valley.

In accordance with current seismotectonic knowledge of the area, the focal mechanism of the most significant shock reveals mechanisms of the compressive type.

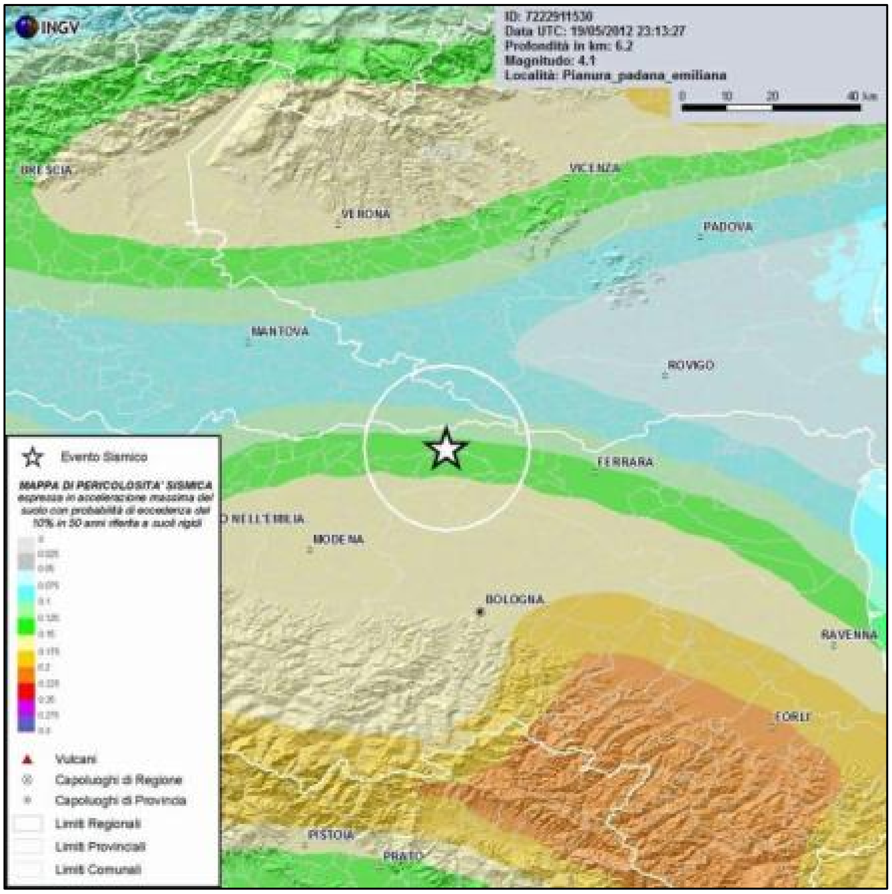


Figure 2-2 Italian seismic hazard map (INGV, 2012)

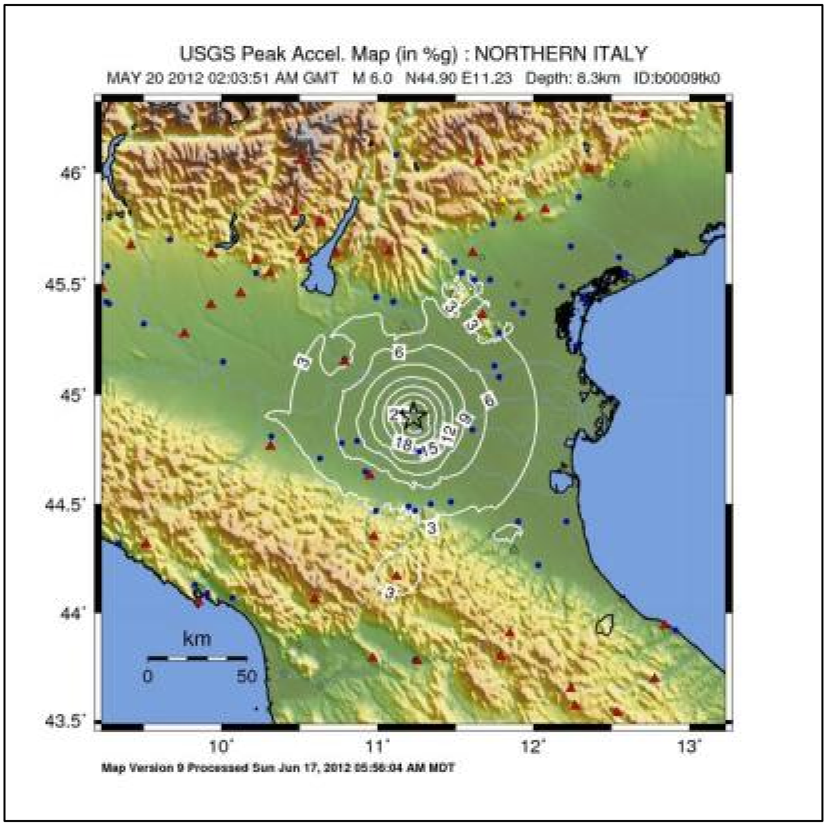


Figure 2-3 PGA contour map (INGV, 2012)

In particular, the focal mechanism of the earthquake shows a main maximum compression in a north-south direction and fault planes oriented from east to west.

By overlaying different maps, a close correspondence between the map of epicenters and the trend of the faults can be seen. The map of the epicenters shows a spatial distribution in the WNW-ESE direction. This orientation is consistent with the trend of regional structures like the Apennine.

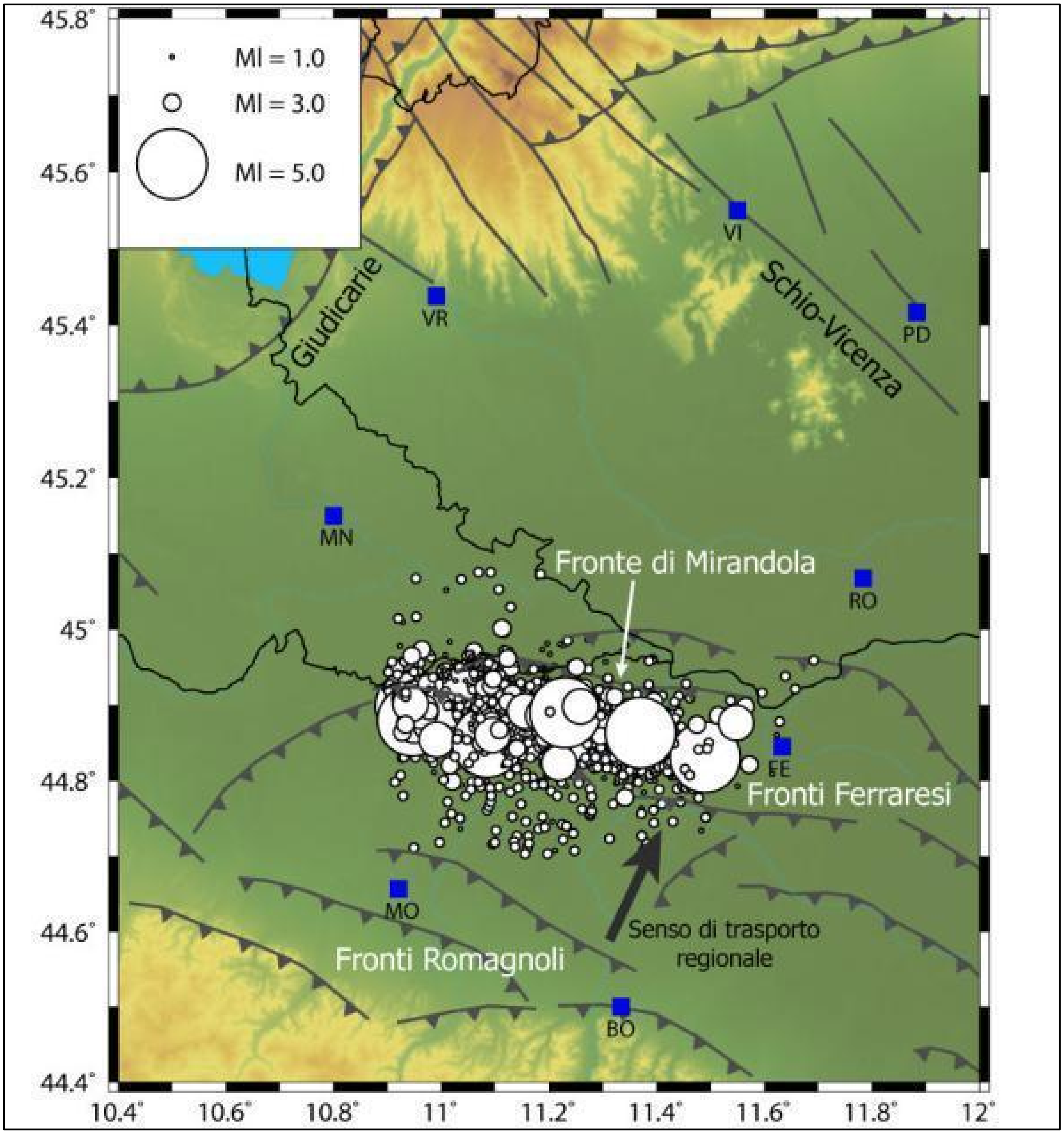


Figure 2-4 Map of active faults near Mirandola. Features on fault lines are oriented towards the hanging wall. The big circles indicate the epicenters of major events (M_w > 4) associated with the seismic sequence of the May 20 Earthquake (INGV, 2012b)

It can be seen that the major earthquakes of the swarm have originated from depths between 5 and 10 feet. They are also aligned along the axis of the currently active tectonic structure from the seismic point of view (Figure 2-4).

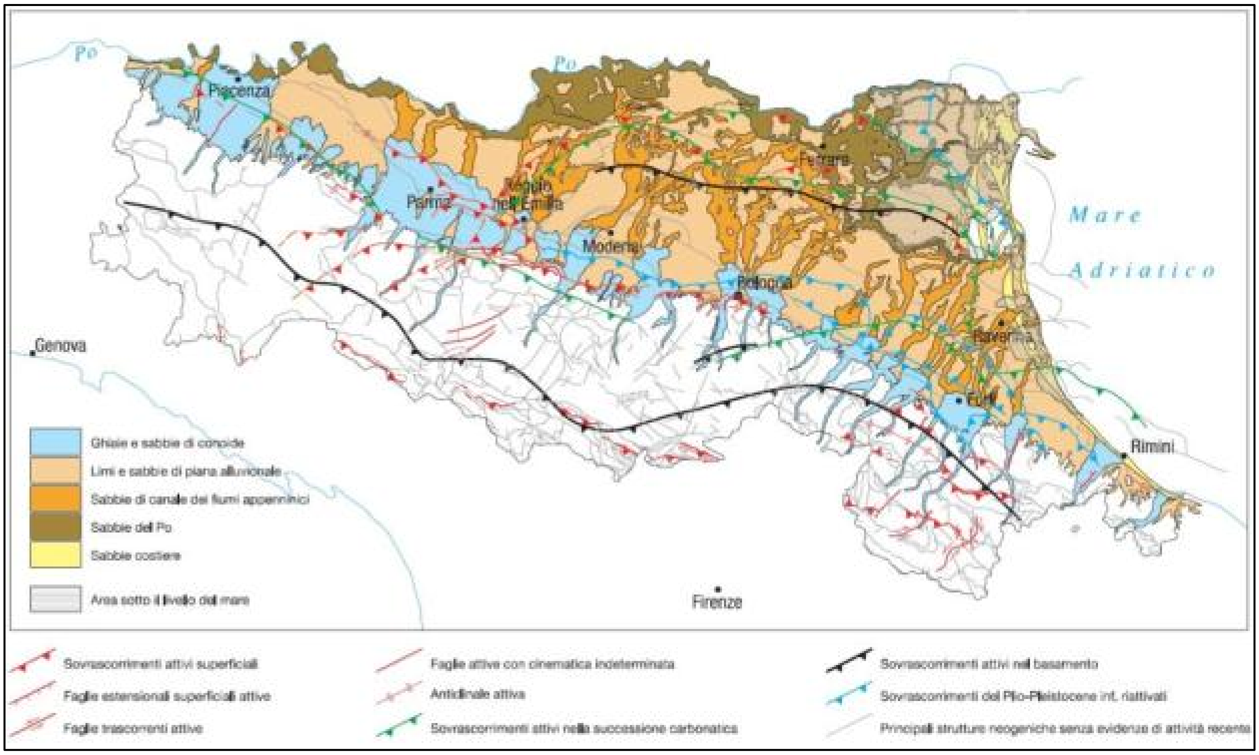


Figure 2-5 Map of the alluvial deposits (Emilia-Romagna regional archive)

From a geological point of view, the Po Valley is characterized by different ancient alluvial deposits. Figure 2-5 represents a detailed map of the alluvial deposit together with a map of the active fault. One can see the presence of different deposits: light blue indicates gravel and alluvial fan sand; pink, the silts and sands of the floodplain; orange, the channel sands of the Apennine rivers; brown, the sands of the Po; and yellow, the coastal sands. The presence of a net dashed line indicates the area below sea level.

The seismogenic structure of Mirandola is the cause of the recent earthquakes. It has a maximum depth of 7.6 km and is about 8.7 km long. All the recorded earthquakes are associated with shallow focal depths, long periods and small amounts of released energy (Boccaletti et al., 1985). Figure 2-6 represents the seismogenic structure of Mirandola.

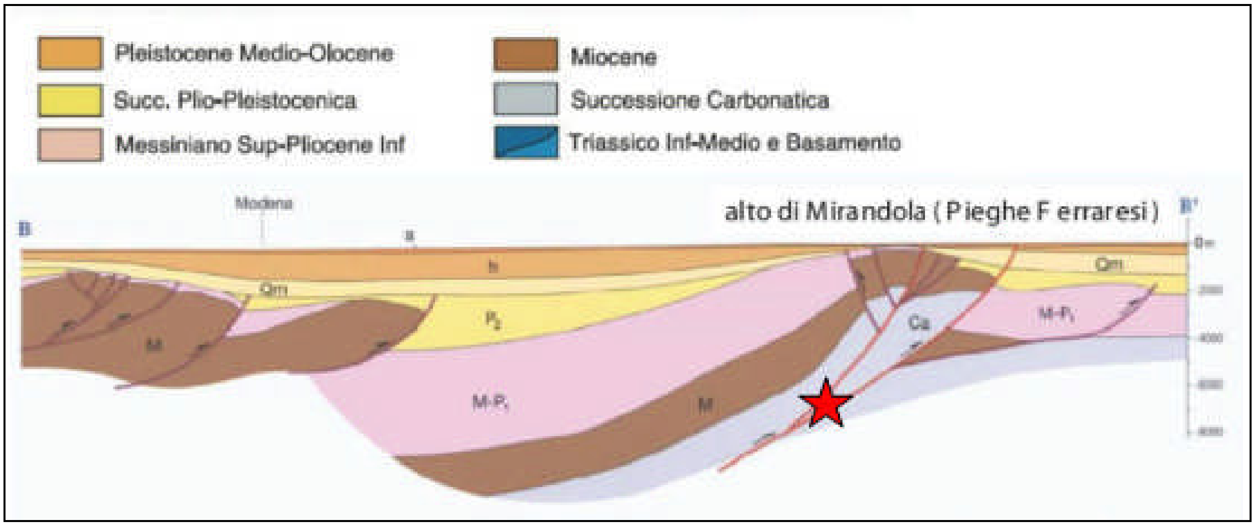


Figure 2-6 Profile of the seismogenetic source of the May 20 earthquake (INGV, 2012b)

2.3 Historical Seismicity

Without the memory of destructive events of the past, the perception of potential risk is also lost.

By the twelfth century, Ferrara was an important center of culture. Many memoirs have been preserved from that time until today.

Some historical records report that in the Duchy of Ferrara, a strong earthquake occurred between 16 and 17 November, 1570. The swarm lasted until 1574, and is thought to have produced more than two thousand aftershocks, most of them in the first three months following the earthquake. About 40% of homes were damaged, as well as almost all public buildings. Churches suffered partial collapses, damage, disconnections of load-bearing walls, and serious disruptions. It was a disaster from which the city and its dynasty of rulers, the Este, would not recover.

Several explanations were given for this event. The earthquake was interpreted by some as a sign of divine disfavor towards the sovereignty. Theories of natural philosophers (scientists of the time) were undermined, because they thought that an earthquake would not have happened in the plain and could not occur in winter. The population was forced to live in makeshift shelters, and various social classes were forced to cohabit. This situation caught the imagination of contemporaries, and many journals and reports were written about these events.

Pope Pius V accused the ducal regime of licentiousness in an attempt to delegitimize the dukes and break their privileged relations with the French crown. In this context, several treatises were written on the earthquake of Ferrara. A treaty bound the earthquake to reclamation of large areas of the duchy. The architect Pirro Ligorio wrote '*de diversi terremoti'*. This book contained the first provisions for building earthquake-resistant buildings. It also argued that earthquakes were always happening, and to support this assertion, Ligorio began to write down all the seismic events that occurred during his life.

Ligorio's writings can be considered the precursor of the methodology used today for the construction of buildings that have to withstand seismic input.

In more recent times, Toscani et al. (2008) identified specific seismogenic sources in Emilia Romagna. These results are shown in Figure 2-7, where the yellow boxes represent the sources: Ferrara is marked as 'FE' and Bologna as 'Bo'. These relate to six known earthquakes, including the 1570 earthquake, which struck almost directly under Ferrara, as well as the 1505 and 1929 earthquakes near Bologna, and the 1688 and 1781 earthquakes near Forlì.

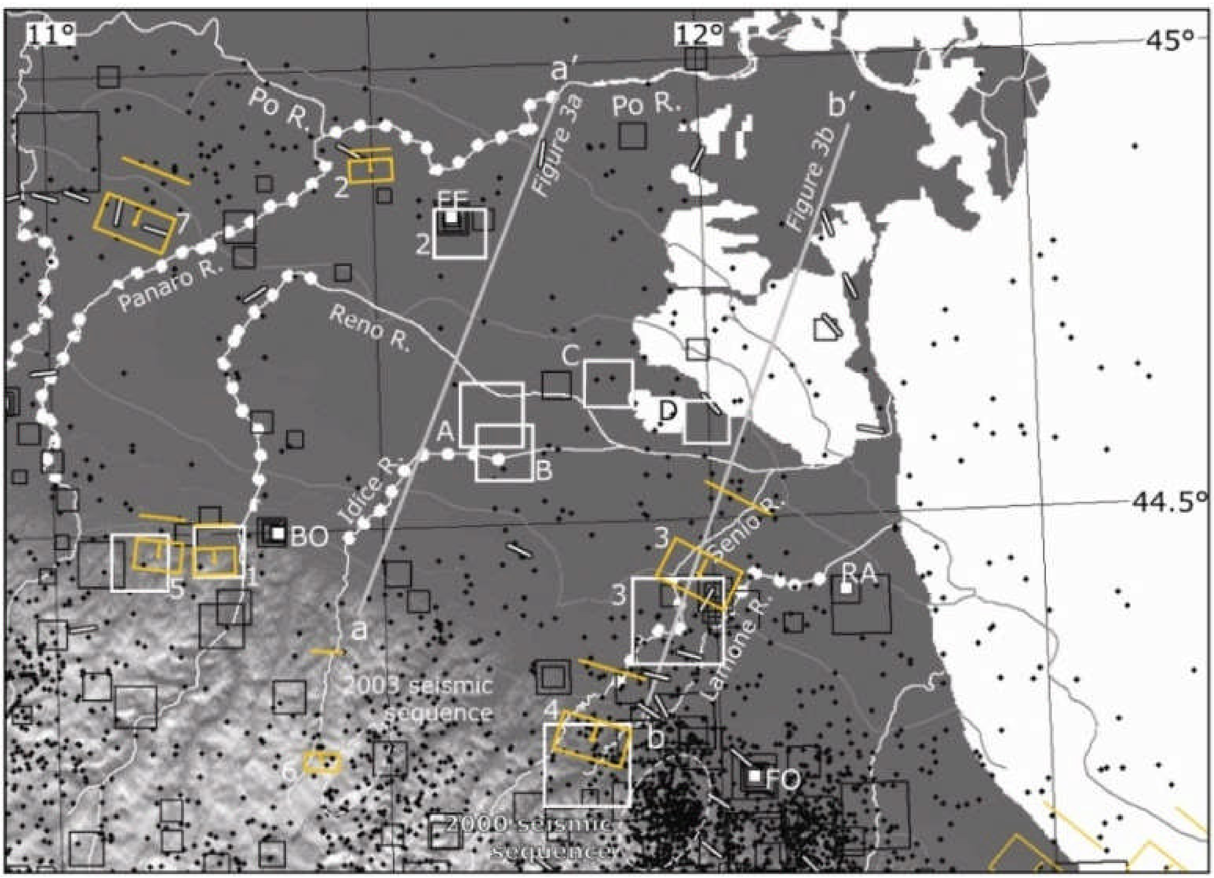


Figure 2-7 Seismogenic source identified by Toscani et al. (2008)

On the basis of these data, Toscani suggests a maximum magnitude for future events in this region of around $M_w = 5.8$; which is a value very similar to that recorded in recent earthquakes.

A more recent study of the historical seismicity of the Po Valley was done by Rovida in 2011 (Meletti et al., 2012). They analyzed some recent catalogs to gather historical information about seismic events. Their results are shown in Figure 2-8.

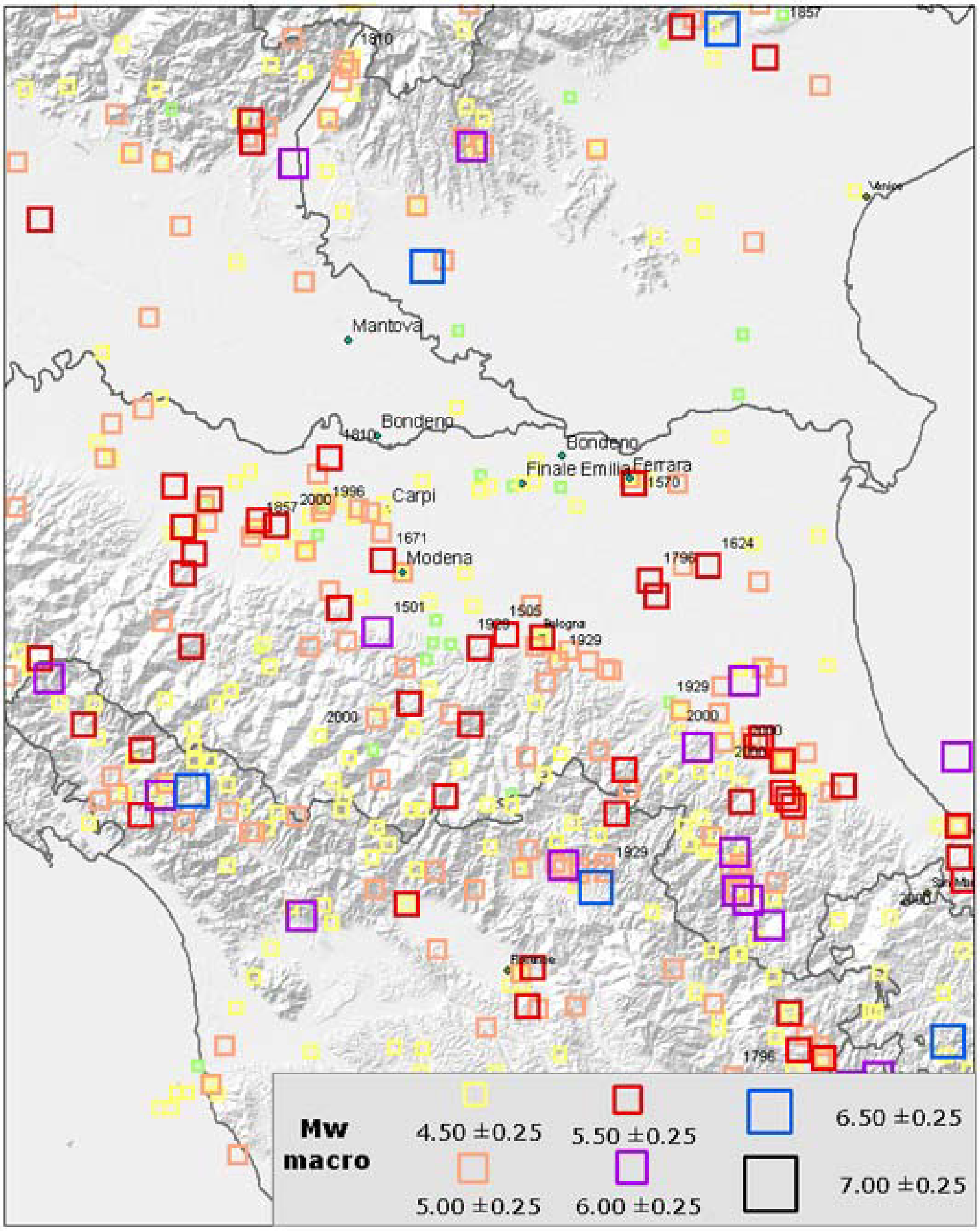


Figure 2-8 Historical seismicity of the Po Valley (Rovida et al., 2011)

There is also a more recent INGV instrumental catalog. Figure 2-9 shows that since 2005, there has been a belt of earthquakes along the northern Apennines, although these are predominantly more than 50 km from the May 2012 epicenters. These earthquakes have been of low magnitude and shallow depth.

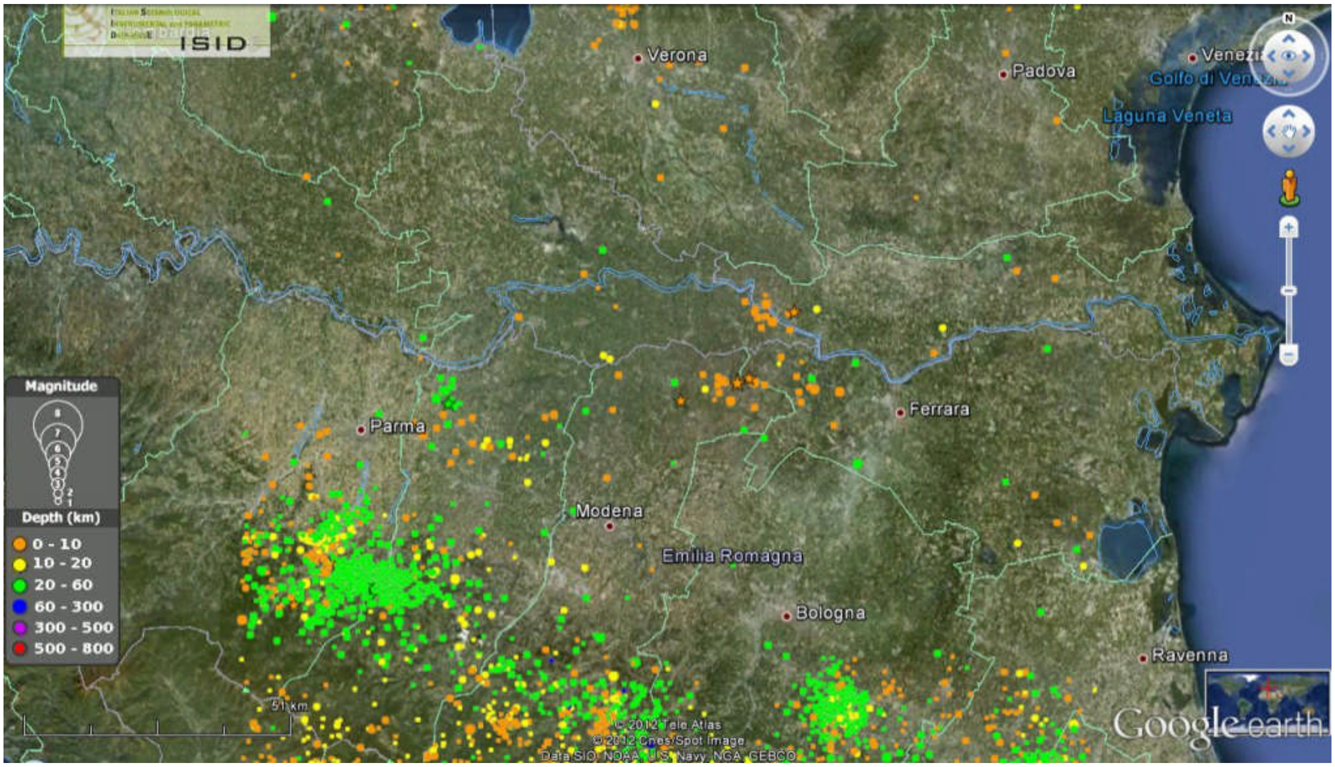


Figure 2-9 Instrumental earthquake catalog (INGV, 2012)

The USGS NEIC catalog (2012b) dates back to 1973 and is shown in Figure 2-10 for M_w > 4.0. Within a radius of 100 km from the May 20 epicenter, there have been 141 such earthquakes in the last 39 years. In this period, only ten earthquakes had M_w>5.0 and the most recent was on December 23rd 2008, 30 km south of Parma, with M_w > 5.4.

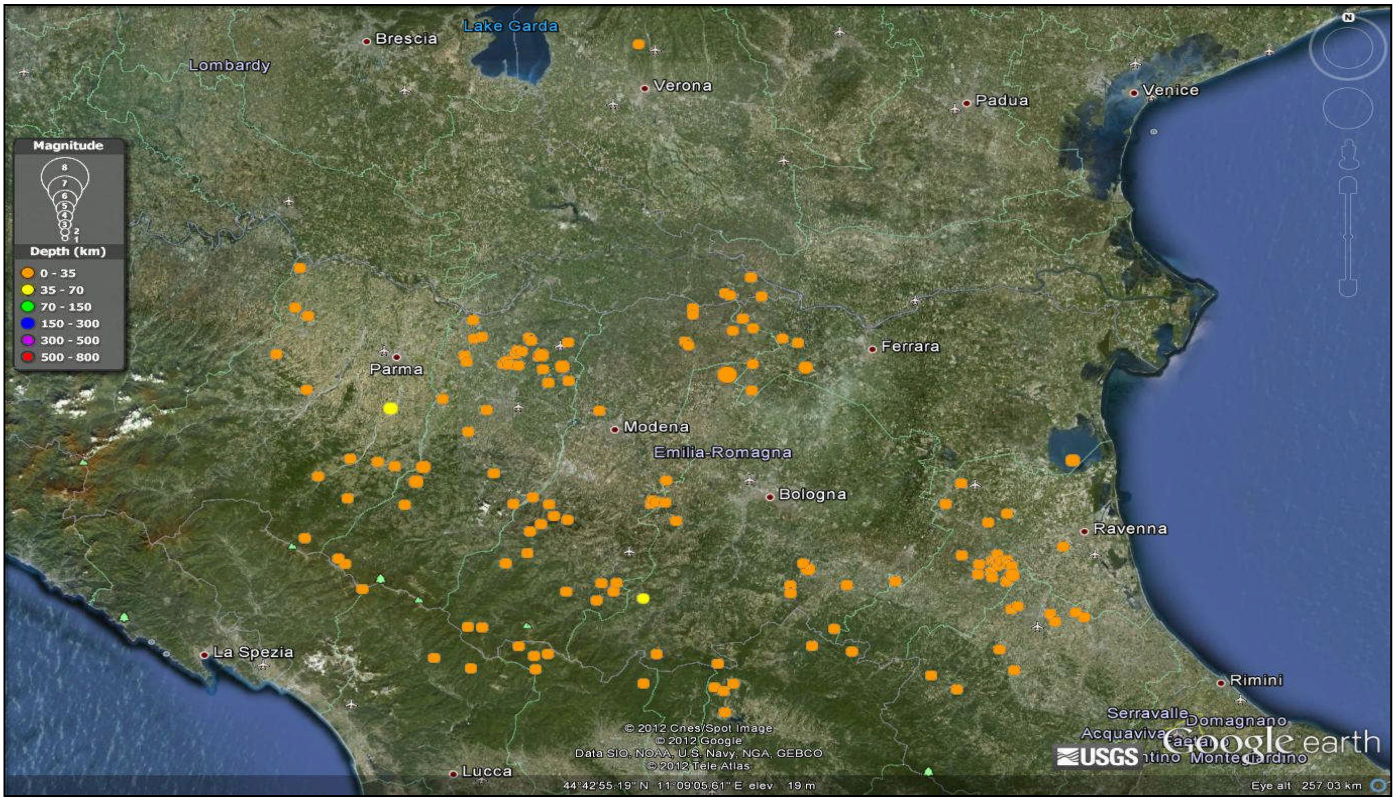


Figure 2-10 USGS NEIC earthquake catalog 1973-2012 for M_w >4 (USGS 2012)

SECTION 3
GROUND MOTIONS AND SPECTRAL ORDINATES

3.1 Recording Stations

A network of 388 recording stations – RAN (Rete Accelerometrica Nazionale) – monitors the Italian territory. Every station is equipped with digital and analog strong motion instruments. This is a project managed by the Italian Department of Civil Protection (DPC) and the recorded data are available on the Internet (*http://ismd.mi.ingv.it/ismd.php*).

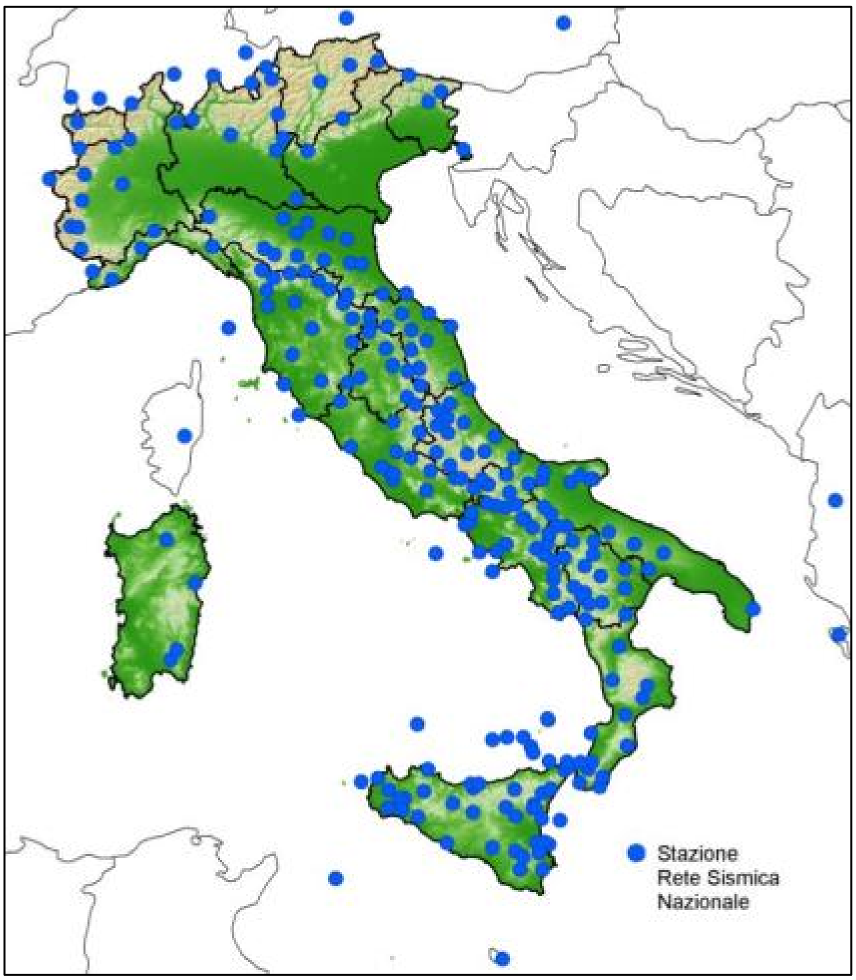


Figure 3-1 Italian seismic network

The seismic sequence in the Po Valley was recorded by many stations as represented in Figure 3-2. All the ground motion time-histories and spectral ordinates are available through

ITACA (2012), the Italian Accelerometric Archive (http://itaca.mi.ingv.it/ItacaNet/) (Working Groupp ITACA, 2008). Table 3-2 lists the main events:

Table 3-1 List of main events (ID only present for the events examined in the report)

Date (GMT)	Time	Long	Lat	Depth	ML	AGY	ID
120520	020352	11.230 E	44.830 N	6.30	5.9	INGV-CNT	120520020352
120520	020630	11.189 E	44.886 N	7.70	4.8	INGV-CNT	
120520	020731	11.370 E	44.863 N	5.00	5.1	INGV-CNT	
120520	021146	11.370 E	44.840 N	7.80	4.3	INGV-CNT	
120520	021242	11.220 E	44.820 N	20.40	4.3	INGV-CNT	
120520	030250	11.100 E	44.860 N	10.00	4.9	INGV-CNT	
120520	091321	11.241 E	44.879 N	3.10	4.2	INGV-CNT	
120520	131802	11.490 E	44.831 N	4.70	5.1	INGV-CNT	
120520	173714	11.380 E	44.880 N	3.20	4.5	INGV-CNT	
120523	214118	11.251 E	44.868 N	4.80	4.3	INGV-CNT	
120527	181845	11.158 E	44.882 N	4.70	4.0	INGV-CNT	
120529	070003	11.090 E	44.850 N	10.20	5.8	INGV-CNT	120529070003
120529	082551	10.943 E	44.901 N	3.20	4.5	INGV-CNT	
120529	082723	11.106 E	44.854 N	10.00	4.7	INGV-CNT	
120529	105557	11.008 E	44.888 N	6.80	5.3	INGV-CNT	120529105557
120529	110002	10.950 E	44.873 N	11.00	4.9	INGV-CNT	
120529	110025	10.947 E	44.879 N	5.40	5.2	INGV-CNT	
120531	190404	10.980 E	44.891 N	8.70	4.2	INGV-CNT	
120603	192043	10.943 E	44.899 N	9.20	5.1	INGV-CNT	
120612	014836	10.888 E	44.880 N	10.80	4.3	INGV-CNT	

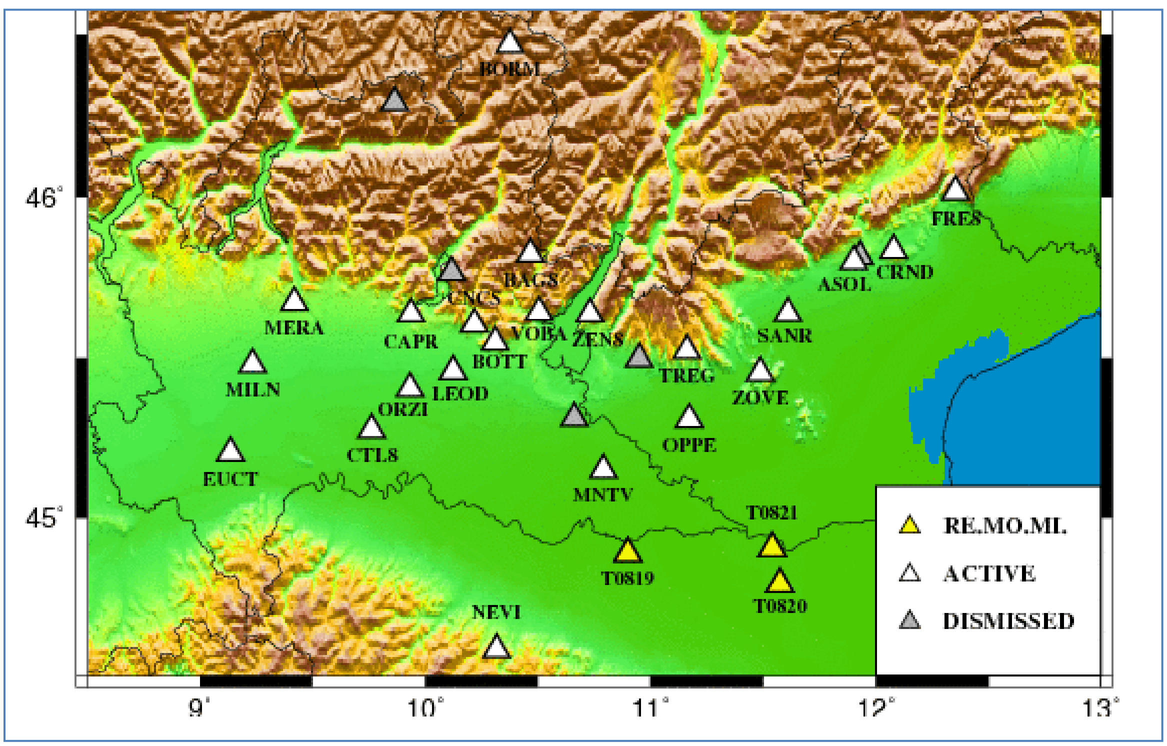


Figure 3-2 Map indicating the seismic stations that recorded the events (INGV, 2012)

In this report, the ground motion histories and spectral ordinates of the three strongest events will be analyzed: the earthquake of May 20, 2012 (02:03:53 UTC) M_w 5.9 (44°50'N 11°17'E) ID 120520020352; the earthquake of May 29, 2012 (07:00:03 UTC) M_w 5.8 (44°85'N 11°09'E) ID 120529070003; and the earthquake of May 29, 2012 (10:55:57 UTC) M_w 5.3 (44°88'N 11°01'E) ID 120529105557.

The following tables and figures illustrate the stations that recorded the earthquake.

Table 3-2 List of recording stations for the earthquake of May 20, 2012 (02:03:53 UTC) M_w 5.9 (44°50'N 11°17'E) ID 120520020352

STATION	LOCATION	EUROCODE8 SITE CLASS	GEOLOGY	LAT. (N)	LON. (E)	ALTITUDE (m)
ASOL	Asolo	A	sandstone/clay	45.8	11.9	181
BAG8	Bagolino	A	limestone	45.82	10.47	807
BDI	Bagni di Lucca	A	schist	44.06	10.6	830
BORM	Bormio	A	filled	46.47	10.38	1235
BOTT	Botticino	A	limestone	45.55	10.31	200
BRIS	Brisighella	A	marls	44.22	11.77	260
CAPR	Capriolio	B	alluvial deposits	45.64	9.93	215
CNCS	Concesio	B	alluvial deposits	45.61	10.22	126
CPGN	Carpegna	A	limestone	43.8	12.32	1400
CRND	Cornuda	C	fluvial-glacial deposit	45.84	12.01	159
CTL8	Castelleone	C	alluvial deposits	45.28	9.76	60
FAEN	Faenza	C	alluvial deposits	44.29	11.88	41
FIR	Firenze	B	alluvial deposits	43.77	11.26	40
FRE8	Fregona	A	conglomerate/marls	46.02	12.36	543
IMOL	Imola	C	alluvial deposits	44.36	11.74	27
LEOD	Capriano del Colle	B	alluvial deposits	45.46	10.12	92
MERA	Merate	B	moranic deposit	45.71	9.43	338
MILN	Milano	B	alluvial deposits	45.4803	9.2321	125
MNTV	Mantova	C	alluvial deposits	45.15	10.79	36
MODE	Modena	C	alluvial deposits	44.63	10.95	41
OPPE	Oppeano	C	alluvial deposits	45.31	11.17	20
ORZI	Orzinuovi	B	alluvial deposits	45.41	9.93	83
SANR	Sandrigo	C	alluvial deposits	45.64	11.61	51
SFI	S.Sofia	A	sandstone/marls	43.9	11.85	548
STAL	Staligial	A	dolomite	46.26	12.71	625
TREG	Tregnano	B	alluvial deposits	45.52	11.16	342
VOBA	Vobarno	B	alluvial deposits	45.64	10.5	292
ZCCA	Zocca	A	marls/sandstone	44.35	10.98	700
ZEN8	S.Zeno di Montagna	A	limestone	45.64	10.73	596
ZOVE	Zovencendo	A	limestone/dolomite	45.45	11.49	376

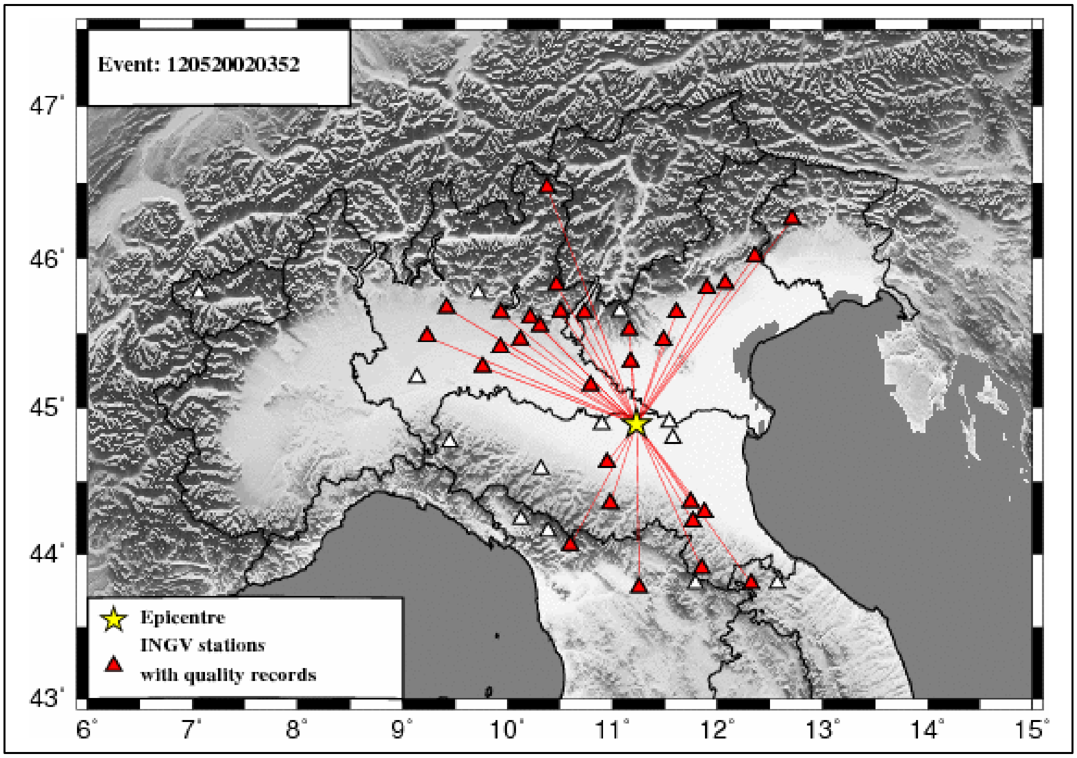


Figure 3-3 Map indicating the seismic stations that recorded the event ID 120520020352 May 20, 2012 (02:03:53 UTC) M_w 5.9 (INGV, 2012)

Table 3-3 List of recording stations for the earthquake of May 29, 2012 (07:00:03 UTC) M_w5.8 (44°85'N 11°09'E) ID 120529070003;the earthquake of May 29,2012(10:55:57 UTC) M_w5.3 (44°88'N 11°01'E) ID 120529105557

STATION	LOCATION	EUROCODE8 SITE CLASS	GEOLOGY	LAT. (N)	LON. (E)	ALTITUDE (m)
ASOL	Asolo	A	sandstone/clay	45.80	11.90	181
BAG8	Bagolino	A	limestone	45.82	10.47	807
BDI	Bagni di Lucca	A	schist	44.06	10.60	830
BOB	Bobbio	A	sandstone	44.77	9.45	910
BORM	Bormio	A	filled	46.47	10.38	1235
BOTT	Botticino	A	limestone	45.55	10.31	200
CAPR	Capriolio	B	alluvial deposits	45.64	9.93	215
CNCS	Concesio	B	alluvial deposits	45.61	10.22	126
CPGN	Carpegna	A	limestone	43.80	12.32	1400
CRND	Cornuda	C	fluvial-glacial deposit	45.84	12.01	159
CTL8	Castelleone	C	alluvial deposits	45.28	9.76	60
FAEN	Faenza	C	alluvial deposits	44.29	11.88	41
FIR	Firenze	B	alluvial deposits	43.77	11.26	40
FRE8	Fregona	A	conglomerate/marls	46.02	12.36	543
IMOL	Imola	C	alluvial deposits	44.36	11.74	27
LEOD	Capriano del Colle	B	alluvial deposits	45.46	10.12	92
MERA	Merate	B	moranic deposit	45.71	9.43	338
MILN	Milano	B	alluvial deposits	45.48	9.23	125
MNTV	Mantova	C	alluvial deposits	45.15	10.79	36
MODE	Modena	C	alluvial deposits	44.63	10.95	41
MOMA	Monte Martano	A	limestone	43.80	12.57	1040
NEVI	Neviano degli Arduini	A	limestone	44.58	10.31	480
OPPE	Oppeano	C	alluvial deposits	45.31	11.17	20
ORZI	Orzinuovi	B	alluvial deposits	45.41	9.93	83
SANR	Sandrigo	C	alluvial deposits	45.64	11.61	51
SFI	S.Sofia	A	sandstone/marls	43.90	11.85	548
STAL	Staligial	A	dolomite	46.26	12.71	625
T820	Chiesuol del Fosso	C	alluvial deposits	44.79	11.57	8
T821	Casaglia	C	alluvial deposits	44.90	11.54	3
TREG	Tregnano	B	alluvial deposits	45.52	11.16	342
VOBA	Vobarno	B	alluvial deposits	45.64	10.50	292
ZCCA	Zocca	A	marls/sandstone	44.35	10.98	700
ZEN8	S.Zeno di Montagna	A	limestone	45.64	10.73	596
ZOVE	Zovencendo	A	limestone/dolomite	45.45	11.49	376

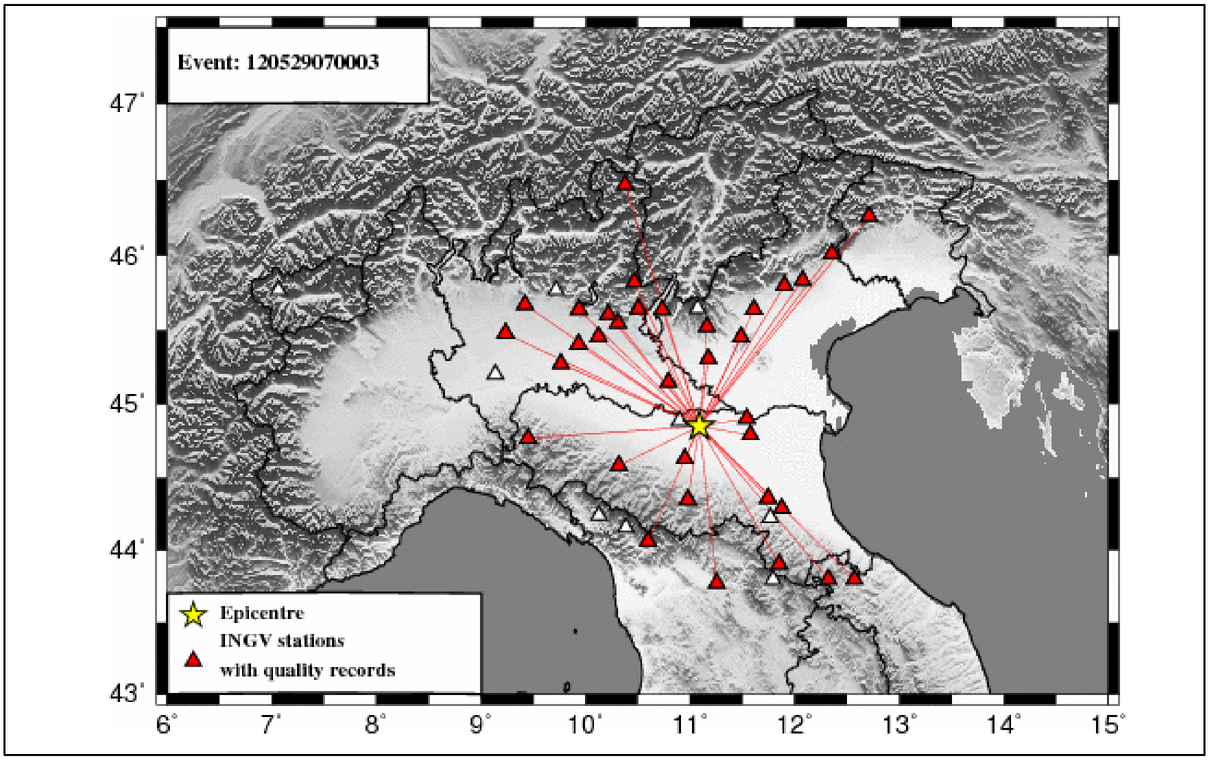


Figure 3-4 Map indicating the seismic stations that recorded the event ID 120529070003 May 29, 2012 (07:00:03 UTC) M_w5.8 (INGV, 2012)

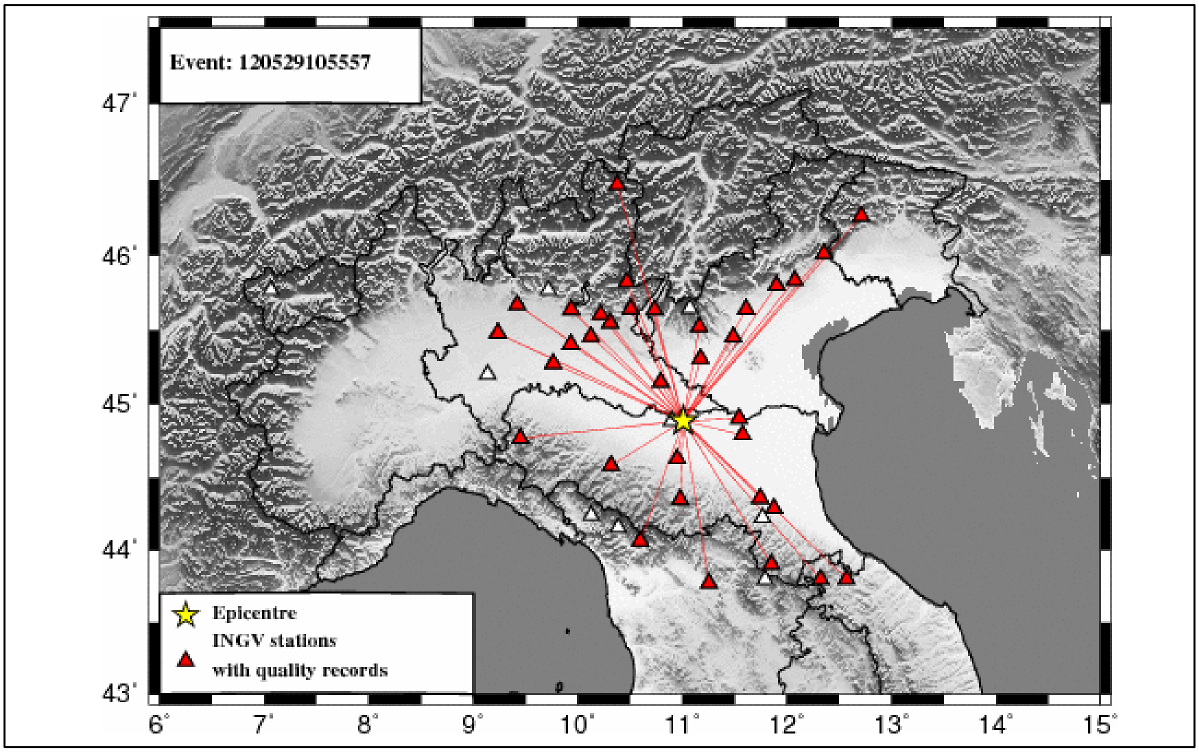


Figure 3-5 Map indicating the seismic stations that recorded the event ID 120529105557 May 29, 2012 (10:55:57 UTC) M_w5.3 (INGV, 2012)

3.2 Ground Motion Histories and Spectral Ordinates

The following tables summarize the peak ground motion ordinates associated with each station; after each table, there is a figure summarizing the data collected for the three strong ground motions.

Table 3-4 Peak ground-motion ordinates ID 120520020352 May 20, 2012 (02:03:53 UTC) M_w5.9

Station	PGA [cm/s^2]			PGV [cm/s]			R_{epi} [km]
	EW	NS	UP	EW	NS	UP	
ASOL	19.3126	14.7788	6.00333	1.12559	0.816833	0.432849	114.47
BAG8	6.71219	5.69156	4.76063	0.382411	0.347372	0.24428	120.22
BDI	3.59651	2.97085	2.05026	0.582019	0.273993	0.229817	104.91
BORM	2.50843	1.5284	1.86078	0.177864	0.089557	0.121704	188.15
BOTT	7.66898	5.79688	3.13281	0.353841	0.347368	0.224065	103.83
BRIS	10.5499	6.32354	5.87542	1.99726	1.62532	1.27084	85.44
CAPR	2.61906	2.43906	1.74107	0.34263	0.317452	0.213053	132.74
CNCS	11.1825	12.316	4.58025	0.687501	0.498096	0.280772	113.5
CPGN	2.73137	3.14224	1.76824	0.657124	0.660906	0.669952	149.07
CRND	6.65023	8.59077	4.77923	0.335187	0.586945	0.417163	124.7
CTL8	9.7141	10.8705	2.00174	0.851523	1.48449	0.386683	124.98
FAEN	9.26659	15.2441	1.58516	2.34475	2.20209	0.758925	84.4
FIR	2.55136	2.79332	1.40268	0.44754	0.3151	0.292887	123.86
FRE8	4.0068	2.9179	1.98786	0.306656	0.237026	0.29838	153.99
IMOL	13.4123	14.8345	5.31525	2.53266	3.26417	1.52694	71.74
LEOD	7.80292	8.22725	3.1163	1.22677	1.10986	0.44243	108.7
MERA	4.82376	5.93047	2.07269	0.403856	0.408765	0.183038	168.97
MILN	2.51811	2.60046	0.399315	0.332648	0.378507	0.03406	172.75
MNTV	18.8378	21.473	12.1072	3.57399	3.56156	0.974903	45.51
MODE	26.9831	41.762	32.386	4.46058	6.38439	2.4522	36.6
OPPE	17.2837	17.6192	9.17316	0.897508	1.19792	0.504974	46.65
ORZI	7.43704	10.8196	2.61764	1.05337	1.24391	0.336855	118.65
SANR	23.4665	22.6482	6.26837	0.721197	1.01778	0.31739	88.63
SFI	3.47197	3.76151	1.94072	0.301302	0.587363	0.374529	120.08
STAL	3.28023	4.21046	2.36477	0.152661	0.187135	0.106715	192.76
TREG	8.70401	18.2682	19.2101	0.254138	0.629089	0.663441	70.48
VOBA	20.0317	18.6151	6.39303	0.764739	0.65304	0.309068	101.78
ZCCA	4.94557	4.71062	3.61196	0.886828	1.68425	0.975096	63.2
ZEN8	7.05377	7.56285	6.33789	0.334836	0.517627	0.340579	92.07
ZOVE	15.1947	16.473	8.58131	0.458102	0.50293	0.316077	65.87

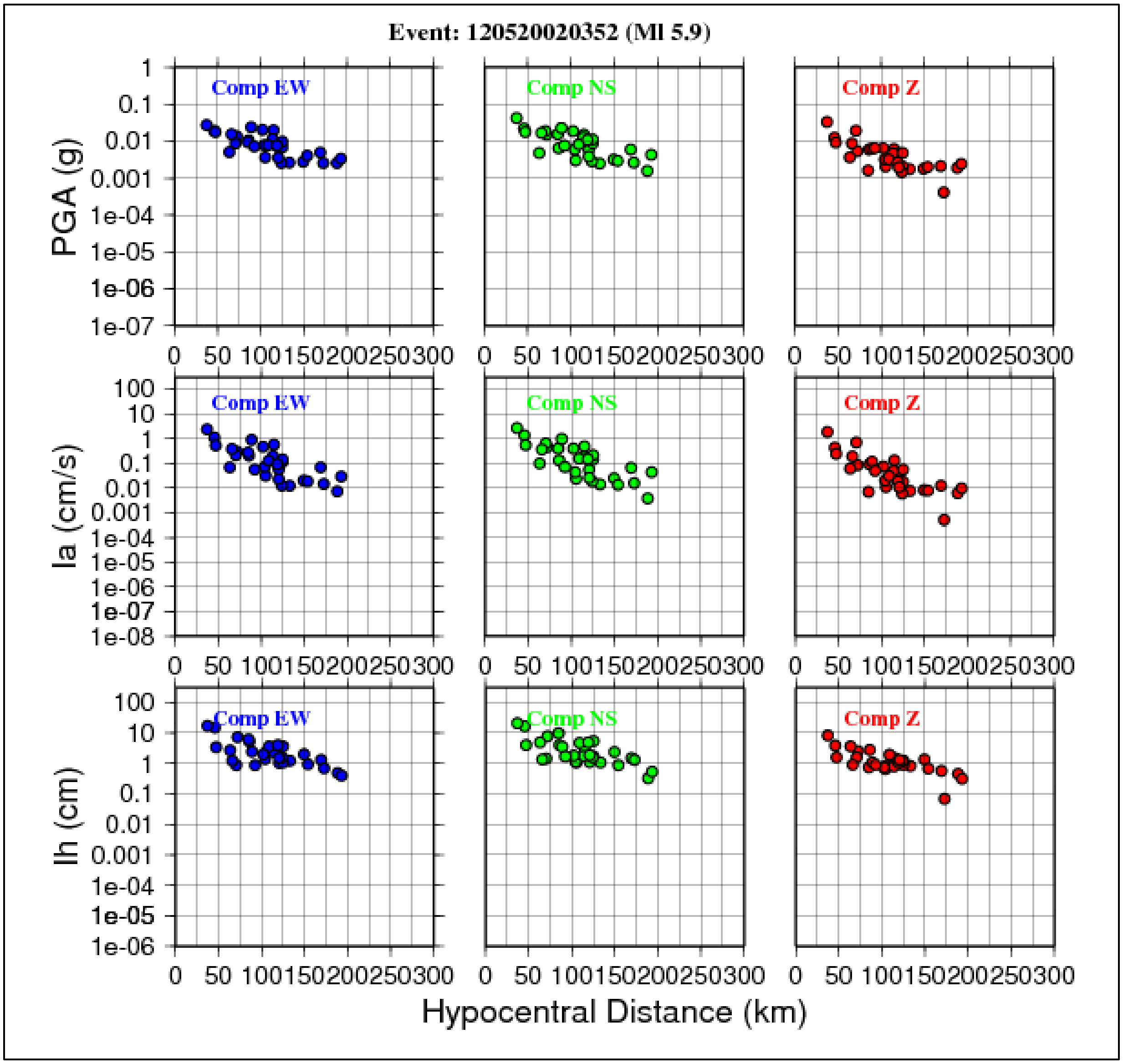


Figure 3-6 Strong motion parameters ID 120520020352 May 20, 2012 (02:03:53 UTC) M_w5.9 (INGV, 2012)

The nearest station is MODE, which recorded the highest ground accelerations in all three directions. It is located on alluvial deposits, corresponding to soil type C according to the Eurocode 8.

Table 3-5 Peak ground-motion ordinates ID 120529070003 May 29, 2012 (07:00:03 UTC) M_w5.8

Station	PGA [cm/s^2]			PGV [cm/s]			R_{epi}[km]
	EW	NS	UP	EW	NS	UP	
ASOL	11.7591	13.3109	5.19237	0.764948	1.17074	0.386217	123.89
BAG8	5.12127	5.11391	2.62804	0.320551	0.333508	0.20051	118.94
BDI	2.87898	3.04674	1.5746	0.337003	0.199633	0.133838	95.92
BOB	2.89937	2.64009	1.54244	0.245151	0.277472	0.191916	131.69
BORM	2.22701	1.45517	1.51353	0.156601	0.105431	0.108035	188.6
BOTT	5.52686	3.92554	2.79916	0.387911	0.243179	0.192771	99.63
CAPR	2.74259	3.08664	1.91029	0.289663	0.470386	0.23791	127.2
CNCS	9.93125	11.936	5.63612	0.631271	0.694185	0.289499	109.17
CPGN	1.3847	1.04637	0.830527	0.284244	0.227145	0.248277	152.47
CRND	5.13005	8.44705	4.31839	0.33192	0.571173	0.29308	134.67
CTL8	6.26085	6.90352	2.0427	0.815082	0.895557	0.346576	116.25
FAEN	10.1244	9.11658	1.2768	0.922919	1.07917	0.192074	88.51
FIR	2.05798	1.74151	0.72651	0.299493	0.228177	0.137466	120.13
FRE8	2.122	1.96176	1.1746	0.291931	0.241363	0.209336	164.26
IMOL	6.80206	9.74198	3.19488	1.42817	1.15651	0.628255	75.42
LEOD	8.92529	10.9984	3.7719	1.03676	1.29425	0.385834	102.65
MERA	4.81844	4.87182	2.11373	0.387963	0.351383	0.129795	161.94
MILN	2.43255	2.78126	0.414602	0.26698	0.202519	0.034539	164.27
MNTV	23.798	23.2538	16.7288	3.514	5.31629	1.17584	41.02
MODE	44.138	21.626	41.6587	3.85121	3.22073	2.14365	26.92
MOMA	0.314767	0.27434	0.156199	0.050771	0.042421	0.055887	165.96
NEVI	1.81602	1.10606	0.266367	0.236287	0.205825	0.042307	68.61
OPPE	13.3529	14.4533	7.37809	0.981835	2.44097	0.863043	51.29
ORZI	5.18776	10.1332	2.88878	0.82645	0.92891	0.421197	111.37
SANR	34.3015	19.7694	8.21996	1.80533	1.76318	0.400193	97.06
SFI	1.76351	1.74813	1.13918	0.231773	0.250112	0.217521	121.25
STAL	1.92765	3.01861	1.27741	0.141666	0.15348	0.103685	203.23
T820	23.7622	29.836	16.2555	2.64363	3.70228	1.22411	39.2
T821	19.8099	18.3376	8.20911	2.14703	1.36544	0.493287	36.53
TREG	7.34287	17.6399	16.2206	0.337152	0.578808	0.597625	74.92
VOBA	15.6381	13.2706	5.56085	0.530286	0.459347	0.236853	99.72
ZCCA	3.85891	4.0638	3.53439	1.00223	0.941505	1.08412	56.15
ZEN8	5.57451	5.43511	5.56866	0.270309	0.538311	0.289359	92.02
ZOVE	12.9338	12.8665	8.69516	0.506168	0.5166	0.324149	74.17

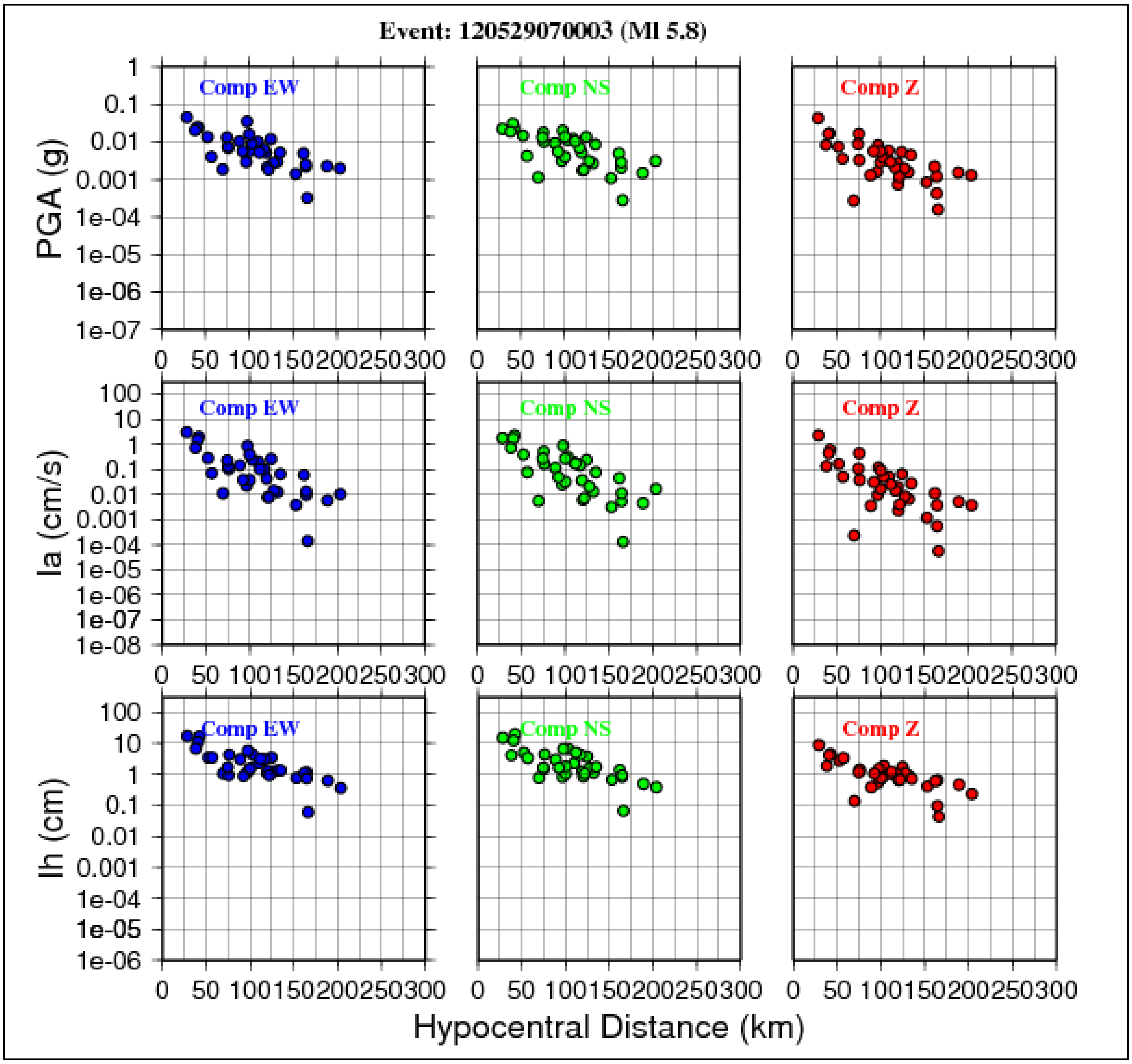


Figure 3-7 Strong motion parameters ID 120529070003 May 29, 2012 (07:00:03 UTC) M_w5.8 (INGV, 2012)

The nearest station again is MODE, which recorded the highest ground accelerations in the vertical direction and in the direction East-West, while the maximum peak ground acceleration in the direction North-South was recorded by the station T820. The station T820 is also located on a soft soil made of alluvial deposit.

Table 3-6 Peak ground-motion ordinates ID 120529105557 May 29, 2012 (10:55:57 UTC) M_w5.3

Station	PGA [cm/s²]			PGV [cm/s]			R_{epi}[km]
	EW	NS	UP	EW	NS	UP	
ASOL	5.14233	3.84592	1.62898	0.372709	0.425316	0.145381	123.99
BAG8	2.74917	3.35146	2.61214	0.157043	0.154312	0.131486	112.44
BDI	1.7021	1.3949	0.91222	0.177007	0.115457	0.093377	97.37
BOB	1.72353	2.25307	1.17578	0.140963	0.202434	0.075135	125.52
BORM	0.960439	0.60339	0.760362	0.071305	0.048687	0.062139	182.66
BOTT	4.1528	3.29289	1.77046	0.243997	0.150597	0.097728	92.26
CAPR	1.74205	1.7168	1.13556	0.121969	0.204727	0.129816	119.55
CNCS	9.54914	10.224	5.25778	0.636433	0.454398	0.248533	101.76
CPGN	0.437633	0.557676	0.229161	0.0652	0.077878	0.042606	159.94
CRND	3.10693	3.31817	1.71761	0.133207	0.201295	0.068677	135.31
CTL8	4.93806	3.75473	1.6561	0.571025	0.665542	0.205787	108.56
FIR	1.00193	1.13892	0.534684	0.154015	0.137011	0.072443	125.19
FRE8	1.10295	0.513716	0.476772	0.090452	0.104147	0.056464	165.17
IMOL	2.6966	3.19751	1.32824	0.242031	0.321159	0.130264	83.02
LEOD	4.4376	5.32062	2.54211	0.746504	0.823765	0.279686	94.94
MERA	3.60724	3.02451	1.71284	0.269293	0.20092	0.117087	154.14
MILN	2.24132	1.96103	0.338358	0.174866	0.189005	0.029093	156.54
MNTV	47.2387	40.5743	14.0672	5.42481	4.66399	1.15803	33.87
MODE	19.6689	16.4297	22.7641	3.56006	2.21651	0.967942	29.05
MOMA	0.158618	0.107986	0.061343	0.012991	0.012612	0.010864	173.6
NEVI	1.10126	0.911308	0.20239	0.165152	0.139471	0.036511	64.84
OPPE	4.90226	7.26413	3.94811	0.53437	0.716723	0.395607	48.47
ORZI	3.86796	3.04879	1.9071	0.696662	0.639769	0.332614	103.58
SANR	9.59593	14.3102	3.04157	0.540244	0.917899	0.20875	96.36
SFI	0.734432	0.754598	0.479637	0.059816	0.128359	0.071472	128.24
STAL	0.988063	1.16401	0.519331	0.039527	0.039624	0.026246	204.32
T820	4.62502	6.8161	2.81605	0.401274	0.506866	0.11853	46.48
T821	4.75066	6.09633	2.22333	0.358397	0.436622	0.121799	42.64
TREG	4.28886	7.93136	7.30977	0.123181	0.257729	0.248137	71.54
VOBA	8.4312	6.54921	4.38563	0.325286	0.40154	0.158331	92.99
ZCCA	2.58119	2.35988	2.2992	0.595494	0.678327	0.34251	59.68
ZEN8	3.22263	2.98717	1.92815	0.085832	0.143584	0.094085	86.11
ZOVE	4.98032	7.30559	3.38428	0.162427	0.253399	0.113183	73.58

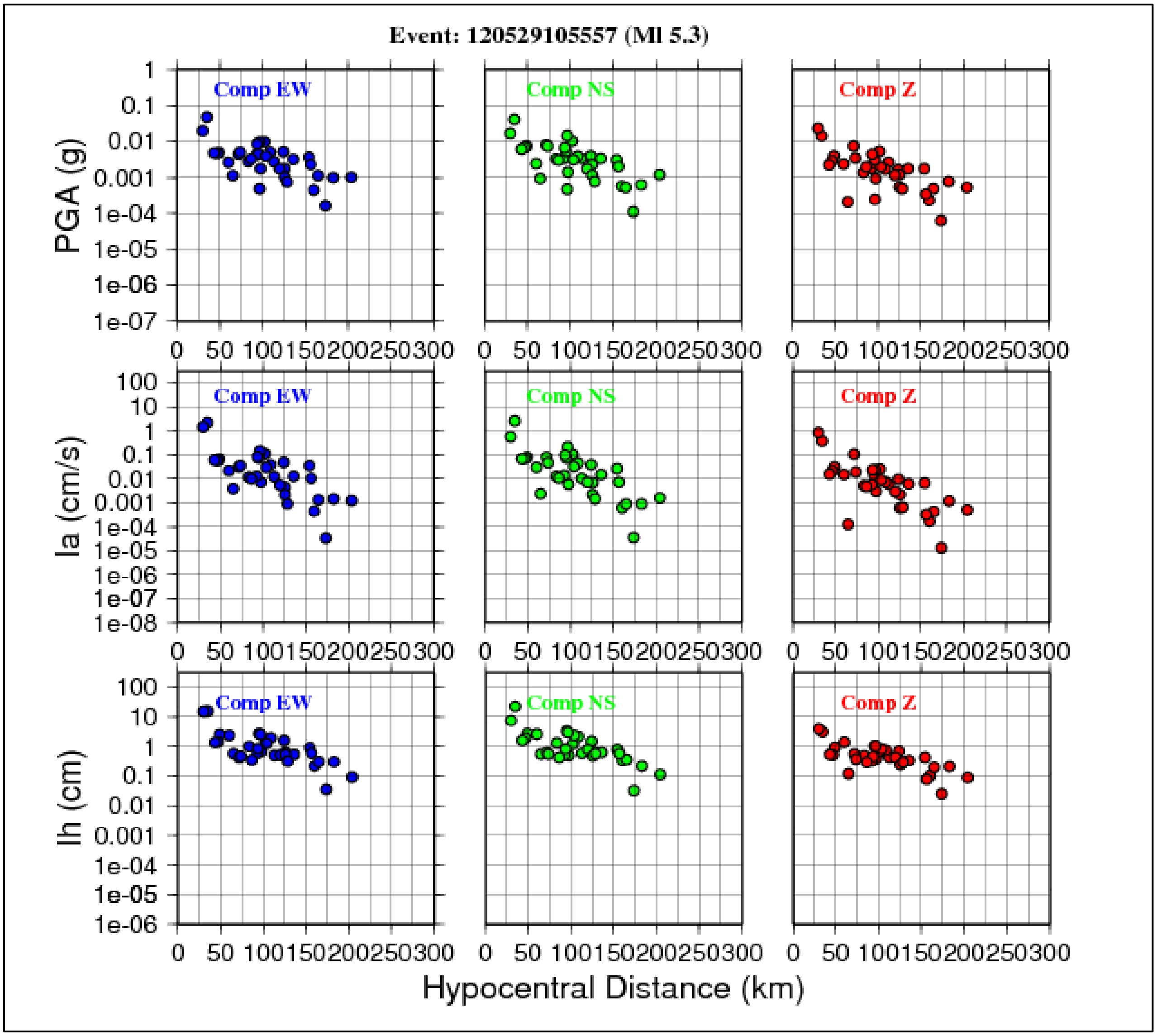


Figure 3-8 Strong motion parameters ID 120529105557 May 29, 2012 (10:55:57 UTC) M_w5.3 (INGV, 2012)

Again, the nearest station is MODE, which recorded the highest ground accelerations only in the vertical direction. In the East-West and North-South directions, the maximum peak ground acceleration was recorded by the station MNTV. This station is also located on a soft soil made of alluvial deposit.

3.2.1 Filter Analysis

All the stations listed in the previous tables registered the waveforms in all directions; these data were edited with Matlab®. A linear baseline line correction was applied with an order 4 bandpass Butterworth filter with a frequency range of 0.25-25 Hz. These corrected data were used to calculate the elastic response spectra. In order to understand the importance of this filtering process, the following figures show the differences between unfiltered data and the processed data.

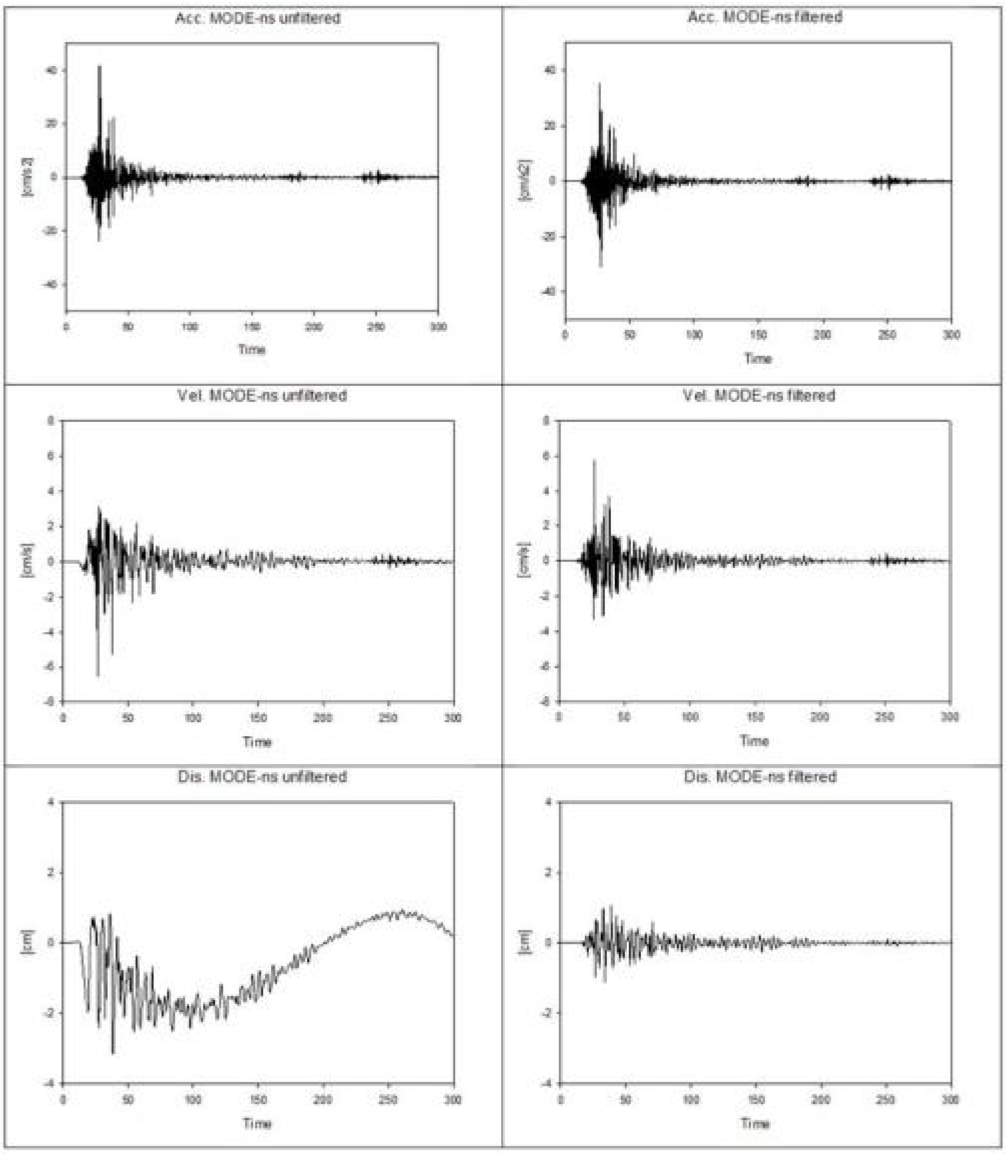


Figure 3-9 Differences between filtered data and unfiltered data

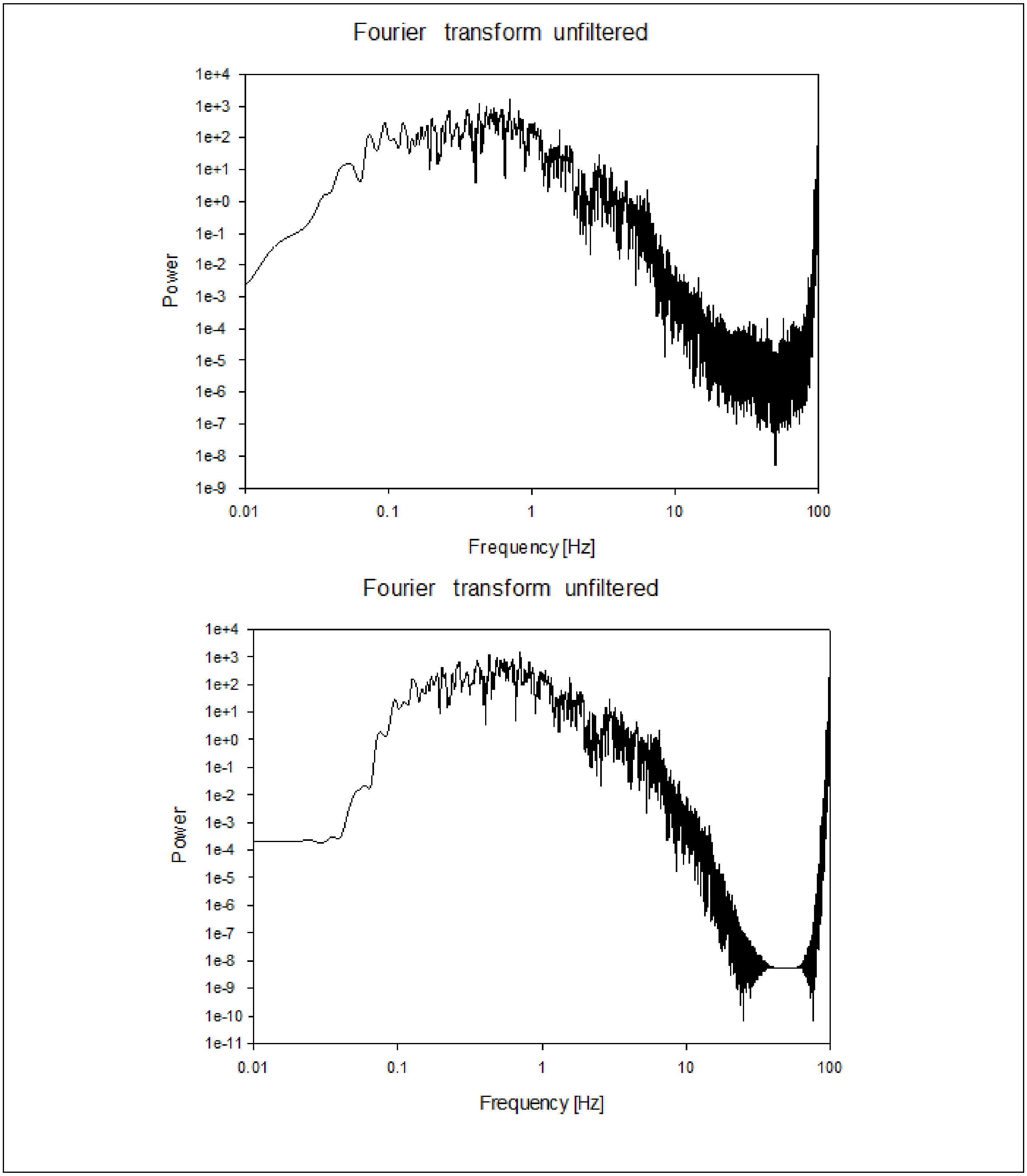


Figure 3-10 Fourier transform differences between filtered data and unfiltered data

In the following sections, the pseudo-spectra acceleration of each accelerogram is shown for all directions.

3.2.2 Earthquake of May 20, 2012 (02:03:53 UTC) M_w 5.9 (44°50’N 11°17’E) ID 120520020352

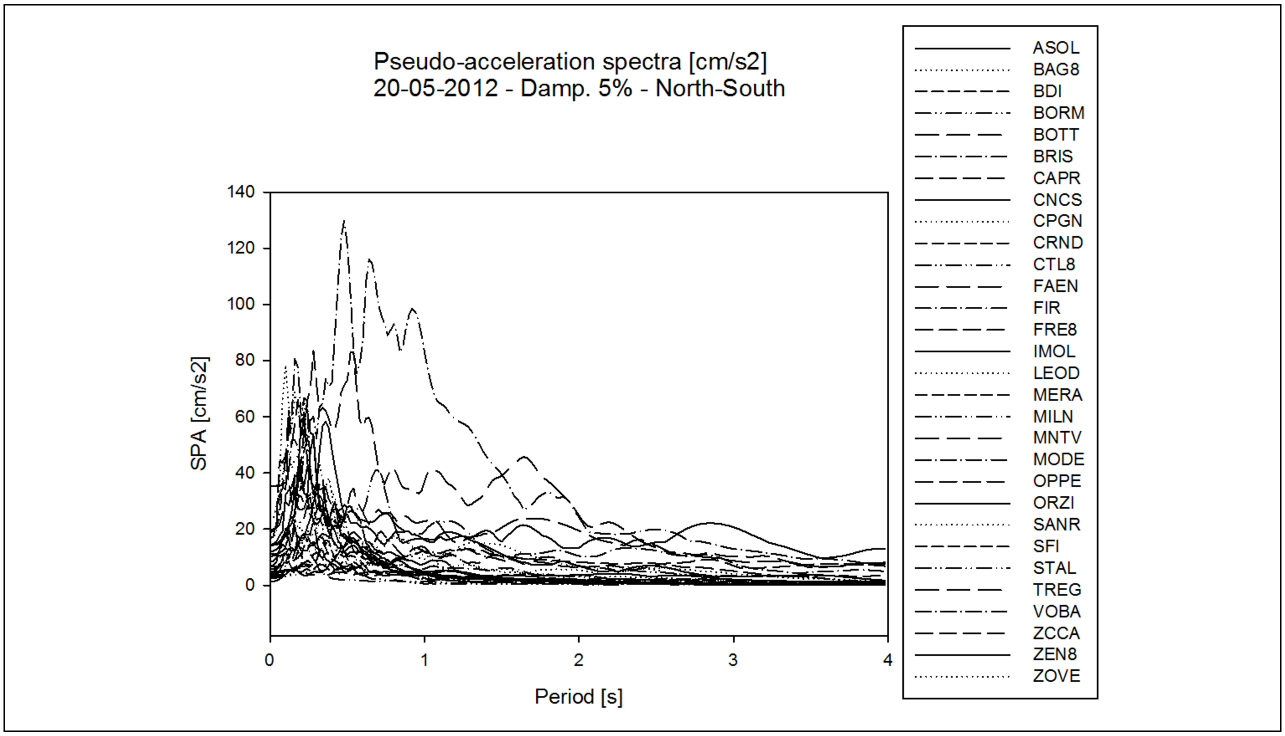


Figure 3-11 PSA Damp 5% North-South

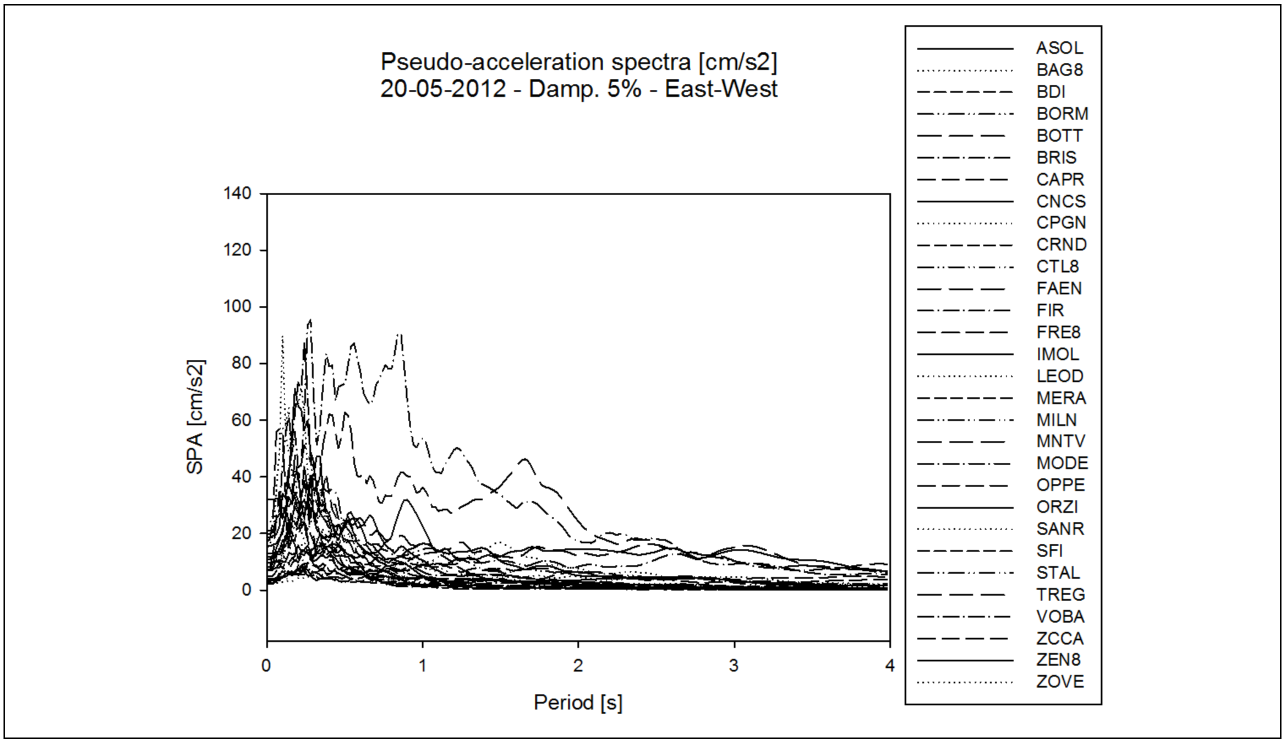


Figure 3-12 PSA Damp 5% East-West

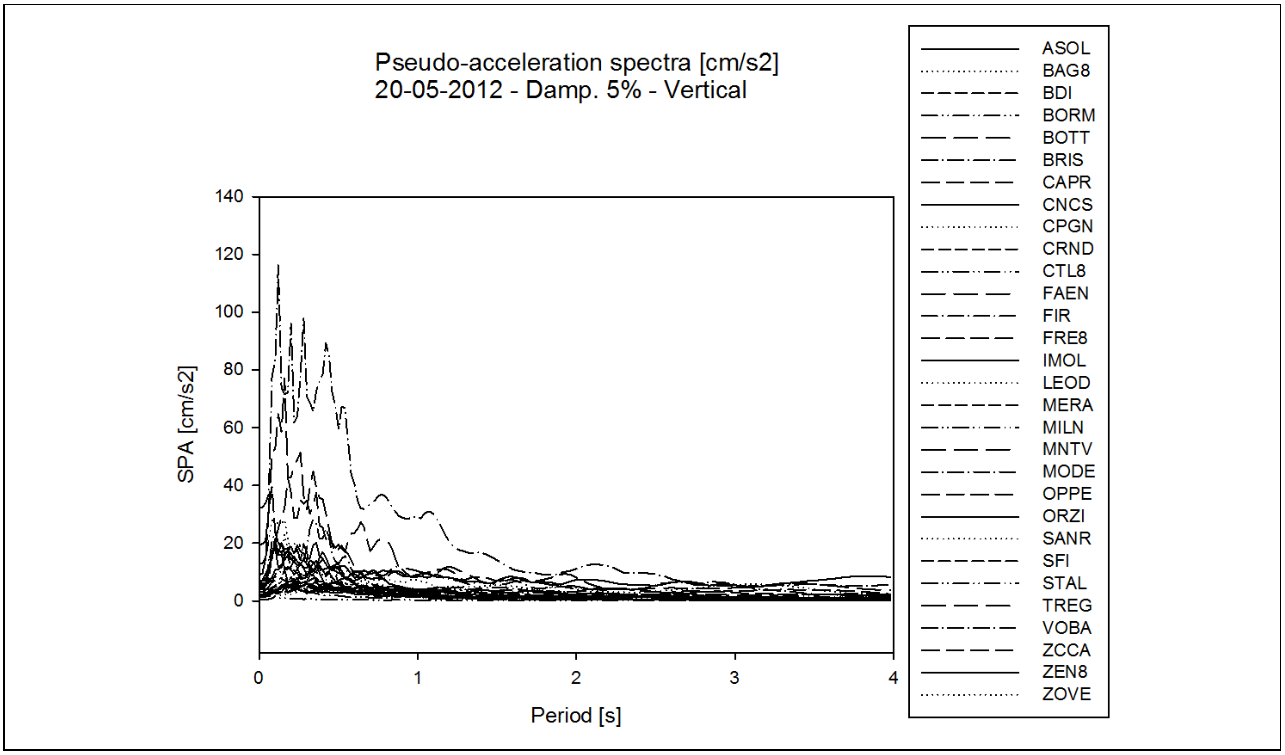


Figure 3-13 PSA Damp 5% vertical direction

To make the results more readable, the following table represents only nine pseudo-acceleration spectra. The criterion by which they were chosen is as follows: the recordings of the three nearest stations in term of epicentral distance, for each category of ground.

Table 3-7 Earthquake records shown in Figures 3-14 to 3-22

Station	PGA [cm/s^2]			PGV [cm/s]			R_{epi} [km]	EC8 site class
	EW	NS	UP	EW	NS	UP		
ZCCA	4.94557	4.71062	3.61196	0.886828	1.68425	0.975096	63.2	A
ZOVE	15.1947	16.473	8.58131	0.458102	0.50293	0.316077	65.87	A
BRIS	10.5499	6.32354	5.87542	1.99726	1.62532	1.27084	85.44	A
TREG	8.70401	18.2682	19.2101	0.254138	0.629089	0.663441	70.48	B
VOBA	20.0317	18.6151	6.39303	0.764739	0.65304	0.309068	101.78	B
LEOD	7.80292	8.22725	3.1163	1.22677	1.10986	0.44243	108.7	B
MODE	26.9831	41.762	32.386	4.46058	6.38439	2.4522	36.6	C
MNTV	18.8378	21.473	12.1072	3.57399	3.56156	0.974903	45.51	C
OPPE	17.2837	17.6192	9.17316	0.897508	1.19792	0.504974	46.65	C

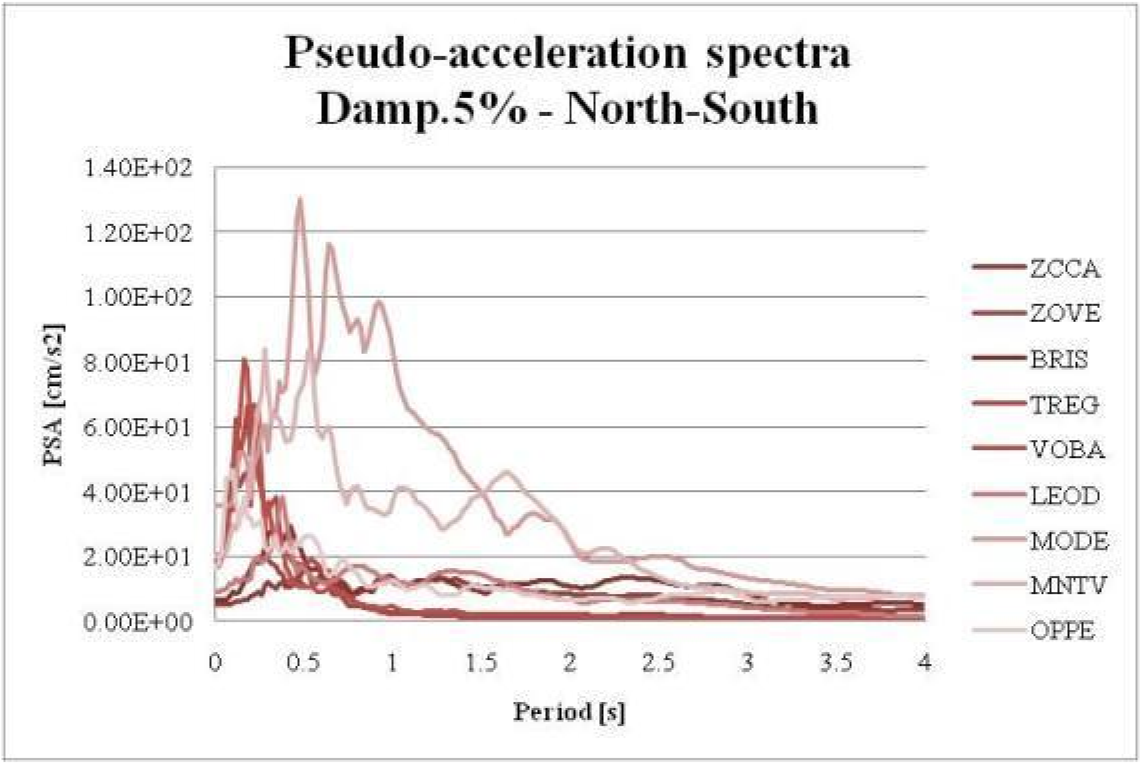


Figure 3-14 PSA Damp 5% North-South

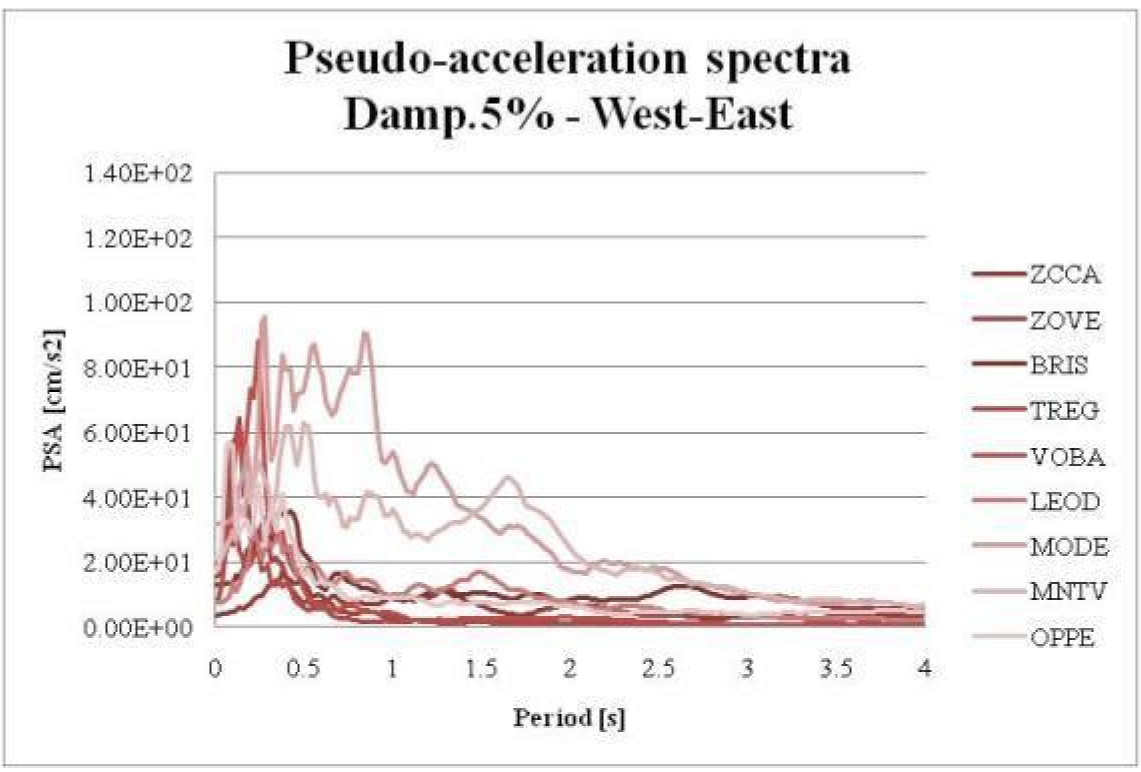


Figure 3-15 PSA Damp 5% East-West

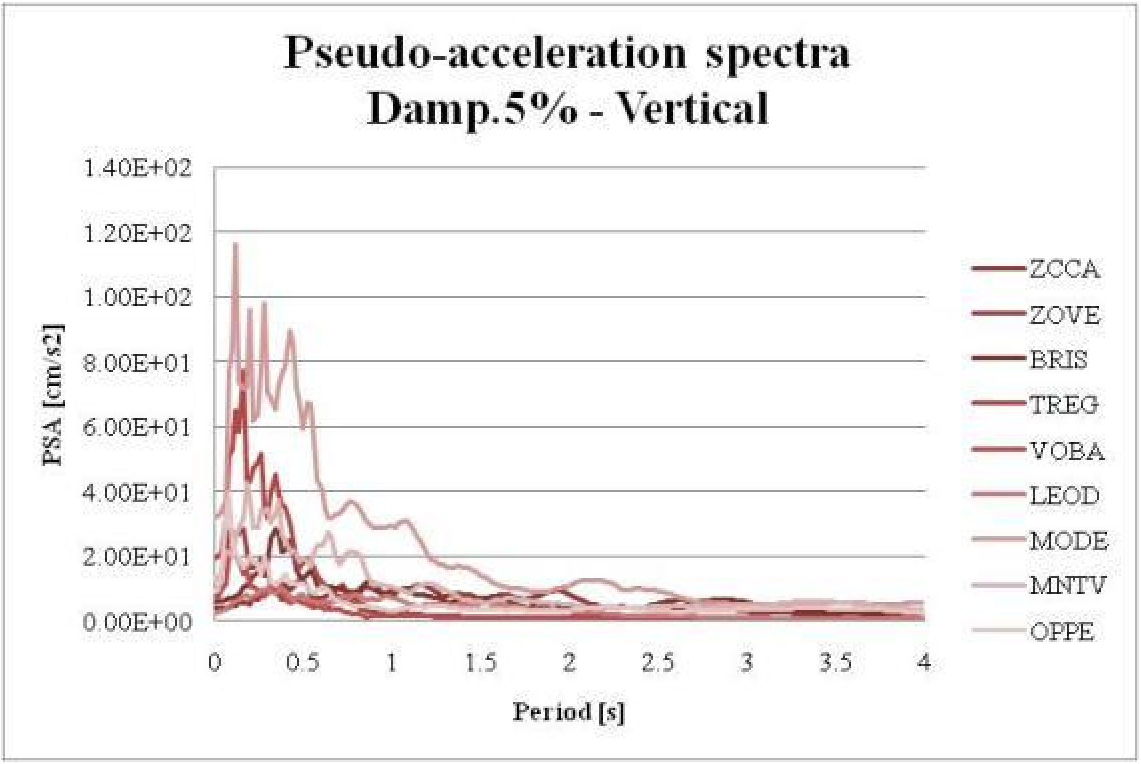


Figure 3-16 PSA Damp 5% vertical direction

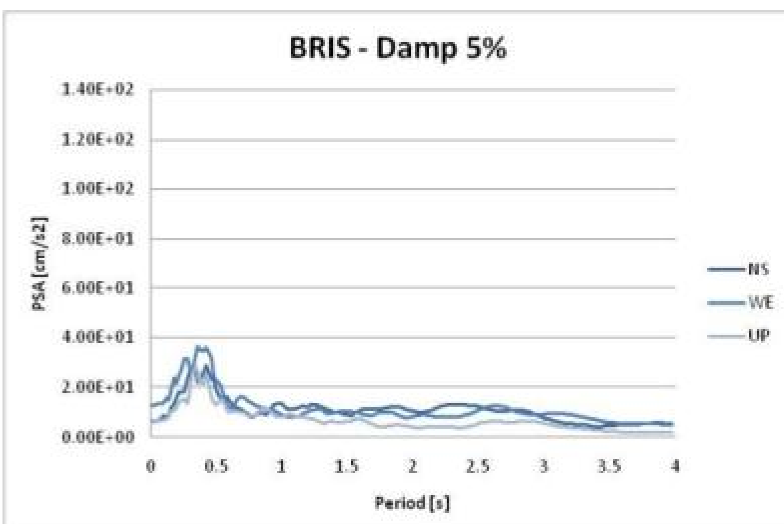


Figure 3-17 PSA Damp 5% BRIS station

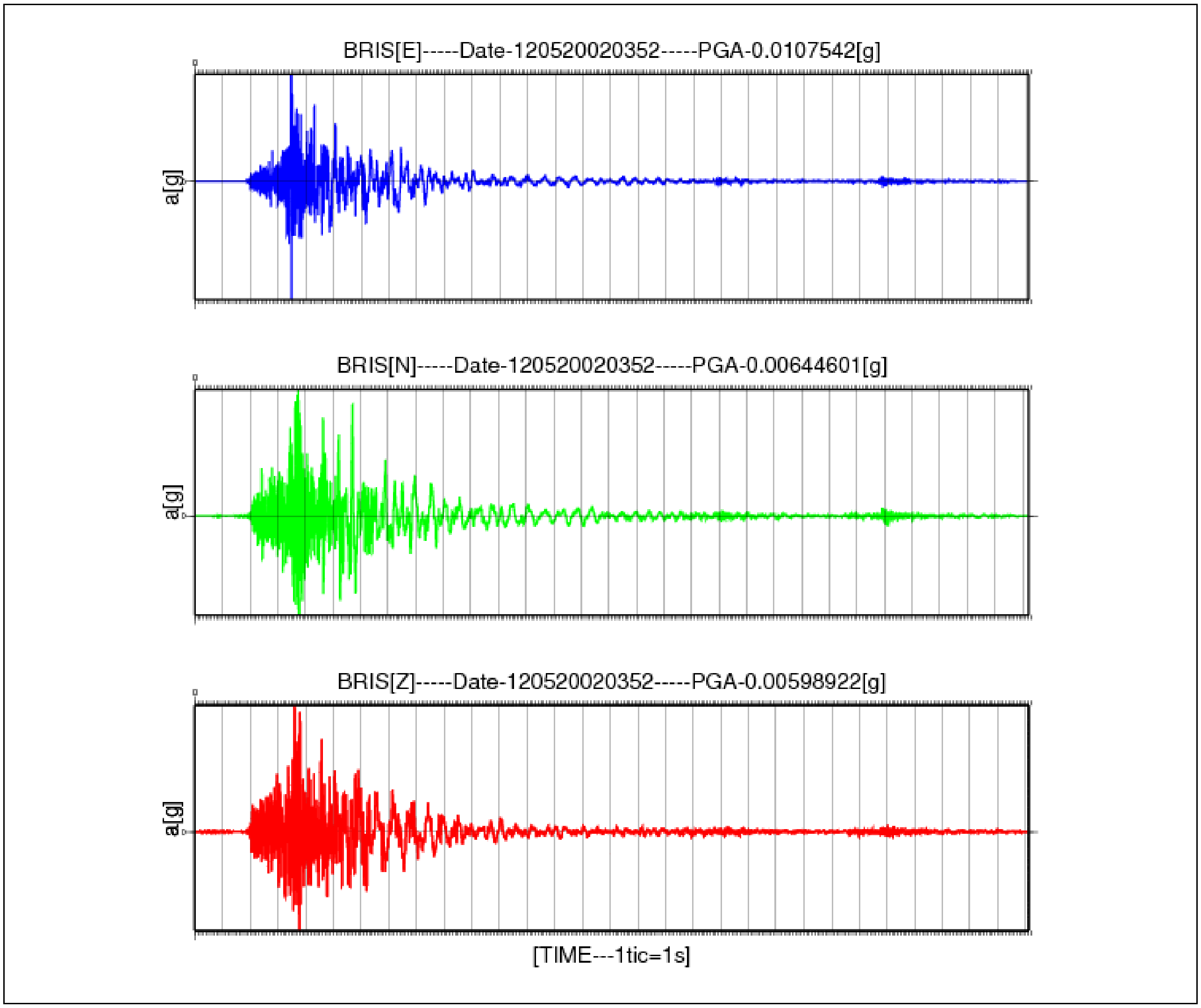


Figure 3-18 Accelerograms BRIS station

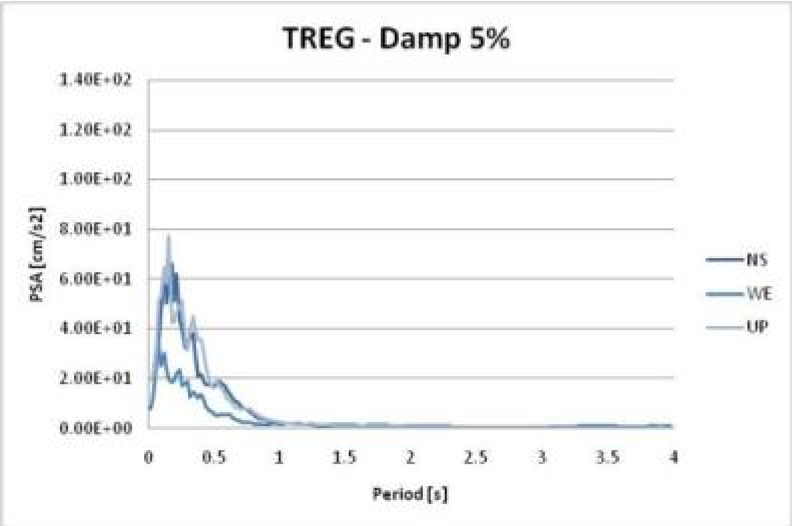


Figure 3-19 PSA Damp 5% TREG station

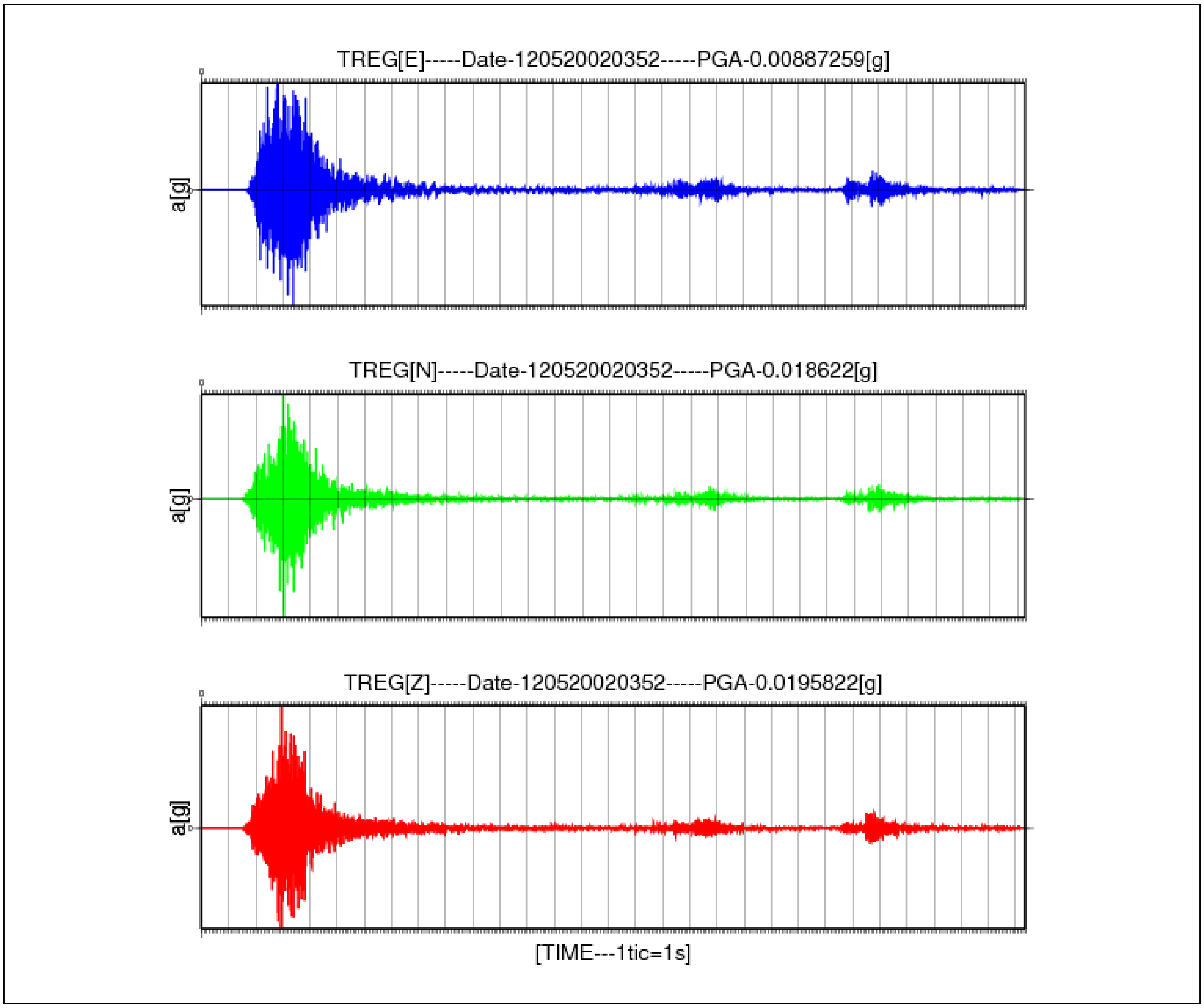


Figure 3-20 Accelerograms TREG station

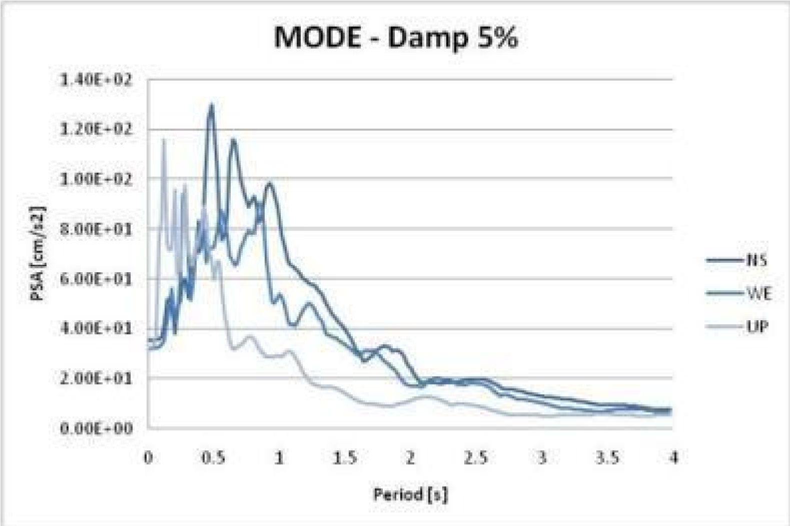


Figure 3-21 PSA Damp 5% MODE station

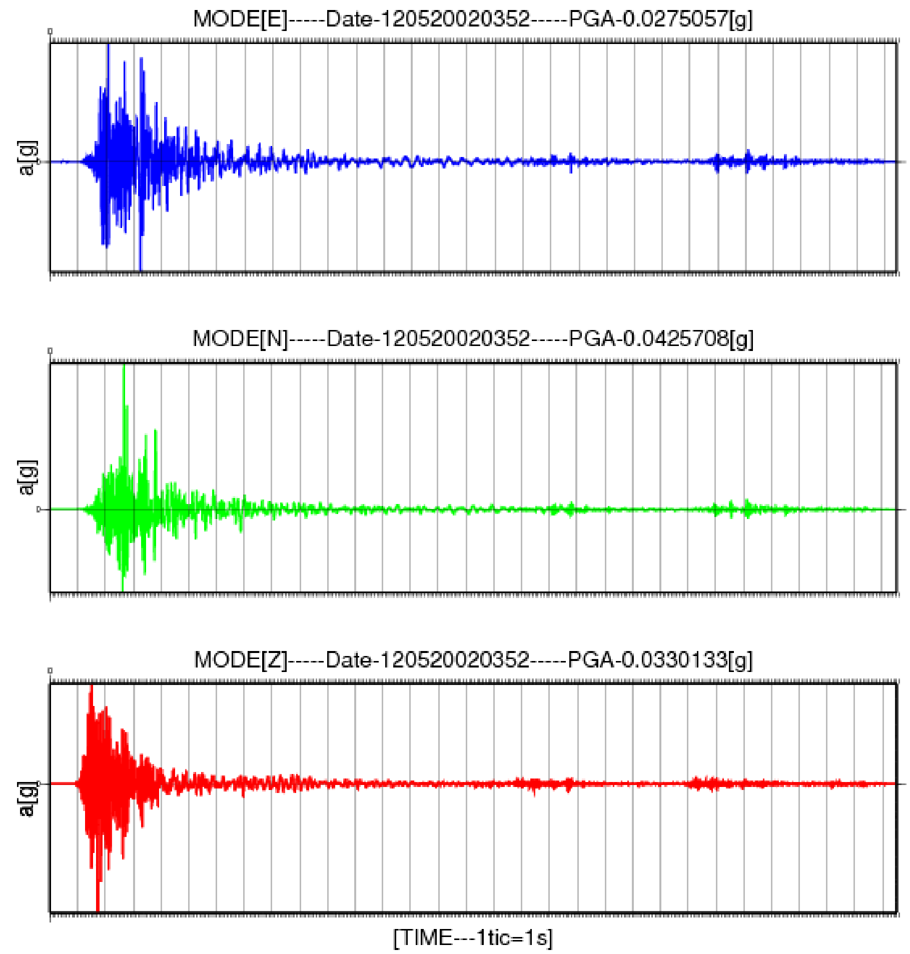


Figure 3-22 Accelerograms MODE station

3.2.3 Earthquake of May 29, 2012 (07:00:03 UTC) M_w 5.8 (44°80'N 11°09'E) ID 120529070003

Figure 3-23, Figure 3-24 and Figure 3-25 represent only nine pseudo-acceleration spectra. The criterion by which they were chosen is as follows: the recordings of the three nearest stations in terms of epicentral distance, for each category of ground.

Table 3-8 Earthquake records shown in Figures 3-23 to 3-31

Station	PGA [cm/s²]			PGV [cm/s]			R_{epi} [km]	EC8 site class
	EW	NS	UP	EW	NS	UP		
ZCCA	3.85891	4.0638	3.53439	1.00223	0.941505	1.08412	56.15	A
NEVI	1.81602	1.10606	0.266367	0.236287	0.205825	0.042307	68.61	A
ZOVE	12.9338	12.8665	8.69516	0.506168	0.5166	0.324149	74.17	A
TREG	7.34287	17.6399	16.2206	0.337152	0.578808	0.597625	74.92	B
VOBA	15.6381	13.2706	5.56085	0.530286	0.459347	0.236853	99.72	B
LEOD	8.92529	10.9984	3.7719	1.03676	1.29425	0.385834	102.65	B
MODE	44.138	21.626	41.6587	3.85121	3.22073	2.14365	26.92	C
T820	23.7622	29.836	16.2555	2.64363	3.70228	1.22411	39.2	C
T821	19.8099	18.3376	8.20911	2.14703	1.36544	0.493287	36.53	C

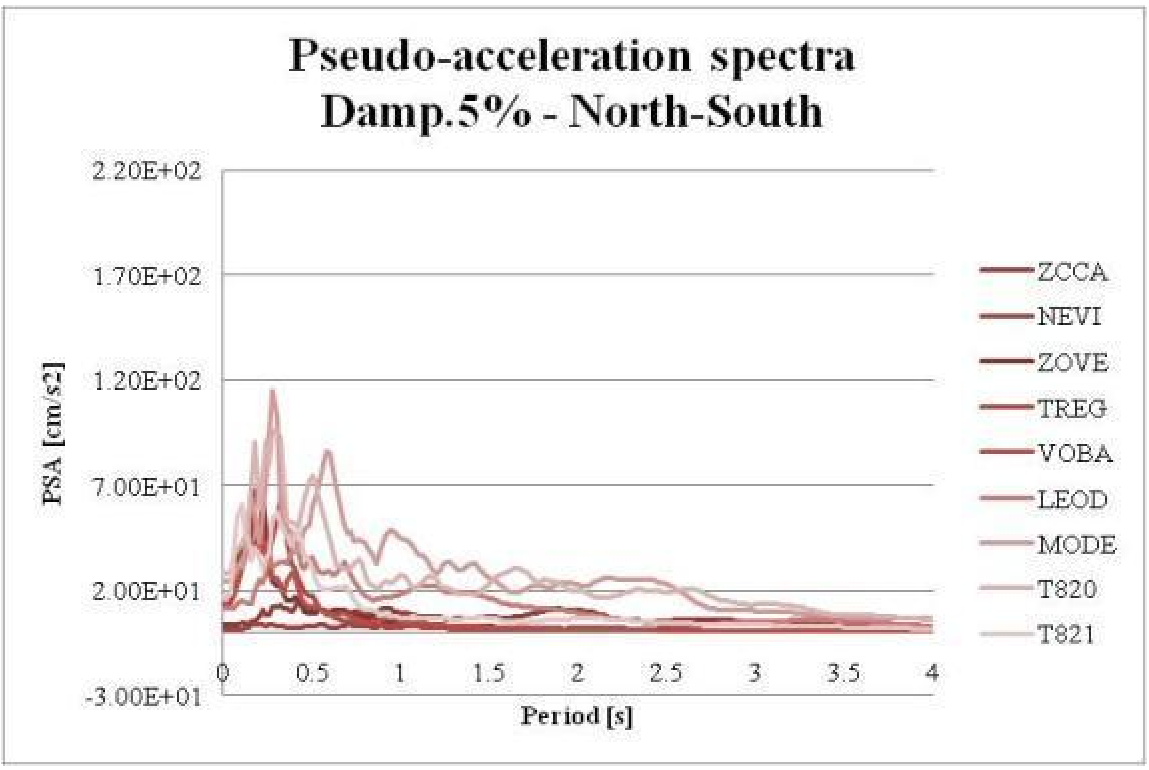


Figure 3-23 PSA Damp 5% North-South

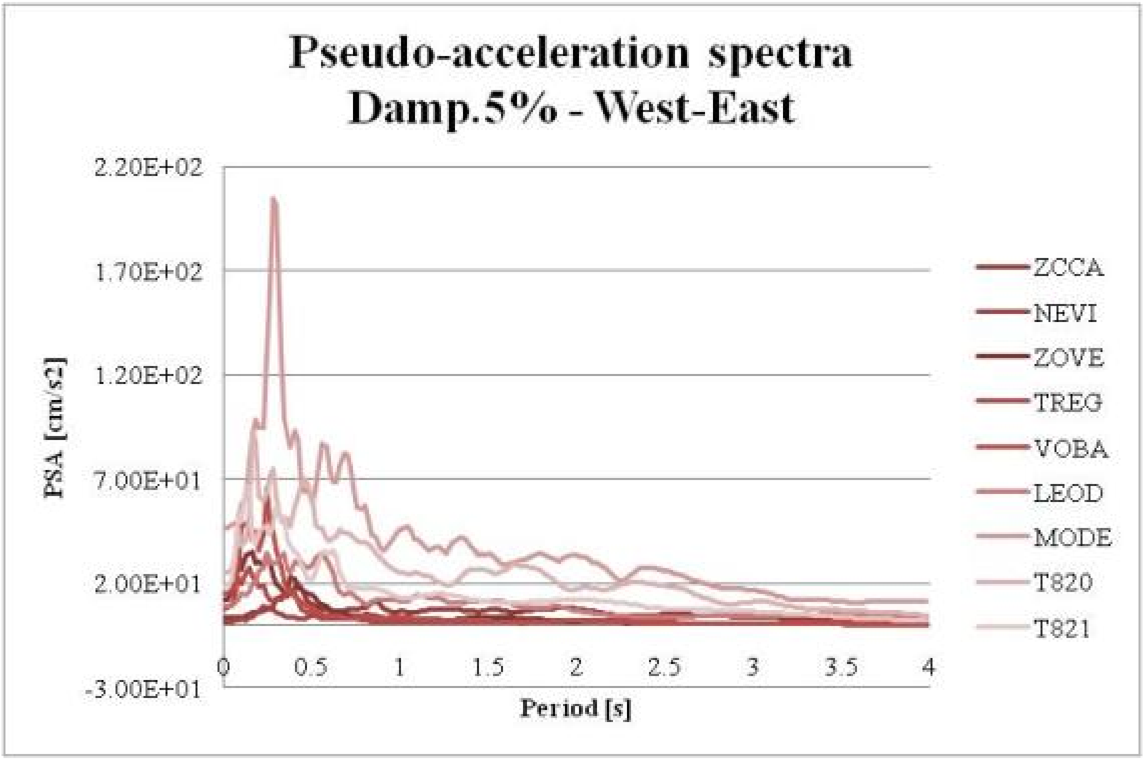


Figure 3-24 PSA Damp 5% East-West

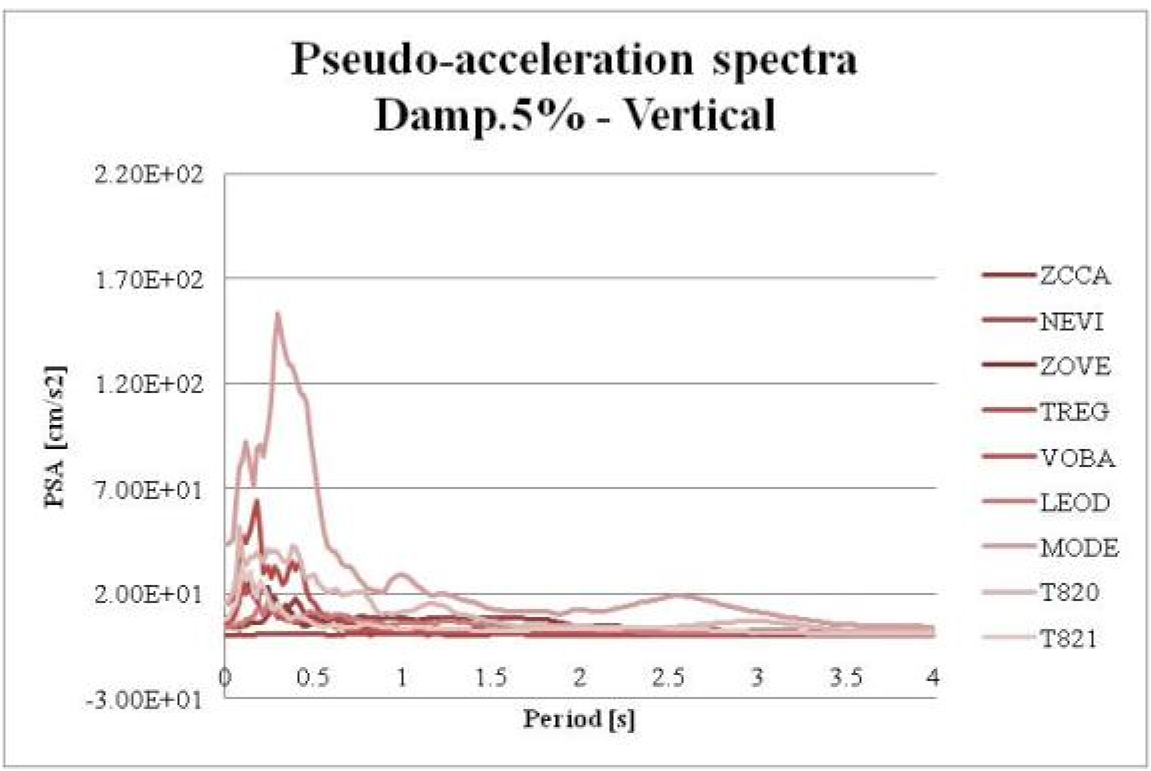


Figure 3-25 PSA Damp 5% vertical direction

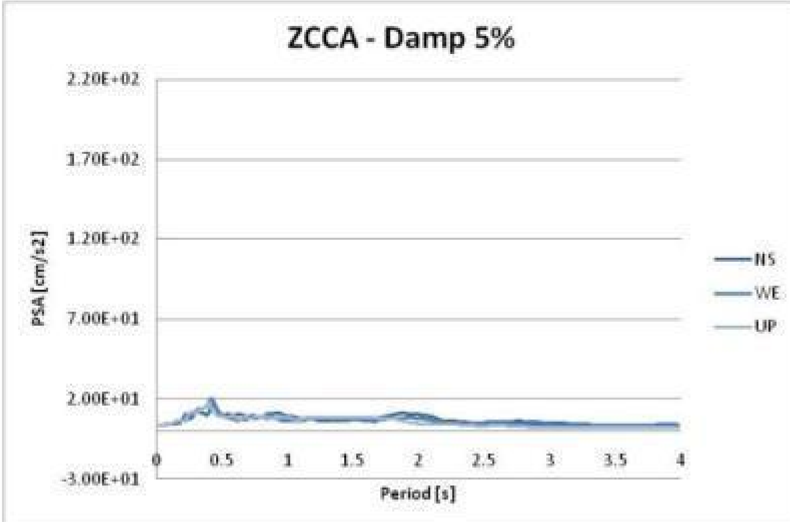


Figure 3-26 PSA Damp 5% ZCCA station

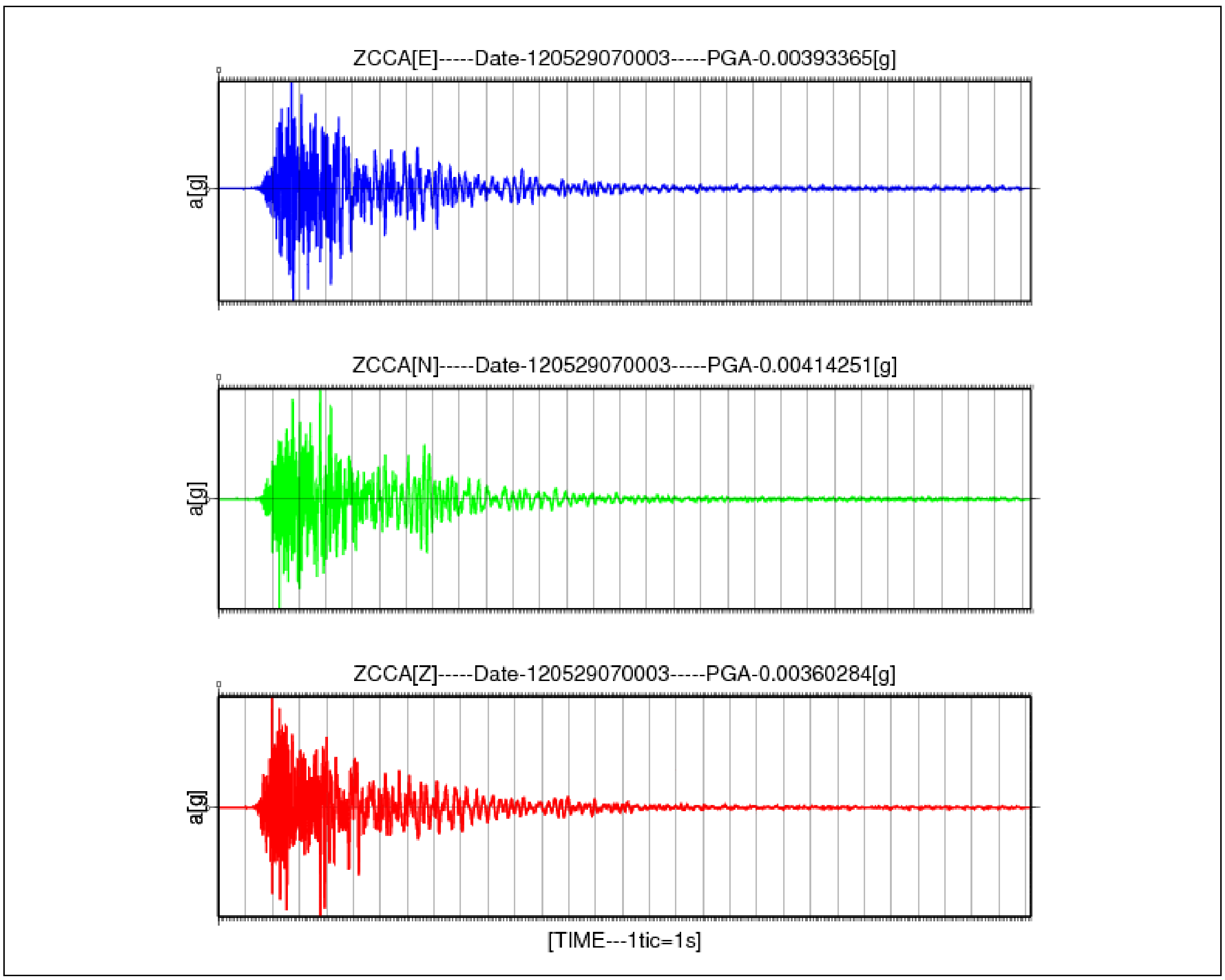


Figure 3-27 Accelerograms ZCCA station

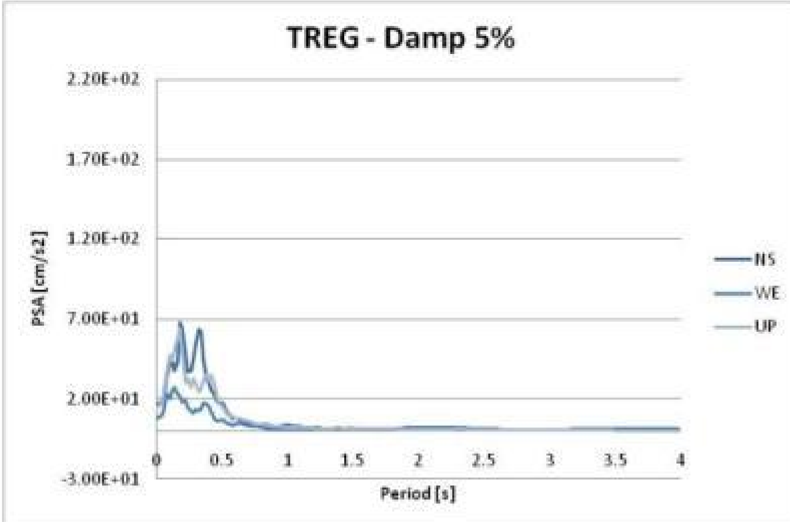


Figure 3-28 PSA Damp 5% TREG station

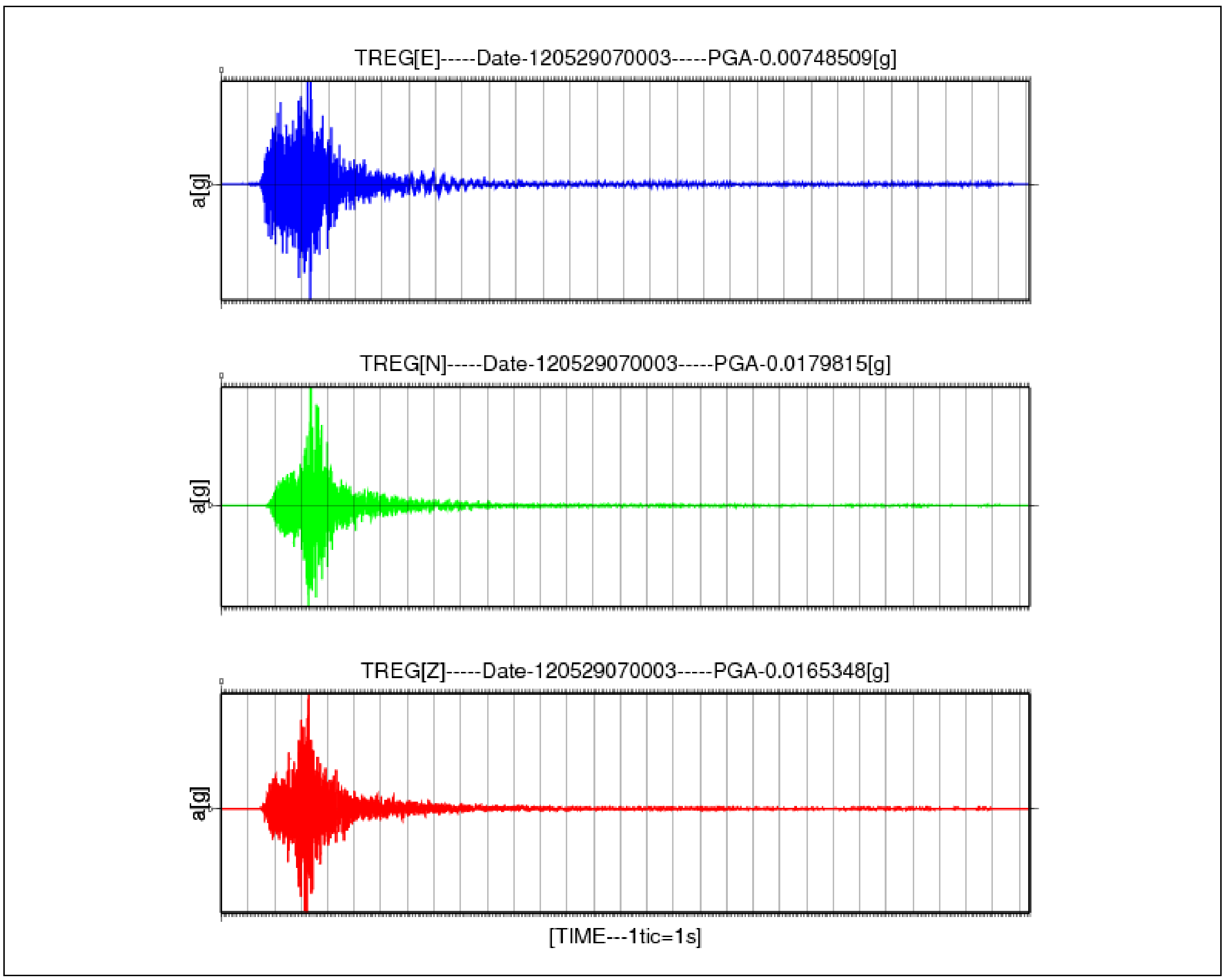


Figure 3-29 Accelerograms TREG station

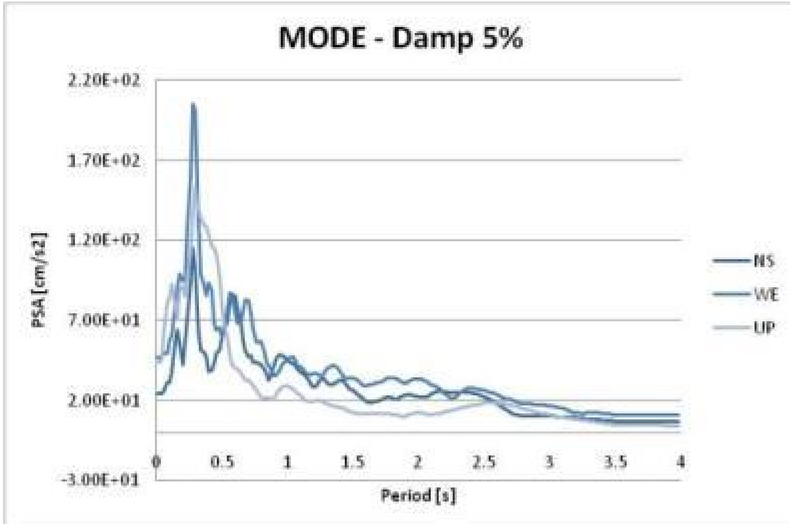


Figure 3-30 PSA Damp 5% MODE station

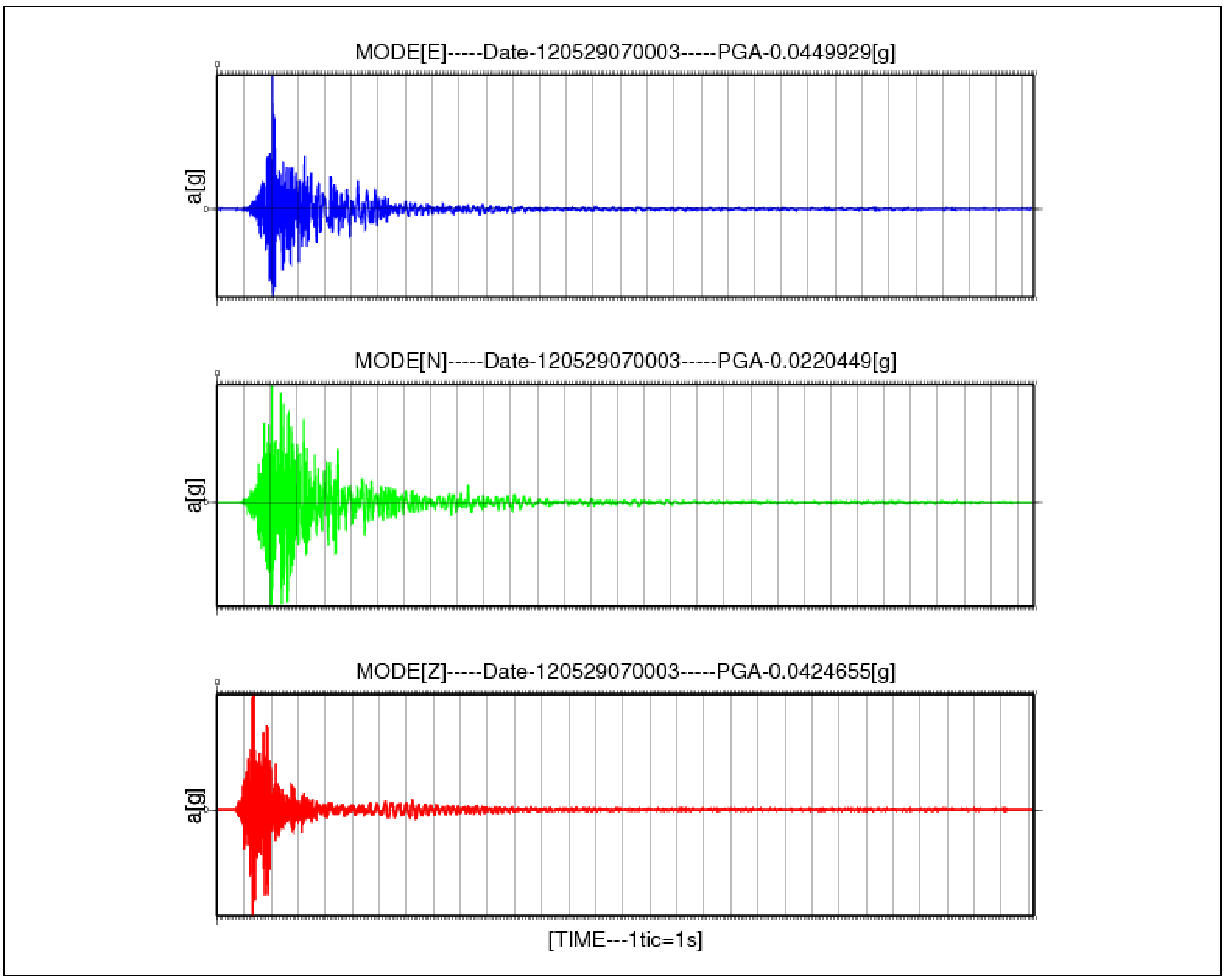


Figure 3-31 Accelerograms MODE station

3.2.4 Earthquake of May 29, 2012 (10:55:57 UTC) M_w 5.3 (44°88'N 11°00'E) ID 120529105557

Figure 3-32, Figure 3-33 and Figure 3-34 represent only nine pseudo- acceleration spectra. The criterion by which they were chosen is as follows: the recordings of the three nearest stations in term of epicentral distance, for each category of ground.

Table 3-9 Earthquake records shown in Figures 3-32 to 3-46

Station	PGA [cm/s²]			PGV [cm/s]			R_{epi} [km]	EC8 site class
	EW	NS	UP	EW	NS	UP		
ZCCA	2.58119	2.35988	2.2992	0.595494	0.678327	0.34251	59.68	A
NEVI	1.10126	0.911308	0.20239	0.165152	0.139471	0.036511	64.84	A
ZOVE	4.98032	7.30559	3.38428	0.162427	0.253399	0.113183	73.58	A
TREG	4.28886	7.93136	7.30977	0.123181	0.257729	0.248137	71.54	B
VOBA	8.4312	6.54921	4.38563	0.325286	0.40154	0.158331	92.99	B
LEOD	4.4376	5.32062	2.54211	0.746504	0.823765	0.279686	94.94	B
MODE	19.6689	16.4297	22.7641	3.56006	2.21651	0.967942	29.05	C
MNTV	47.2387	40.5743	14.0672	5.42481	4.66399	1.15803	33.87	C
T821	4.75066	6.09633	2.22333	0.358397	0.436622	0.121799	42.64	C

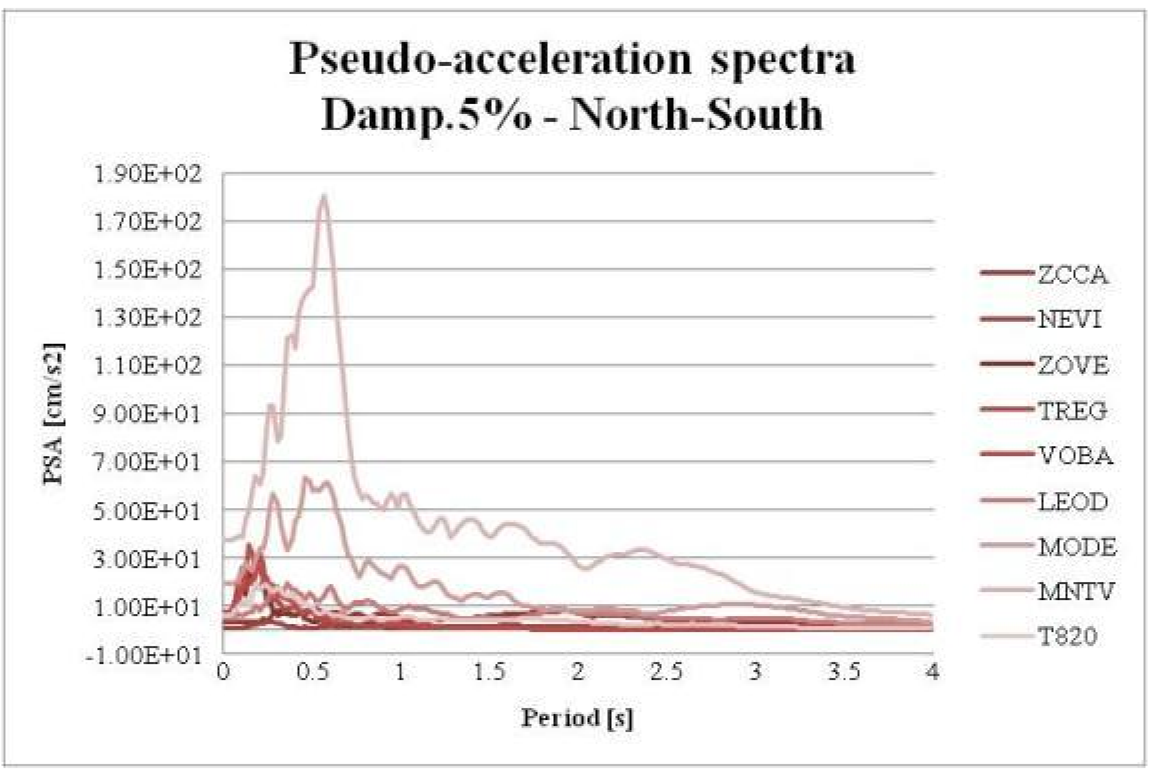


Figure 3-32 PSA Damp 5% North-South

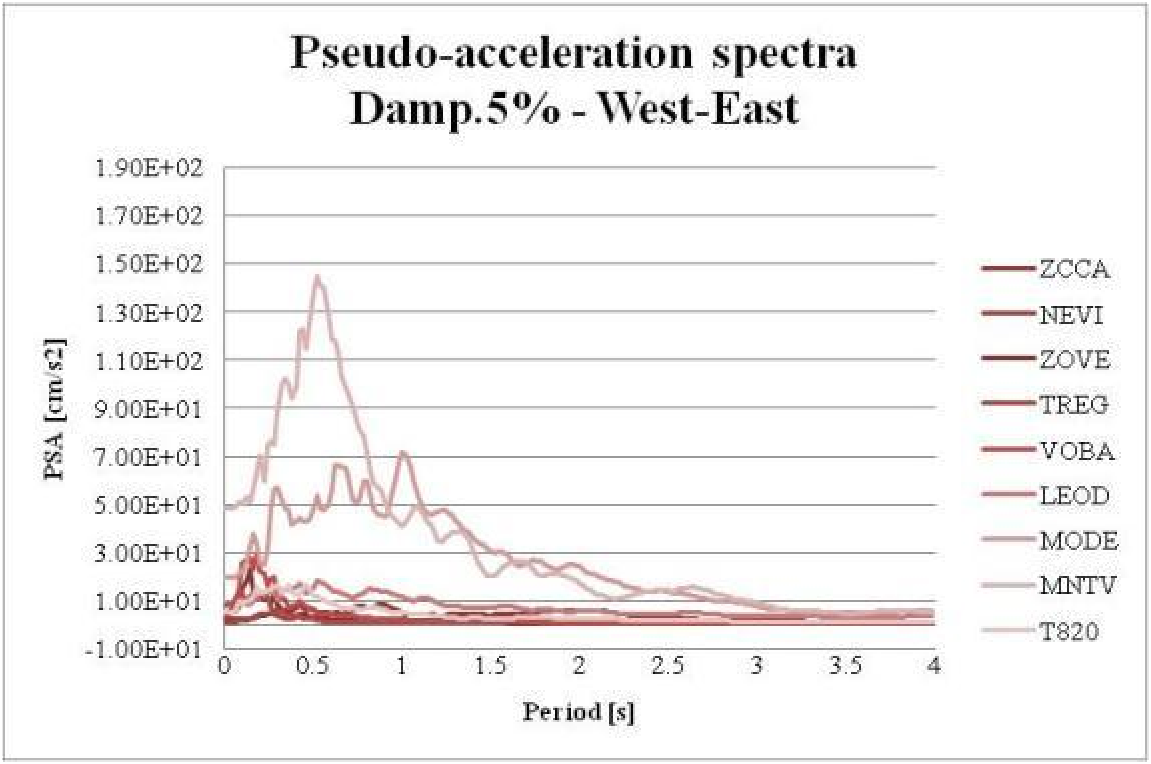


Figure 3-33 PSA Damp 5% East-West

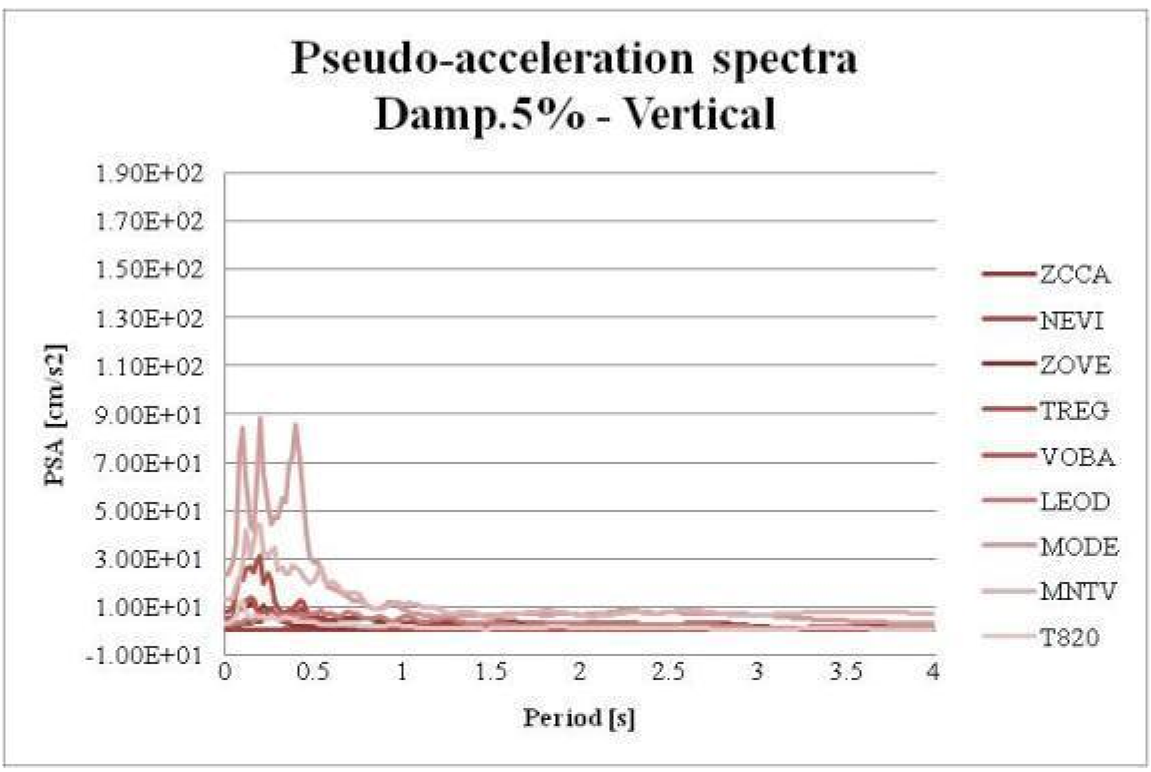


Figure 3-34 PSA Damp 5% vertical direction

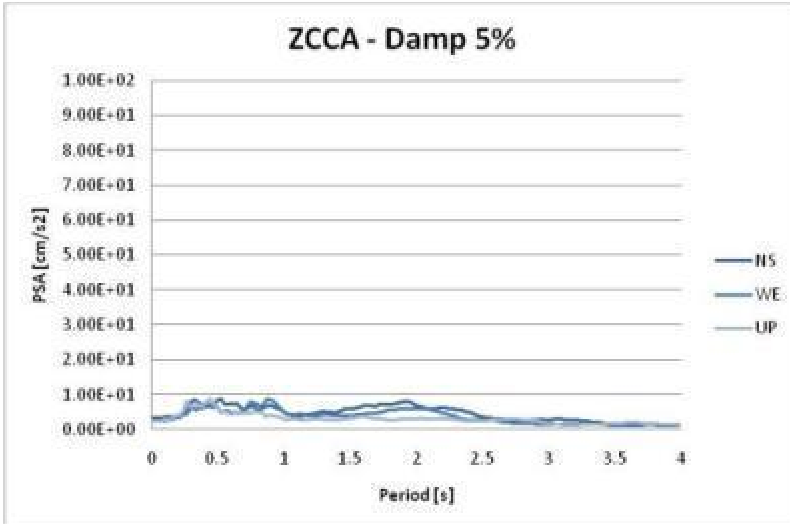


Figure 3-35 PSA Damp 5% ZCCA station

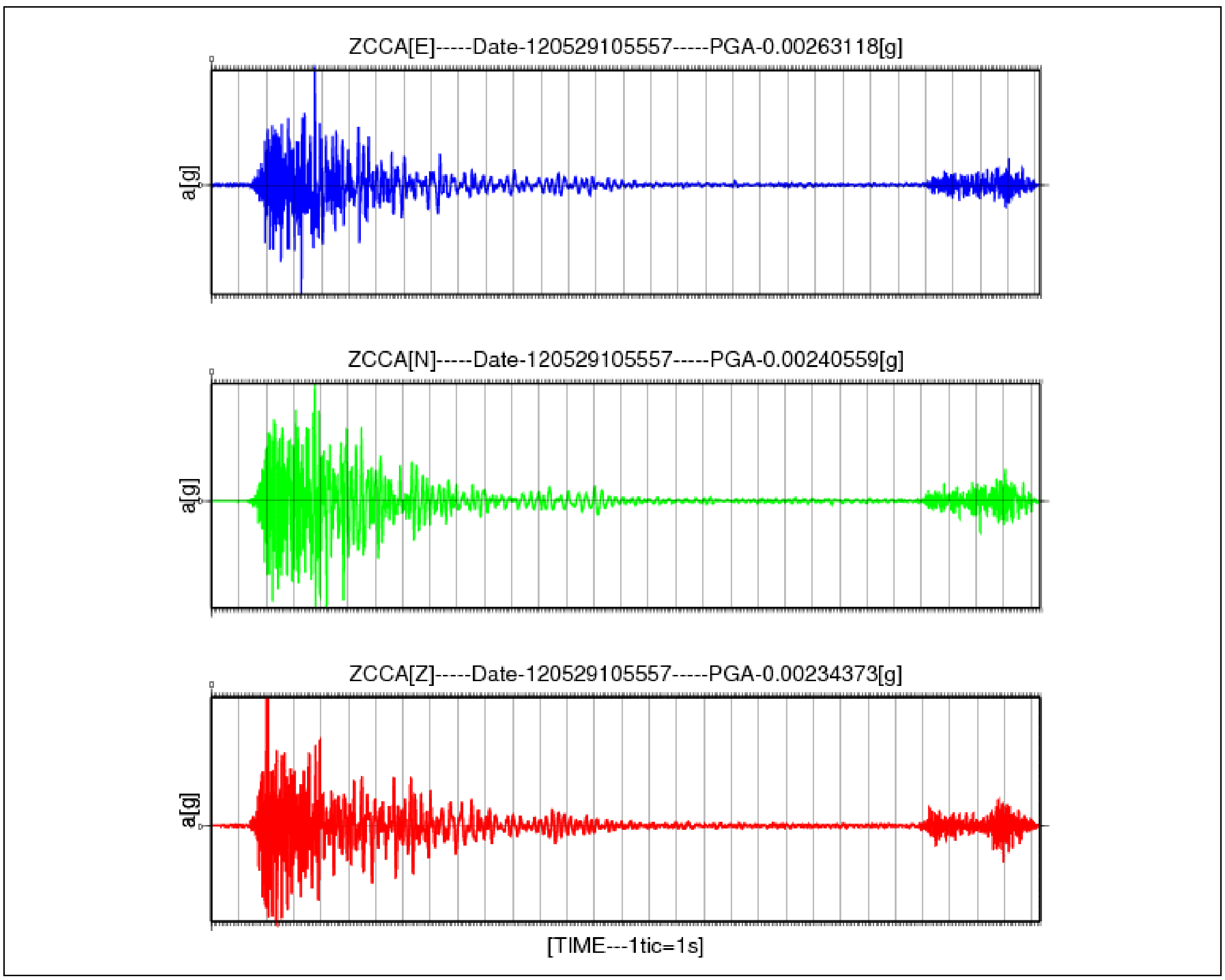


Figure 3-36 Accelerograms ZCCA station

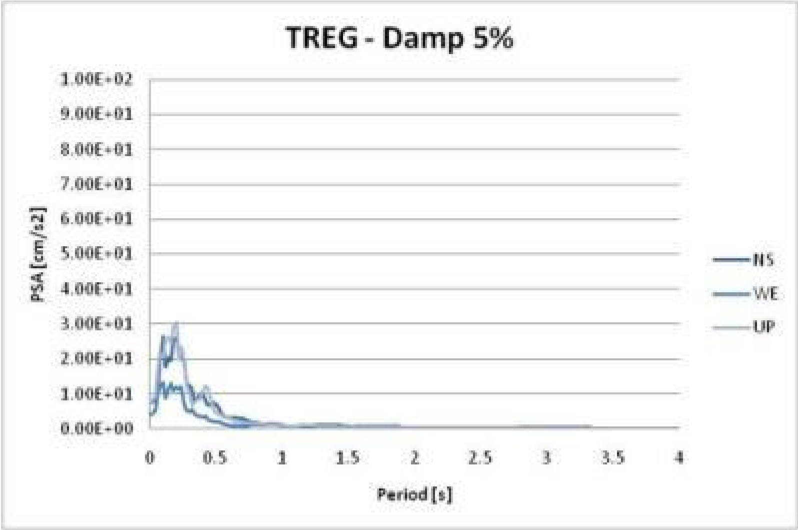


Figure 3-37 PSA Damp 5% TREG station

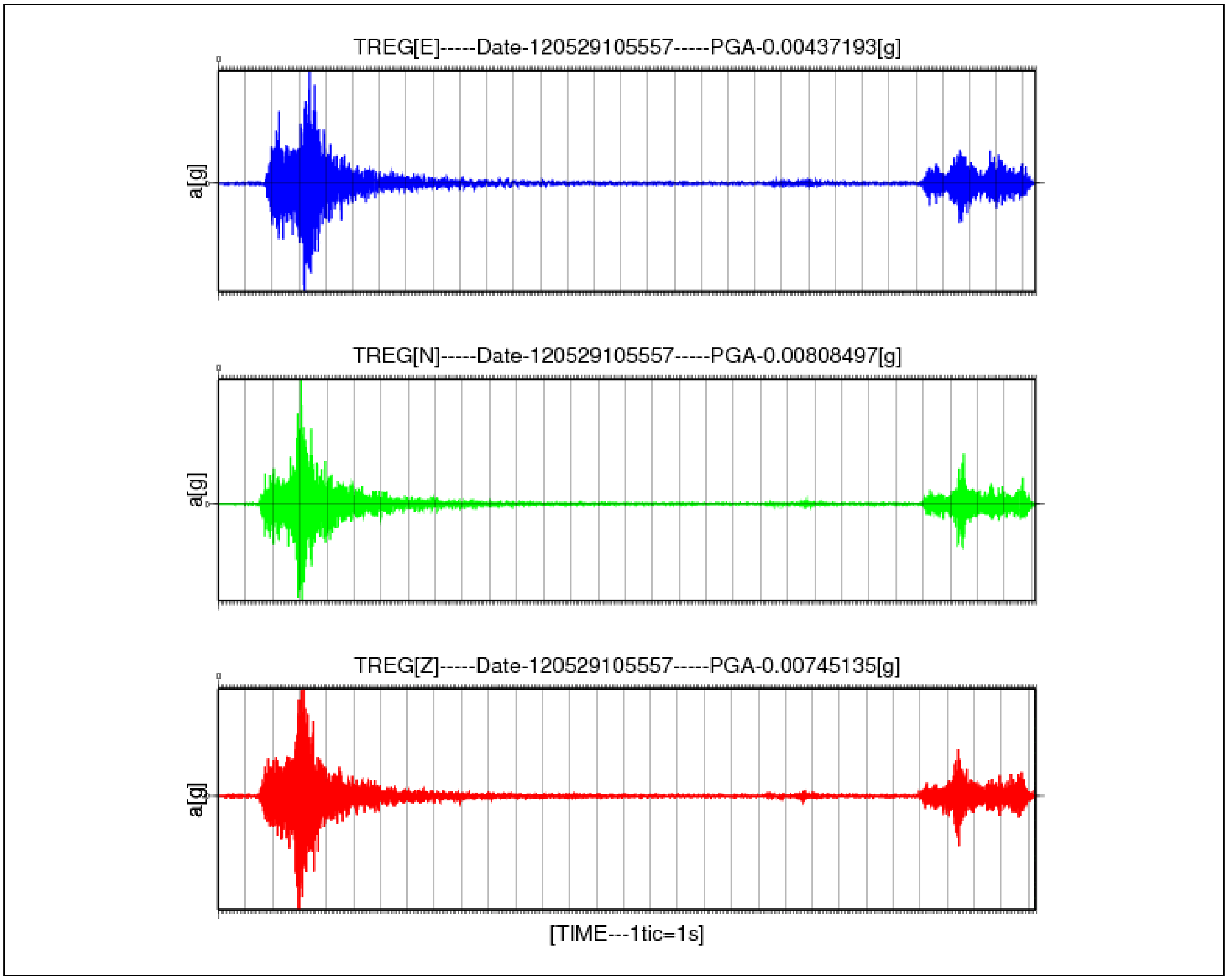


Figure 3-38 Accelerograms TREG station

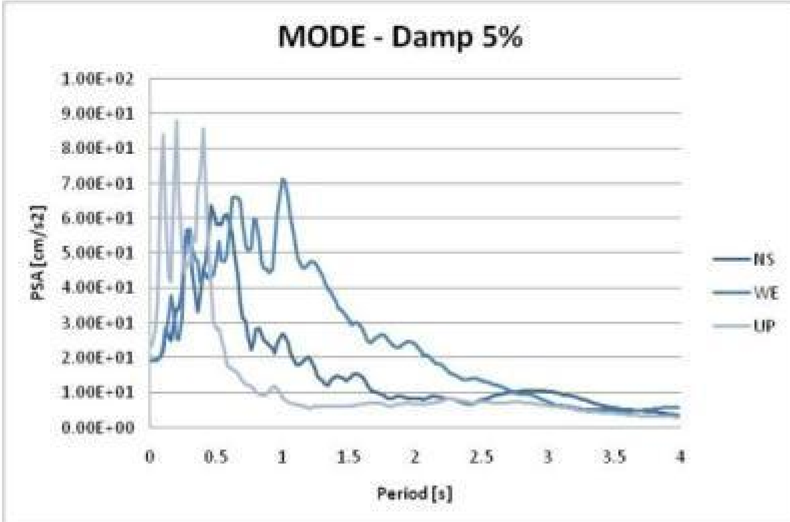


Figure 3-39 PSA Damp 5% MODE station

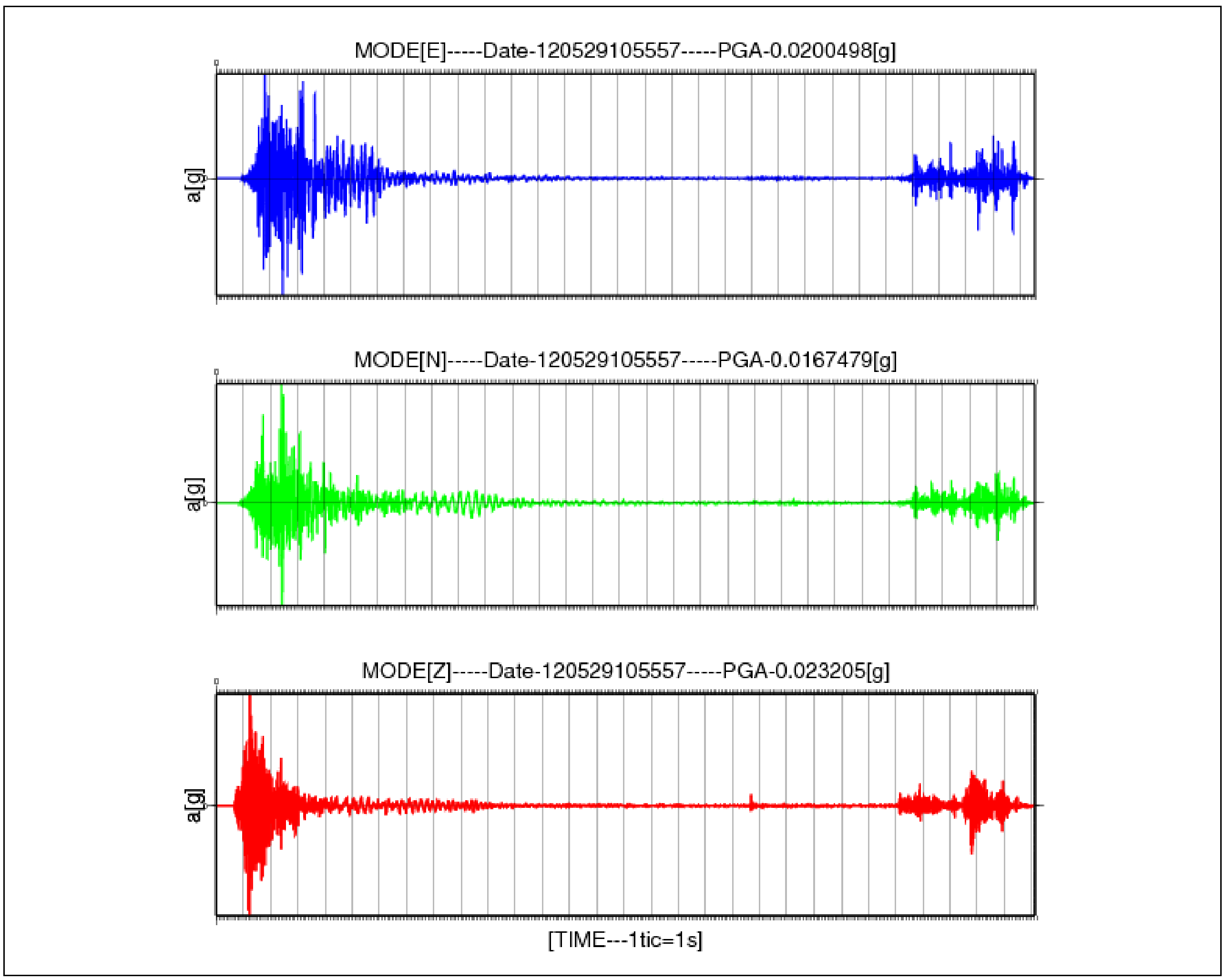


Figure 3-40 Accelerograms MODE station

3.3 Implications for Seismic Hazard Analysis

After the Messina earthquake in 1908, the Italian government imposed certain regulations for new buildings in seismic regions. Since then, in Italy after each earthquake, there is a new code for seismic design.

The main modifications to the Italian seismic standard initiated after 1980 Irpinia earthquake, when the first seismic zonation (Figure 3-41) in Italy was introduced, and concluded in 2003 with the OPCM 3274/2003 seismic code.

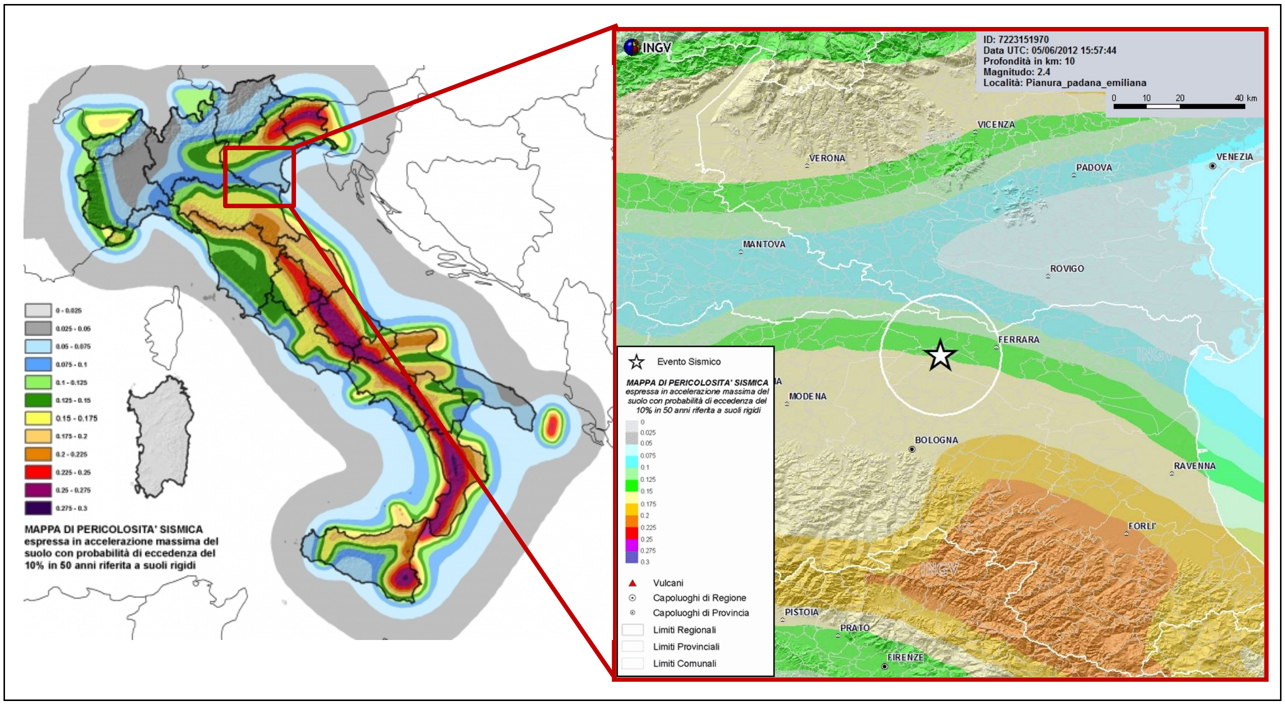


Figure 3-41 Seismic hazard map of Italy

Almost the entire Italian territory was divided into four zones (e.g., in the first category, severe earthquakes have the highest probability to occur).

The towns of the Po Valley affected by the earthquake are classified mostly in zone 3 (low hazard). This is according to the resolutions of the Board Emilia Romagna Regional n. 1435 of 21 July 2003 in acknowledgment of the reclassification of the entire seismic territory referred to OPCM 3274/2003.

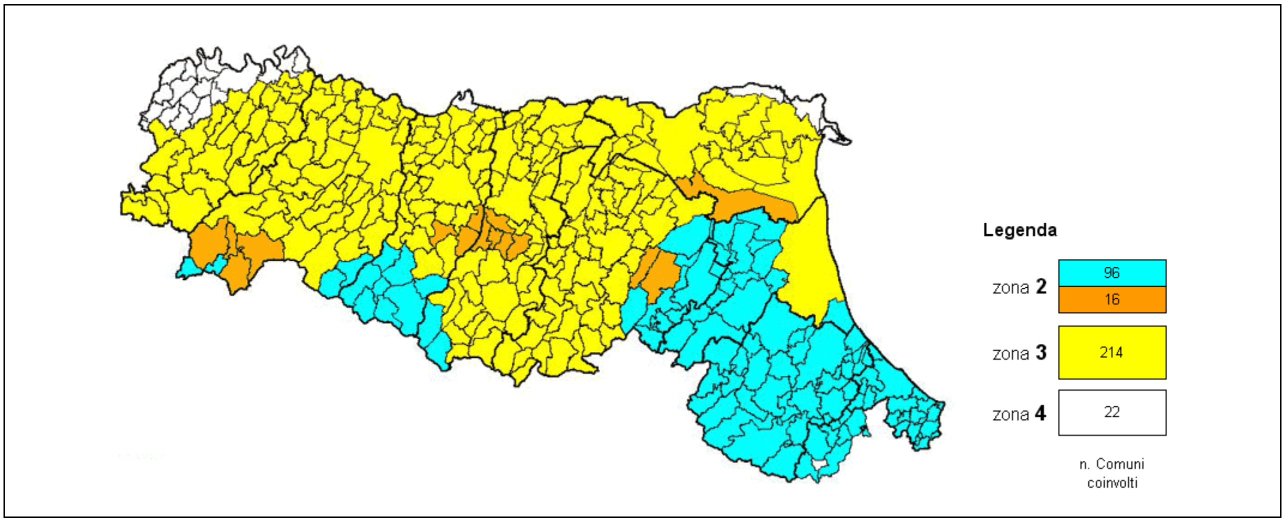


Figure 3-42 Seismic hazard map of Emilia Romagna

Today, seismic regions in Italy cover more than 70% of the territory, but only 18% of the buildings have been constructed in accordance with the seismic code. The most recent seismic code was released in January 2008 (NTC, 2008), but was not mandatory for non-critical facilities until after June 2009.

SECTION 4
GENERAL OVERVIEW OF OBSERVED DAMAGE

The earthquake epicenters followed a trajectory that goes from east to west. During this earthquake swarm, many municipalities were damaged. By observing the damage in these municipalities and collecting data, an overall picture of the situation can be obtained.

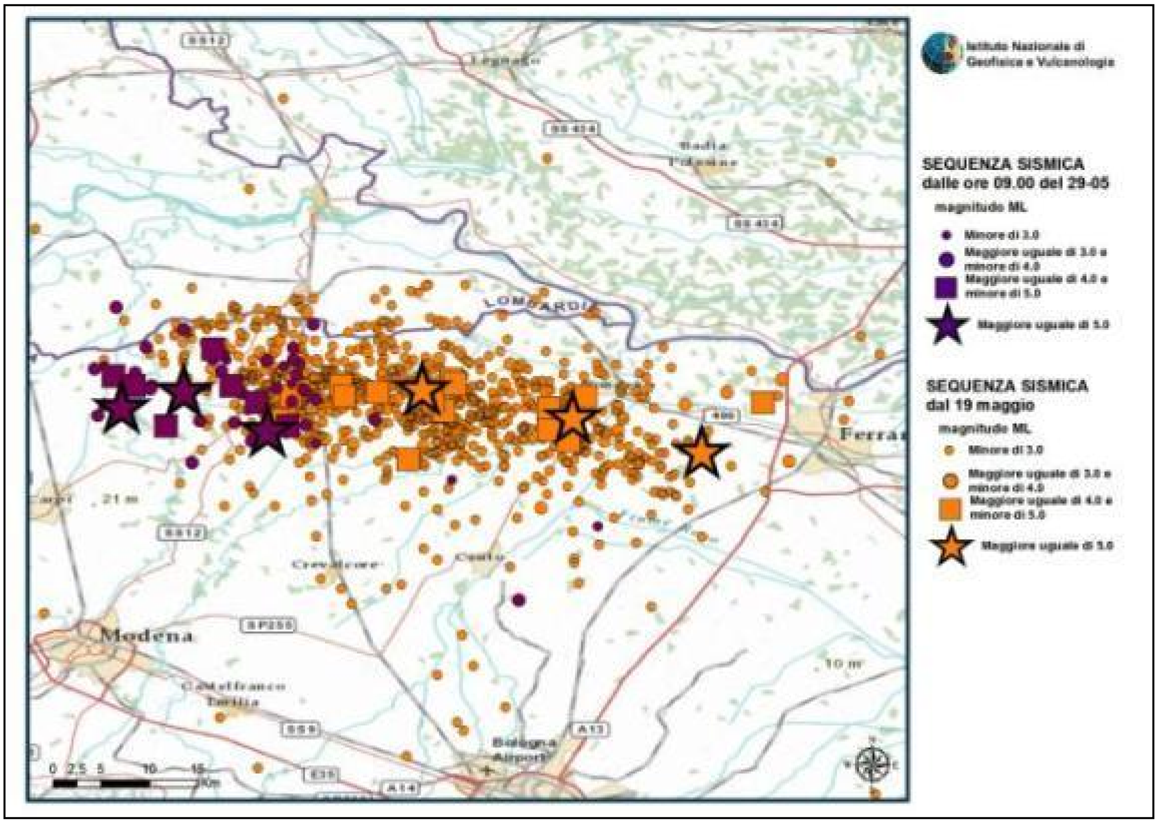


Figure 4-1 Path taken by the earthquake's epicenter

In Vigarano Mainarda, damage to the local church was reported, while the damage to masonry and reinforced concrete low-rise residential housing and small local businesses was minor. In this town, approximately 100 local people were evacuated from their homes as a precaution, but the captain of the fire brigade estimated that only a quarter of them would need re-housing.

In the town of Mirabello, a movement of buildings lining the main street occurred as rigid bodies down slope. This was due to liquefaction of the soil at a relatively shallow depth. This was visible as uplift of the pavement stone and by the cracks that indicated movement.

Figure 4-2 Evidence of lateral spreading in the street in Mirabello

The street affected by the lateral spreading was originally a small river, and, according to the locals, the river flowed in the direction of S. Carlo e S. Agostino, where further evidence of lateral spreading and liquefaction was found. The damage to residential structures outside the main street was negligible; only some nonstructural elements suffered minor damage. The new reinforced concrete low-rise residential houses were undamaged.

Figure 4-3 Damage to a residential building in San Carlo due to soil liquefaction

The town of San Carlo suffered liquefaction of soils and encountered a large amount of damage to residential buildings, elementary schools and industrial facilities built with precast reinforced concrete.

Figure 4-4 Damage to industrial facilities in San Carlo

The church and the town hall in Sant'Agostino collapsed and were declared inaccessible. However, the greatest damage occurred to industrial facilities. Here, the collapse of a warehouse of the S. Agostino Ceramic Factory caused the death of two workers.

Figure 4-5 Collapse of a ceramic tile warehouse in S. Agostino

Many people were displaced in Finale Emilia. In fact, a lot of damage was reported, especially for old and poorly maintained masonry structures. However, new private houses did not have accessibility and/or livability issues.

In Felice sul Panaro, residential buildings were either not damaged or only slightly damaged, while monumental and historical buildings, including the old castle, suffered major damage. Industrial and commercial buildings suffered damage when conditions of structural vulnerability were present.

Figure 4-6 Collapse of a masonry house in Finale Emilia

Figure 4-7 Damage to the old castle in Felice sul Panaro

SECTION 5

GEOTECHNICAL EFFECTS

The soil where the most damage was observed is characterized by unconsolidated ground layers. This has led to the amplification of ground acceleration resulting in damage to infrastructure and buildings due to settlement. The ground is characterized by a clay material overlaying layers of sand, possibly saturated due to the flood plain region and other underlying clays. For this reason, these regions are susceptible to liquefaction that causes differential settlement in the structures and lateral movement of the ground underlying the structures.

Figure 5-1 Liquefaction in San Carlo

5.1 Geological Lithology, Stratigraphy and Ground Amplification

The area between Modena and Ferrara consists mainly of clay or clay prevailing material, with some zones of clay sand or sand. The area is quite flat and there have been numerous floods in the past, mainly due to the Po and Reno rivers. For this reason, the ground consists mainly of an alluvial plain, stratified with layers of fine sand and sometimes silts.

Figure 5-2 Surface lithology of Finale Emilia and San Felice sul Panaro

The soil is characterized by unconsolidated ground and its layered structure is the reason for the large seismic amplification.

5.2 Liquefaction

Widespread liquefaction phenomena were observed at some ancient rivers now abandoned.

These phenomena have been particularly important in some of the towns in the western sector of the province of Ferrara, especially in San Carlo, a suburb of Sant'Agostino, where they caused a temporary unavailability of some buildings, the closure of some roads, and the breaking of water pipelines. Mirabello also suffered from this problem.

The liquefaction in these towns was triggered by the main shock of 20 May, and the aftershocks did not cause any significant problems.

Based on historical data, the area where liquefaction was discovered falls between the alluvial plain areas within which there have been previous cases of liquefaction, during earthquakes of similar intensity to the main event.

Therefore, the area is considered geologically susceptible to liquefaction due to the presence of sandy-silty deposits of recent origin in the surface layers. However, the environment in this area has been visibly changed by man, with the intervention of defense against floods and stagnation in large inter-fluvial depressions. The plain in this area is crossed by ancient drains and streams that got lost in the underground and became marshes.

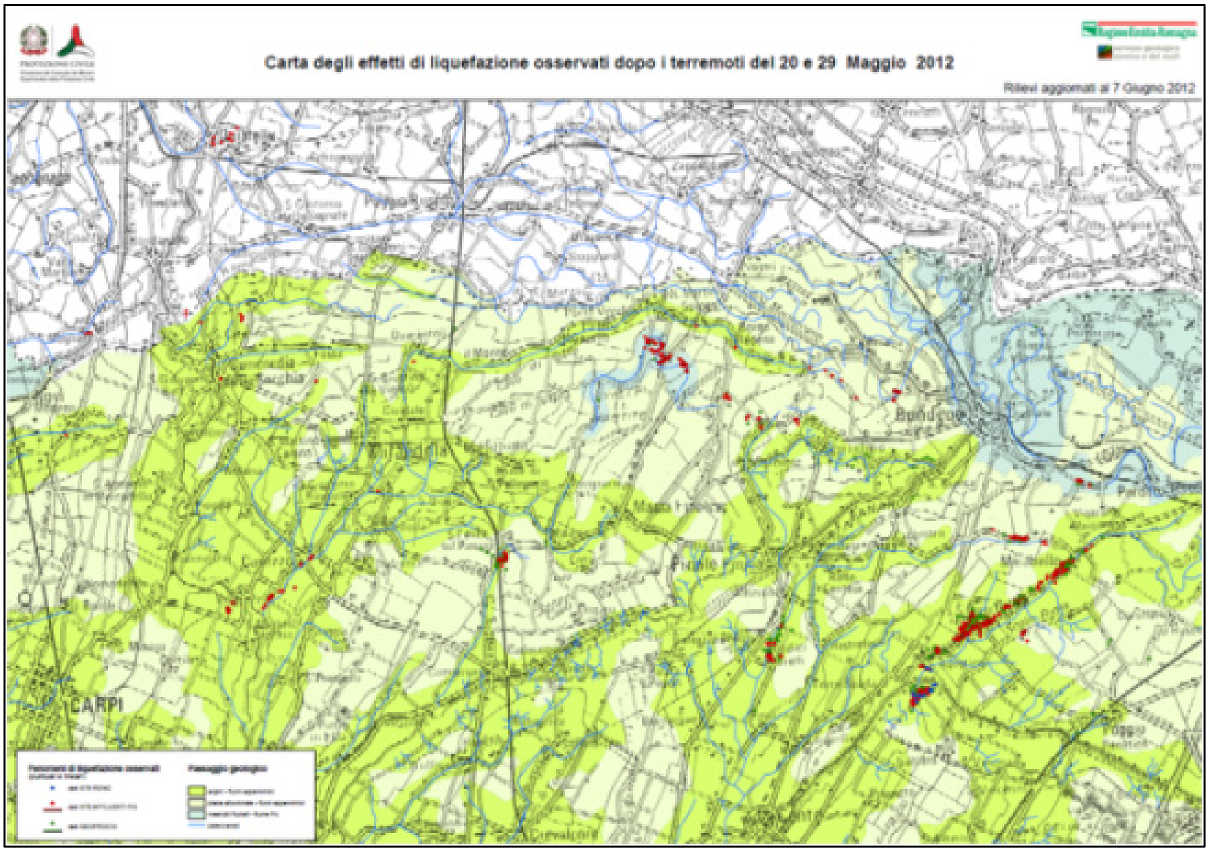


Figure 5-3 Map of the effects of liquefaction

The localization of the effects observed shows a correlation with the presence of paleo river bed of the Secchia, Panaro and Reno rivers. The effects observed are due to three main causes: liquefaction due to overpressure of the aquifer hosted by areas of sandy soil, extensional fracturing with predominant horizontal separation, and liquefaction associated with fracturing.

Figure 5-4 River valley in San Carlo

5.2.1 Liquefaction due to Overpressure of Aquifer Hosted by Areas of Sandy Soil

The liquefaction phenomena involve mainly grayish fine sand and, in some cases, yellow sand. In most cases, the alignment of numerous ducts and sand spills arranged in coalescent volcanoes can be observed. Furthermore, wells for pumping water for irrigation (10-15 m) that served as conduits and were later filled with sand were observed to be leaking in some cases.

Figure 5-5 Wells in San Carlo (Sant'Agostino)

Figure 5-6 Aquifer level in the wells in San Carlo (Sant'Agostino)

In the towns, liquefaction is often linked to the presence of artifacts that may have functioned as preferential escape routes.

Figure 5-7 Liquefaction phenomena

In some sporadic cases, observations associated with liquefaction included bulges and subsidence of the ground.

Figure 5-8 River valley in San Carlo

San Felice sul Panaro, San Carlo in Sant'Agostino and Bondeno are the municipalities most affected by these phenomena.

Figure 5-9 Structural damage due to liquefaction in San Carlo (Sant'Agostino)

5.2.2 Extensional Fracturing with Predominant Horizontal Separation

Open fractures with little or no systematic vertical discards, with an apparent en-echelon, were mostly found in the eastern sector, and can be followed for several hundred meters. Locally, small spills with sand were also observed.

Figure 5-10 River valley in San Carlo

Figure 5-11 River valley in San Carlo

Figure 5-12 Damage due to liquefaction

5.2.3 Liquefactions Associated with Fracturing

The fractures associated with liquefaction are also more prevalent in the eastern sector, in the area between Bodeno, Mirabello and San Carlo.

They consist of fractures ten meters long, often in en-echelon apparent, which leak a large amount of fine sand gray.

Figure 5-13 Structural damage due to liquefaction in San Carlo (Sant'Agostino)

Figure 5-14 Structural damage due to liquefaction in San Carlo (Sant'Agostino)

SECTION 6
WAREHOUSES AND INDUSTRIAL SHED STRUCTURES

6.1 Introduction

In Emilia, many industrial shed structures were used for different purposes such as schools, gyms, commercial buildings and the like. They can be classified according to type of structural elements and roof coverage.

The type of structural elements can be further distinguished as:

i. Continuum systems (e.g. panels);
ii. Punctual systems (e.g. columns);
iii. Mixed systems (e.g. panels and columns)

Another option for distinguishing industrial structures in the Emilia region, which is adopted in this report, is based on the type of material used as follows:

- Precast RC
- Pre-stressed precast concrete
- Steel frames
- Masonry with reinforced concrete or timber frames.

However, 90% of the warehouses in the Emilia region were constructed using RC and pre-stress precast techniques, with large internal spans. In these sheds, there are only corner pillars and sometimes a central row and two edge rows. Sheds are precast. Columns, footings, and beams are made in special plants, transported to the site, and assembled there for reasons of rapidity. Most precast structures are statically determined, with beams simply supported with only a neoprene layer (Cimellaro et al., 2014).

6.2 Probable Reasons for Collapse

The most probable reason for the collapse of industrial sheds during the earthquake is that they were built without following seismic design criteria. The area, however, was not classified as one of high seismicity; therefore, engineers that designed the warehouses were not obliged to connect plinths at the foundation level or beams with columns.

Most of the columns in the industrial sheds do not have foundations (plinths) connected to each other. Columns are also very slim and therefore highly deformable, so the masses on top are free to move when subjected to a horizontal excitation. Columns are flexible and are able to deform, while beams are generally simply supported; therefore, in the absence of particular connections, they collapse with the entire roof. For these reasons, this type of structure might have large vibration periods and, because of the soil conditions, the ground shaking had amplification at smaller frequencies. Therefore, shed structures had significant horizontal forces and were the most damaged type of structure during the earthquake. Indeed, at the top of the columns supporting the shed, displacements of about 20-30 cm were recorded. The beam or the plate was placed on these columns with 10-15 cm of support; therefore, when subjected to the displacements recorded, they collapsed.

Other reasons for collapse of industrial sheds during the Emilia earthquake are:

- Eccentricity between masses and stiffnesses (Figure 6-16, Figure 6-19, Figure 6-20)
- Panel-structure interaction (Figure 6-7, Figure 6-8, Figure 6-12)
- Nonstructural components (e.g., scaffold systems, machines etc.)
- Vertical earthquake component

6.3 Precast Reinforced and Precast Pre-stressed Concrete Industrial Structures

The most common design scheme is a single bay portal frame with RC columns (Figure 6-1, Figure 6-12, Figure 6-13, Figure 6-16), supporting pre-stressed long span beams in the transversal direction (Figure 6-20). On top of the columns, RC precast T or rectangular beams connect the series of portal frames in the longitudinal direction. The beams in either direction are generally simply supported on the top of the columns and are held in position by shear key U-shaped or L-shaped extrusions.

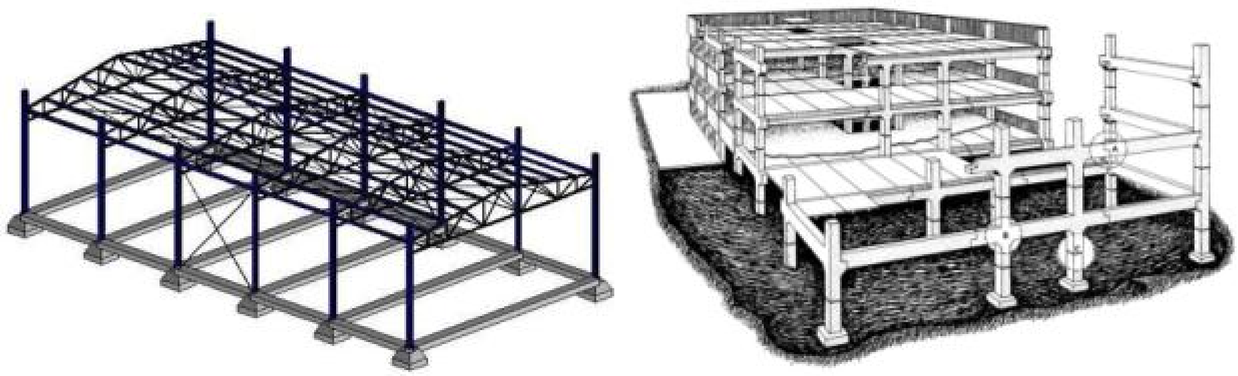


Figure 6-1 Precast building systems

In the absence of shear keys, the transverse beam is connected to the column by means of a system of steel plates and bolts. Many columns also have corbels in the transverse plane to support a bridge crane (Figure 6-21, Figure 6-30).

Some of the columns have an I-shaped cross section in order to support precast wall panels between successive columns. For rectangular columns, the precast RC cladding is connected to the columns using metal plate connectors and bolts (Figure 6-44), which were not able to resist the earthquake forces when the panels were located horizontally.

Other structures had masonry infill instead of RC precast panels (Figure 6-14, Figure 6-16). For most of these structures, the roof consisted of double T-precast pre-stressed slabs spanning in the longitudinal direction.

The lightly connected beams and columns are equivalent to a pin/roller connection at the upper part of the structure (Figure 6-48, Figure 6-3), and it is only the column to foundation connection that prevents the structure from failing under static load conditions (Figure 6-52). This made the structures very vulnerable, particularly to lateral loads induced by the earthquake. As a result, the most common type of failure mechanism observed consisted of the rotation of columns in opposite directions, such that the transverse and longitudinal beams slipped off the column connection and collapsed (Figure 6-2).

Plastic hinges were also observed at the base of the columns (Figure 6-54, Figure 6-55). In most cases, the shear key also failed (Figure 6-5, Figure 6-6). It was observed that the latter was not adequately detailed with reinforcement, and no redundancy provisions were provided to make a monolithic connection (Figure 6-6, Figure 6-38).

6.3.1 Failure due to Slip of Beams from their Shear Key

Figure 6-2 and Figure 6-3 show the failure mechanism of a factory constructed in 2007. The columns on one side of the structure formed plastic hinges at the level of the corbel (Figure 6-3). In particular, in Figure 6-2, the columns are no longer vertical and it is possible to see the plastic hinges located at the mid height of the columns, which allowed the column rotation. Consequently, the beams, which were simply supported on top of the columns, collapsed.

On the same side, the transverse beam is very deep and was connected by two bolts to the lower column. The beams slipped from the shear key on the other side, where no mechanical fixity was observed (Figure 6-2). The most probable reason for collapse in this case was the poor strength of the columns, which were slim and flexible.

(a) *(b)*

Figure 6-2(a) Overview of industrial shed in San Felice sul Panaro, where beams slipped from the shear keys; (b) plastic hinge at the level of the corbel

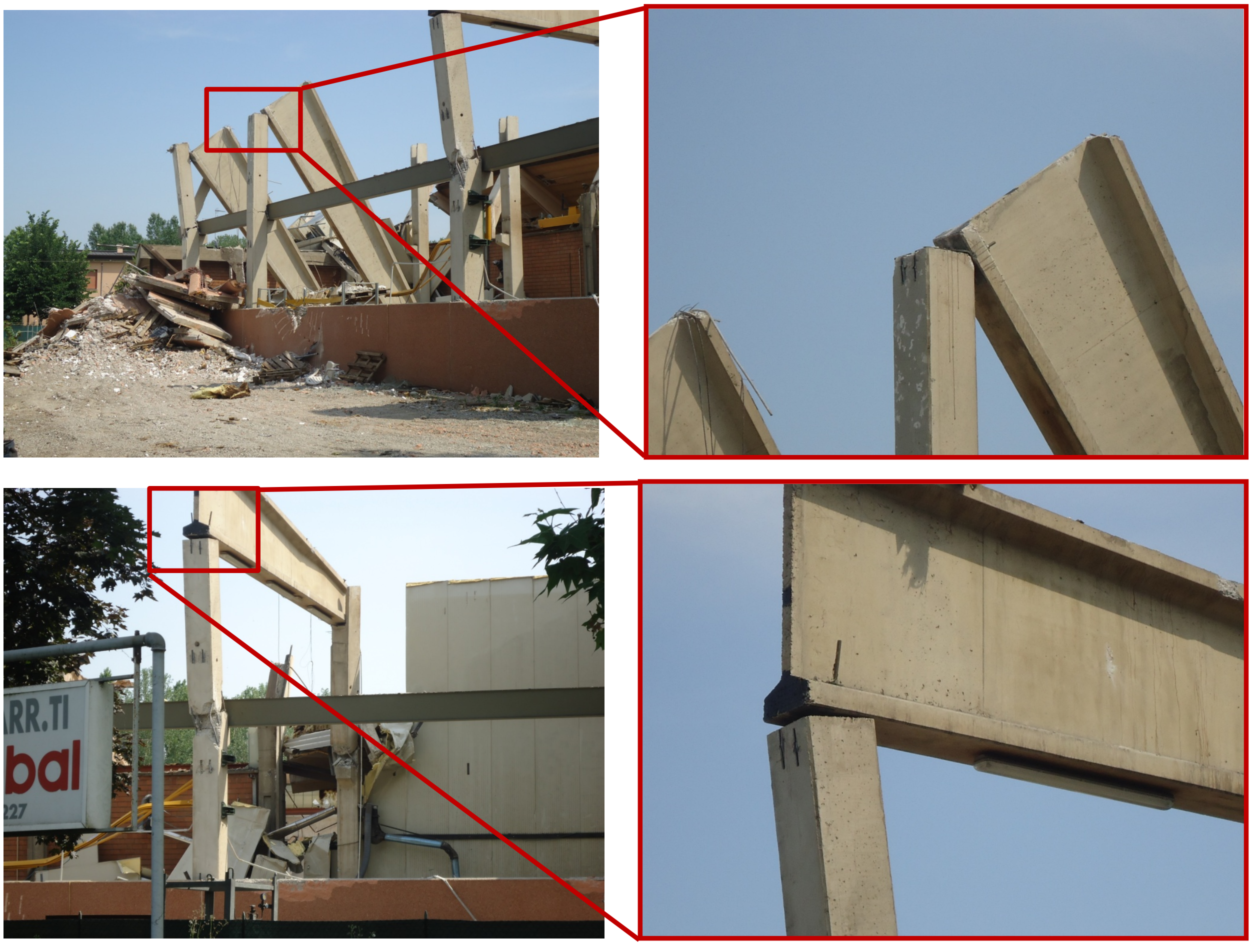


Figure 6-3 Typical flathead beam-column connection with insufficient seismic restraints (Mirandola)

6.3.2 Other Classifications of Industrial Shed Structures in the Emilia Region

1. Industrial shed structures constructed between 1970-1980, which either had slender pillars that were very flexible or brick panels
2. Recent shed structures with oversized beams and columns

These shear keys were not properly reinforced and were the only restraint to horizontal transversal forces caused by the earthquake (Figure 6-5, Figure 6-6).

The reason for this classification is that they behaved differently during the earthquake.

Figure 6-4 Overview of industrial shed of BBG.srl

Figure 6-5 Shear keys with no reinforcement of BBG.srl

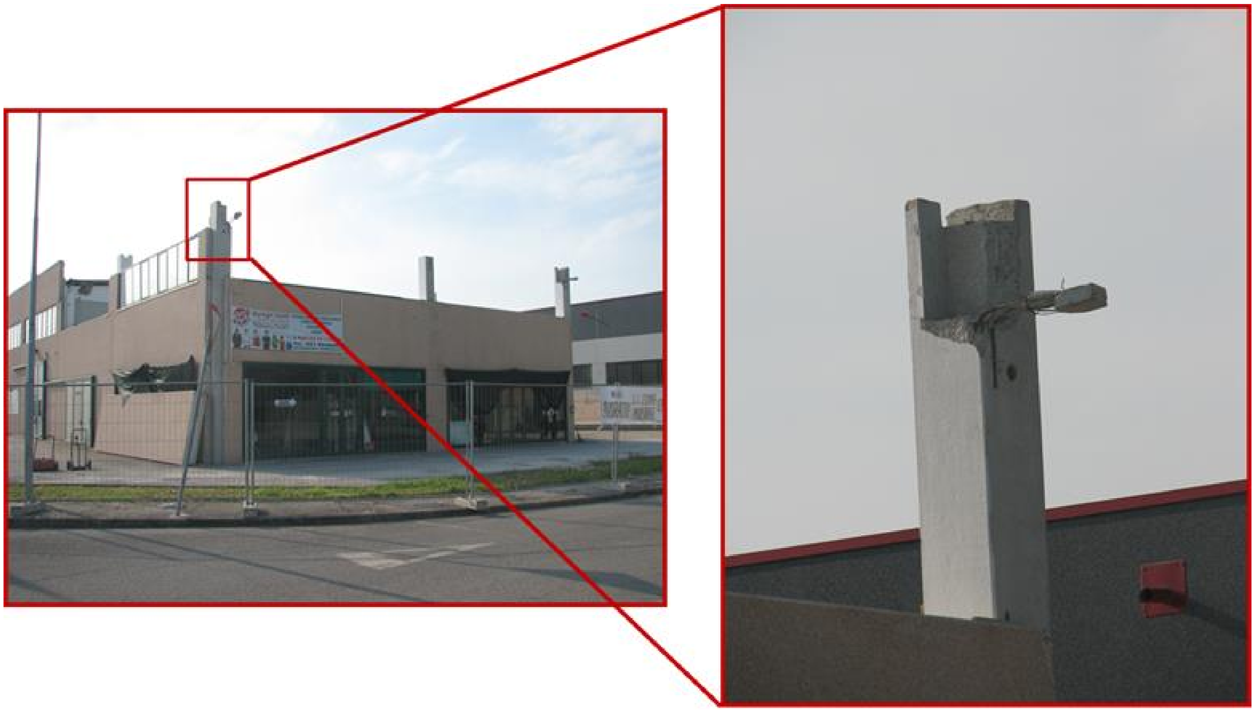


Figure 6-6 Examples of shear key with no reinforcement

Figure 6-7 shows the interaction between the lateral precast vertical panels and the internal scaffold system. Due to the horizontal movements, the heavy material on the shelves shown in Figure 6-7 started pushing against the vertical panels which were hung from the lateral beam at the roof level.

(a) *(b)*

Figure 6-7 (a) Overview of industrial shed of bellco (Mirandola) (b) scaffold-cladding interaction

Figure 6-8 Roof collapse due to the movement of the vertical panels hung from the roof cover (Mirandola)

The insufficient beam column connection shown in Figure 6-9 moved the beam out of place and generated the collapse of the part of the roof supported by the beam.

Figure 6-9 Insufficient beam-column support without restraints (Mirandola)

Another example of roof collapse due to the lateral overturning of the supporting beam is shown in Figure 6-10 and Figure 6-11.

Figure 6-10 Overview of the gymnasium before the earthquake (Mirandola)

(a) *(b)*

Figure 6-11 (a) Lateral overturning of the beam (b) structural detail

In some industrial sheds of the first type (see section 6.3.2), dangerous and heavy nonstructural components (Figure 6-12) caused damage, due to the fact that the sheds were built following the simply supported technique.

Figure 6-12 Dangerous heavy nonstructural elements

Figure 6-13 Panels without connection with the main structural frame CF

6.4 Performance of Industrial Shed with Irregular Cladding

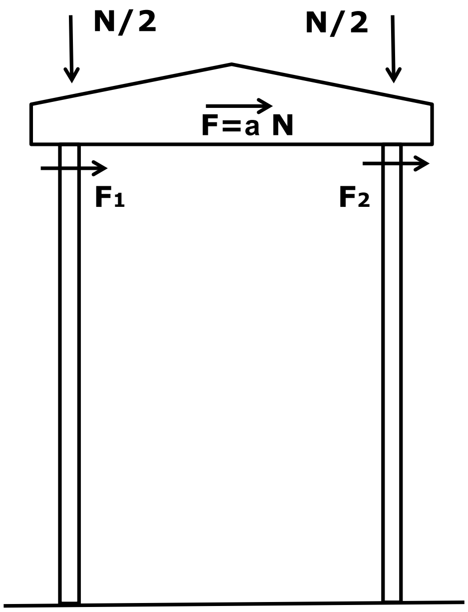
Exterior cladding had a positive effect when it was regular, because in this case, the cladding performed as dampers (Figure 6-15). However, the cladding had a negative effect when it was irregular, for example, due to the presence of windows (Figure 6-16, Figure 6-19, Figure 6-20, Figure 6-21) just below the beam supporting the roof, which caused partial collapse of some parts of the shed. The Emilia earthquake has shown that interaction with nonstructural components such as infill walls should be taken into account during the analysis; otherwise, it can cause the collapse of the structure.

The reason for these types of collapses can be easily explained using a very simple calculation as shown in Figure 6-17 and Figure 6-18. If the portal frame is without cladding, the horizontal forces at the support will be 30% of the vertical loading, which will be absorbed by the friction force at the support. In the presence of irregular cladding, the left pillar will have a short column effect. In this case, the horizontal force on the left pillar will be double with respect to the right pillar of the portal frame. This is the reason for the collapse of many industrial sheds near Mirandola.

Figure 6-14 Panels not properly connected to the main structural frame

Figure 6-15 Positive effect of regular cladding if the cladding is regular

Figure 6-16 Negative effect of irregular cladding (San Felice sul Panaro)



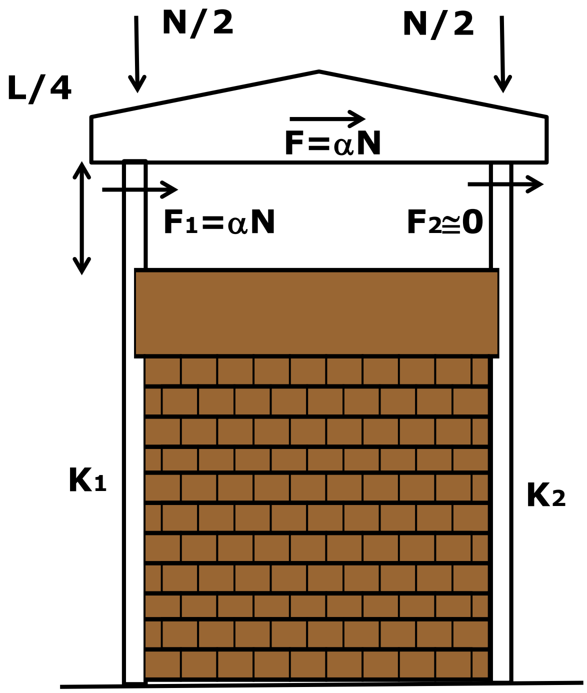
From the seismic action a =0.3-0.4

$$F_1 = F_2 = \alpha \frac{N}{2}$$

$$R_1 = \frac{F_1}{\frac{N}{2}} = \alpha$$

$$R_2 = \frac{F_2}{\frac{N}{2}} = \alpha = 0.3$$

Figure 6-17 Performance of industrial shed without cladding



From the seismic action a =0.3-0.4

$$K = \frac{12EI}{L^3}$$

$$K_1 = 4^3 K_2 = 64 K_2$$

$$R_1 = \frac{F_1}{\frac{N}{2}} = 2\alpha = 0.6$$

Figure 6-18 Performance of industrial shed with irregular cladding

Some examples of collapse due to the irregular cladding behavior described in Figure 6-18 can be observed in Figure 6-19, Figure 6-20 and Figure 6-21. In some cases, plastic hinges at the mid height of the column were observed due to the presence of irregular claddings (Figure 6-22).

Figure 6-19 Collapse of industrial shed due to seismic behavior of irregular cladding

Figure 6-20 Before and after the earthquake in San Giacomo Roncole (Mirandola)

Figure 6-21 Seismic behavior of industrial shed in San Giacomo Roncole (Mirandola)

Figure 6-22 Plastic hinge in the column due to the presence of irregular cladding

Figure 6-23 Collapse of the intermediate span due to the presence of cladding

Figure 6-24 shows an example of a beam head without adequate reinforcement, due to the fact that they were not designed to resist earthquake forces. Some examples of proper reinforcement are shown in Figure 6-25.

Figure 6-24 Beam-column connection without sufficient reinforcement in the beam head

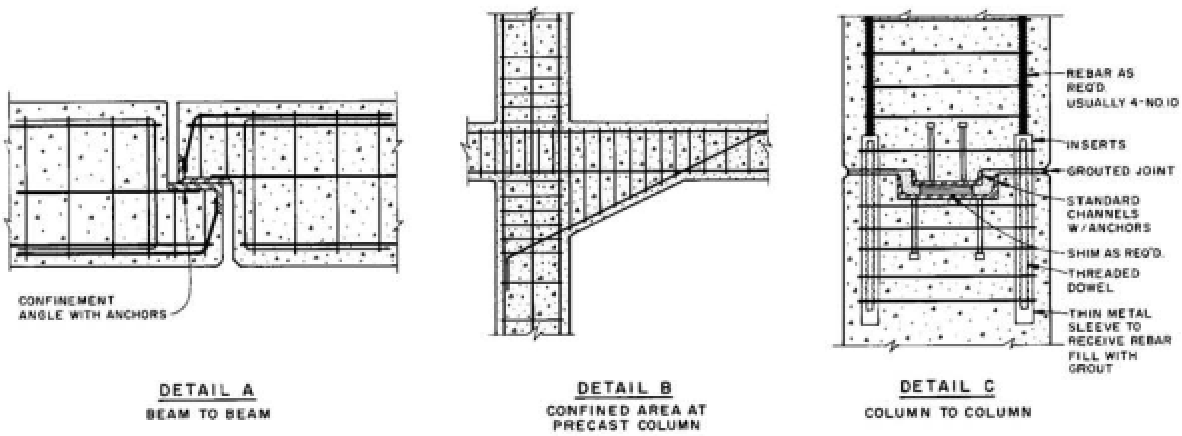


Figure 6-25 Structural details with adequate reinforcement

Figure 6-26 Emergency intervention to avoid collapse of the industrial shed due to beam slippage

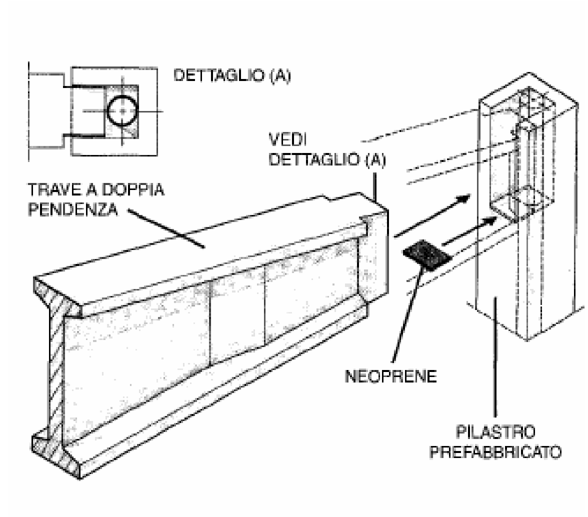


Figure 6-27 Slip of double slope beam from the shear key (San Felice sul Panaro)

Figure 6-28 shows an example of cladding made with clay bricks with an out-of-plane failure.

The roofs of many industrial facilities collapsed as a consequence of failure of the transverse and longitudinal beams supporting them (Figure 6-10, Figure 6-11, Figure 6-19). The precast roof of a modern factory observed close to Finale Emilia had a similar collapse mechanism (Figure 6-2, Figure 6-3). In the older part of the factory, the RC shell roof, which was monolithically attached with RC beams spanning transversely across the column, collapsed with the roof.

(a)

(b)

Figure 6-28 (a) Overview (b) Failure of out of plane claddings in Sant'Agostino

Figure 6-29 Collapse of vertical panels

Figure 6-30 Structural detail

Figure 6-31 Recent industrial shed with horizontal panels connected to the pillars

Figure 6-32, Figure 6-33, Figure 6-34 and Figure 6-35 show some recently built industrial sheds with internal collapse due to probable failure of one of the internal columns caused by the statically determined behavior of the structure and the lack of redundant supports.

Figure 6-32 Recent industrial sheds with internal collapse

Figure 6-33 Probable collapse of internal pillar

Figure 6-34 Beam-column connection without sufficient reinforcement in the beam head

Figure 6-35 Longitudinal toppling of beams for displacement limit

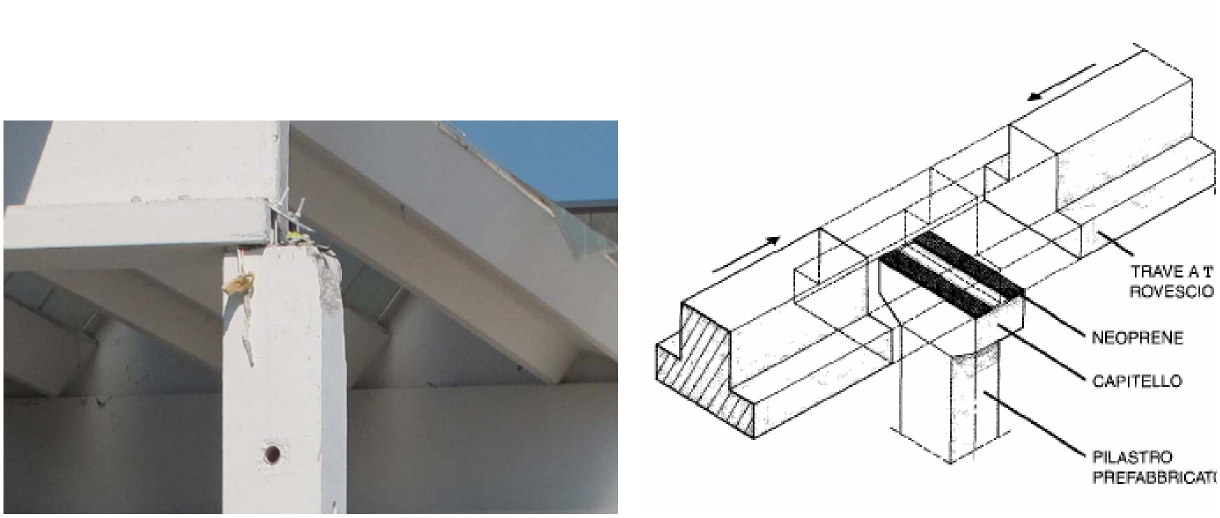


Figure 6-36 Lack of beam-column connection

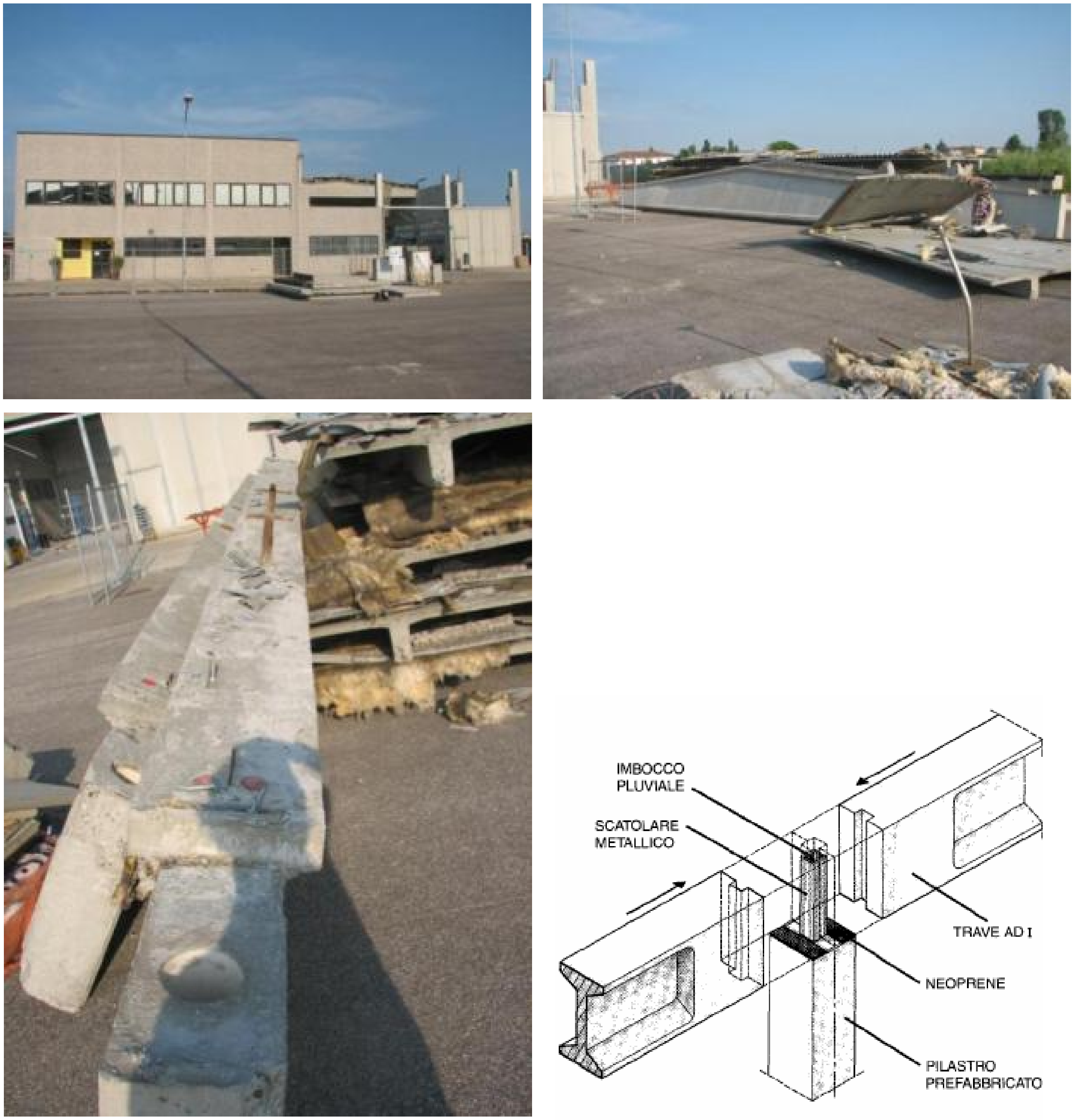


Figure 6-37 Probable roof collapse due to the slip of the beam from the shear key

Figure 6-38 (a) Remains of the collapsed roof; (b) failure of shear key due to lack of reinforcement

6.5 Seismic Behavior of Horizontal and Vertical Panels

External panels can be classified as horizontal and vertical panels (Figure 6-39). Vertical cantilever panels (Figure 6-40) behave properly with respect to horizontal panels and, in some cases, they increased the horizontal strength of the industrial sheds. Vertical panels failed only when they were not rigidly connected at the base, as shown in Figure 6-41.

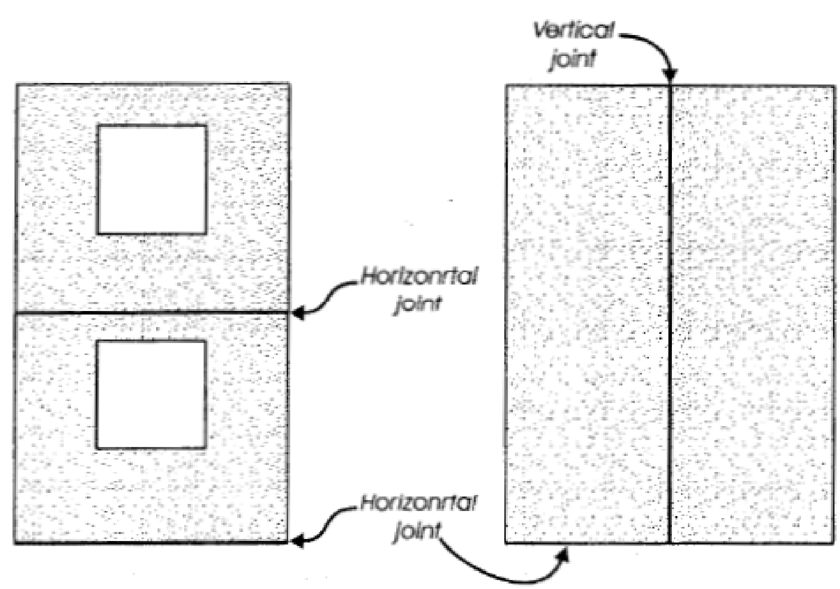


Figure 6-39 Scheme of horizontal and vertical panel joints

Figure 6-40 Vertical panels behave properly when connected at the base

Figure 6-41 Collapse of vertical panels not attached to the foundation curb

Pre-cast RC horizontal panels added mass to the columns and were attached with steel plate connectors. They were observed to fail in several industrial sheds (Figure 6-42, Figure 6-43, Figure 6-44), because they were not able to resist to the earthquake forces (Figure 6-45, Figure 6-46).

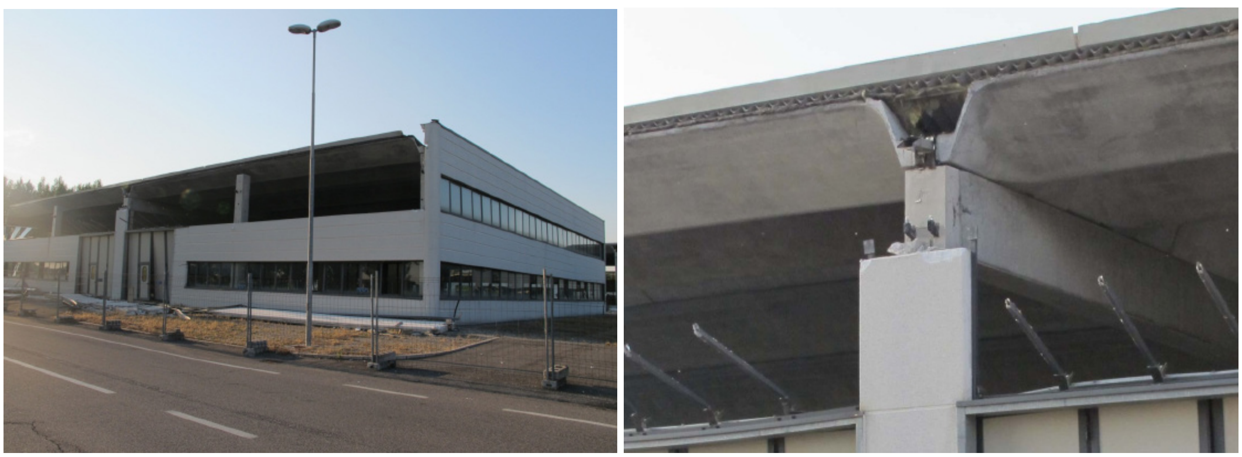
Figure 6-42 Horizontal panels only added mass and did not add stiffness to the structure

Figure 6-43 Detachment of horizontal panels that were not well-connected to the pillar

Figure 6-44 Collapse of horizontal panels due to insufficient connections to the beams

Figure 6-45 Detachment of horizontal panels that were not well connected to the pillar in Sant'Agostino

Figure 6-46 Detachment of horizontal panels (Mirandola)



(a) *(b)*

Figure 6-47 (a) Overview (b) steel plate connector failure (Mirandola)

(b) *(b)*

Figure 6-48 (a) Overview (b) collapse of horizontal panels due to lateral overturning of a beam

Figure 6-49 Sant'Agostino ceramics

6.6 Failure due to Rotation of the Plinths

Problems related to the rotation of footings at the foundation have also been observed in industrial sheds. Typical plinths in precast structures are connected to the structure, as seen in the drawings shown in Figure 6-50 and Figure 6-51. Often, the loss of support of the beam is a consequence, not the cause of the collapse (Figure 6-52, Figure 6-54). In these cases, connecting the beam to the column might not be sufficient; instead, it might be necessary to connect different plinths (Figure 6-53). Examples of entire rotation of the columns at the base can be observed in Figure 6-54.

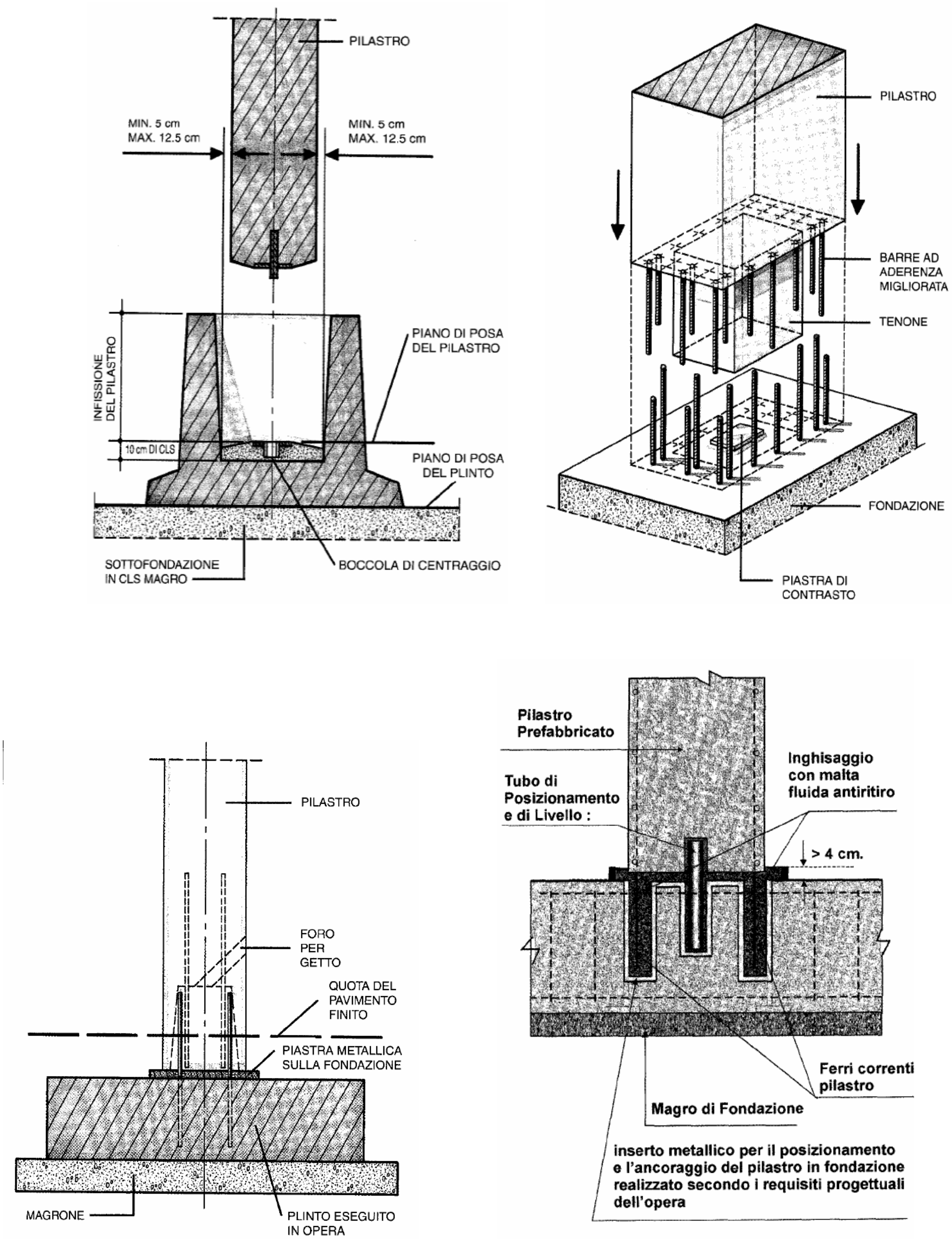


Figure 6-50 Typical plinth column connection at the base

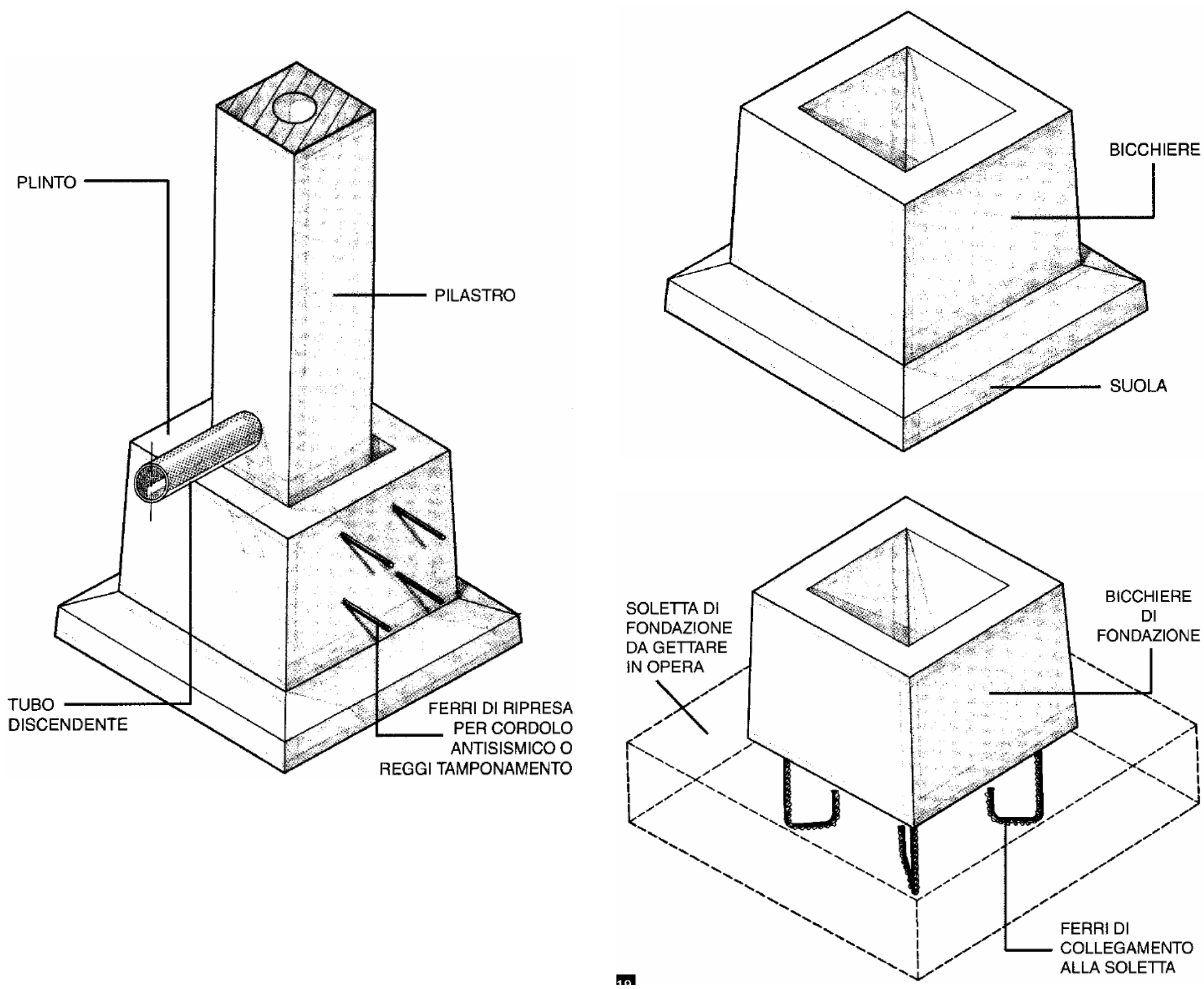


Figure 6-51 Examples of plinth in precast structures

Figure 6-52 Probable rotation of the column at the base in Mirandola

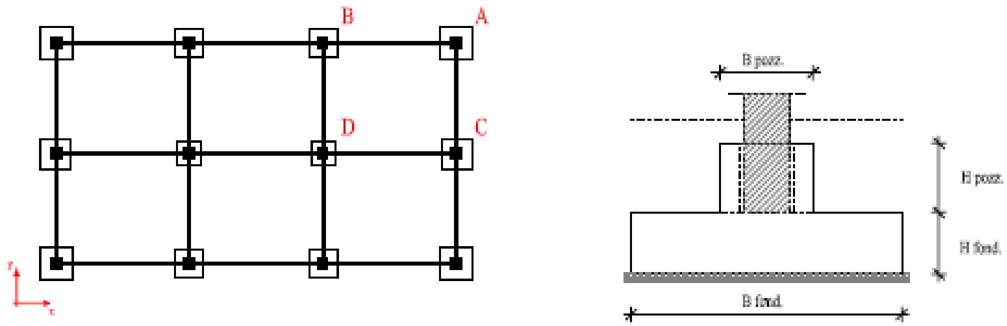


Figure 6-53 Connection of a plinth at the foundation level

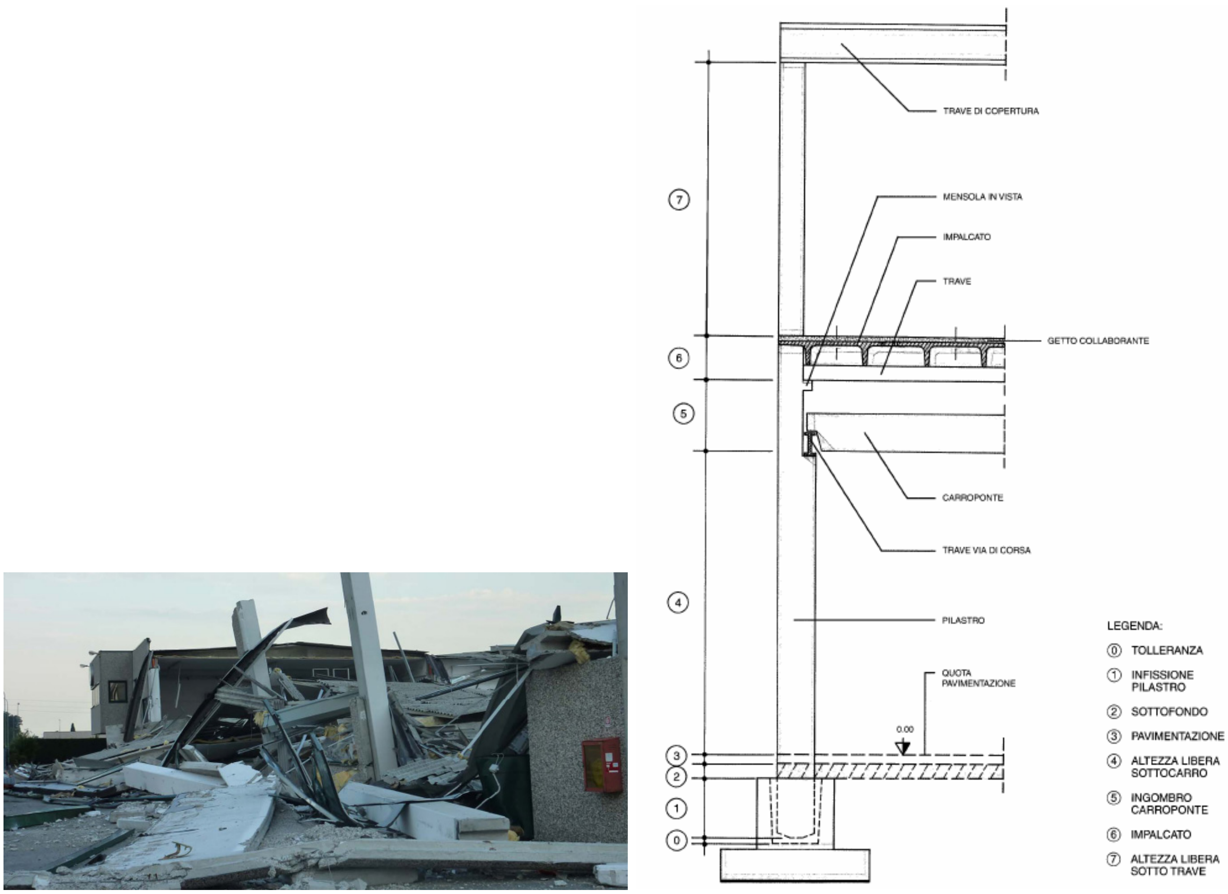


Figure 6-54 Rotation of the column at the base

Figure 6-55 Plastic hinge at the base of the pillar

6.7 Steel Industrial Structures

The automated storage warehouse of the Sant'Agostino ceramics factory was heavily damaged during the earthquake (Figure 6-56, Figure 6-57). The warehouse was a large shelving facility for boxes of ceramics tiles.

Figure 6-56 Automated storage warehouse of Sant'Agostino ceramics factory: overview

Figure 6-57 Damage overview of automated storage warehouse of Sant'Agostino ceramics factory

The internal shelves are made of 12 singular internal rows and each shelf is composed of two parallel multi-level frames that are connected transversally with a diagonal truss system. The parallel frames are connected in the transverse direction at the foundation level and with a truss system at the roof level (Figure 6-58). The internal shelves constitute the main structural component of the warehouse.

Figure 6-58 Overview of the internal structural shelves with heavy boxes of tiles concentrated at the upper levels

Sandwich panels (Figure 6-59) cover the entire warehouse and are connected directly to the external shelving steel frame or to a truss system in the longitudinal direction.

Figure 6-59 (a) Damage to the sandwich insulation panels; (b) roof detail

Approximately 70% of the structure collapsed in the longitudinal direction (Figure 6-57). The horizontal sections appear to have only been connected with the vertical section by means of an L-Plate and 1 bolt, forming a pivot and providing negligible lateral resistance in that direction. In the transverse direction, the lateral resistance of the truss system of each individual shelf is very small, because they are slender. From Figure 6-59b, it can be observed that, at the moment of the earthquake, only the upper levels of the shelves were filled with heavy boxes of tiles, which might have contributed to larger roof displacements and overall instability. The connection of the frames with the foundation was also very weak as the vertical elements were observed to fail at the vertical element-foundation interface (Figure 6-59a).

Vertical and horizontal elements consisted of U-shaped sections and in many sections were observed to experience warping failure effects, particularly at intersections with other elements (Figure 6-60).

Figure 6-60 Warping failure effects of U-shaped sections

Another example of collapse of a steel storage warehouse is shown in Figure 6-61 and Figure 6-62.

Figure 6-61 Shoring intervention on the exterior vertical panels using excavators

Figure 6-62 Detail of the internal scaffolds

6.8 Condominium Realized with Precast Techniques in Mirandola

In Emilia, several schools, as well as malls and condominiums (Figure 6-63) were constructed with the same typology as the industrial sheds. Few of them collapsed, but there were internal failures of nonstructural components (Figure 6-63, Figure 6-64, Figure 6-65). Whenever seismic connections were used, the structure may have been damaged, but it did not completely collapse (Figure 6-67).

Figure 6-63 (a) Overview of the condominium (b) Overturning of furniture

Figure 6-64 Broken suspended ceiling tile

(a) *(b)*

Figure 6-65 (a) Collapse of suspended ceiling system; (b) Suspended ceiling system (internal view)

Figure 6-66 Absence of seismic connections

Figure 6-67 Structural detail of panel-structure connections

6.9 Masonry Industrial Structures

An abandoned industrial structure in Reno Centese made of masonry walls with a wooden roof performed reasonably well during the earthquake. The roof consisted of wooden trusses (Figure 6-69).

Figure 6-68 Masonry industrial structure in Reno Centese

Figure 6-69 Overview of the internal wooden roof

6.10 Typical Beam-Column Connections in Seismic Zone

Precast connections during earthquakes dramatically affect the global performance of the entire structure. Figure 6-70 shows some examples of typical beam column connections for precast structures in seismic zones which would have prevented the collapse of several industrial sheds in Emilia during the 2012 earthquake.

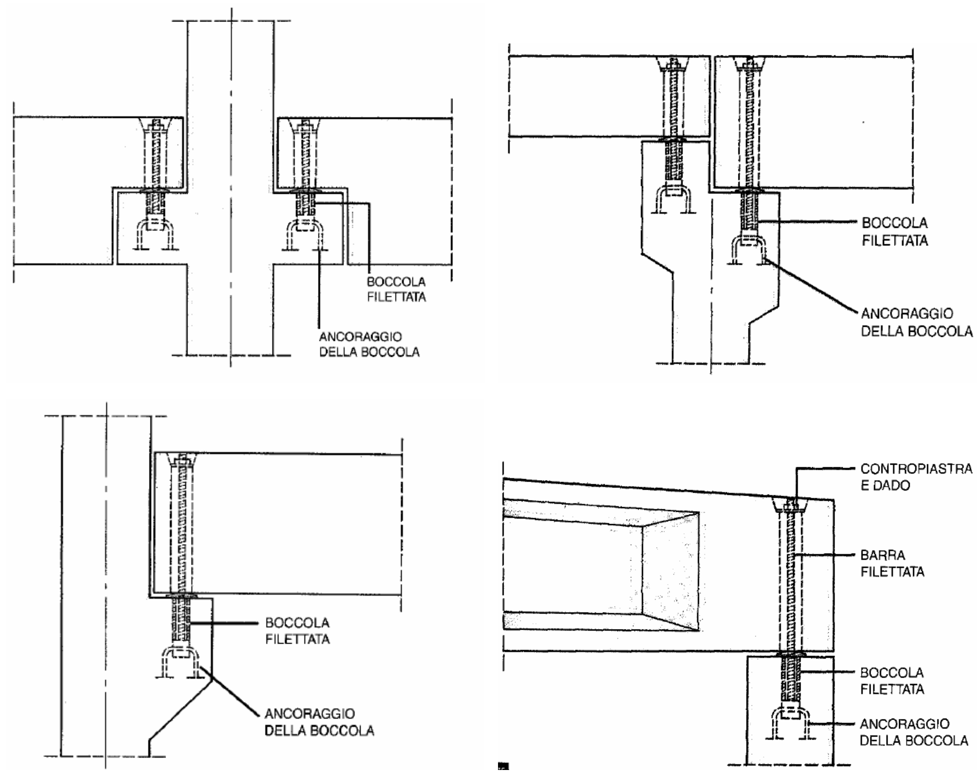


Figure 6-70 Typical beam-column connection in seismic zone

Beam-column connections like the one shown in Figure 6-70 should be able to achieve a global behavior to the entire structure providing a certain level of strength, stiffness and ductility. Figure 6-71 shows a typical beam-column connection using steel brackets connected with bolts. The beam is inserted in a plug, which prevents the sliding of the beam with respect to the pillar.

Figure 6-71 Typical beam-column connections in seismic zone

6.11 Concluding Remarks

Precast structures in seismic zones should be designed by looking at the connection between the beams and columns as well as between the columns and foundation plinth. Connections should be able to reduce deformation of the structures through cantilever systems and/or transversal braces and/or passive connections. A hyperstatic scheme is preferred with respect to the isostatic scheme.

SECTION 7
BUILDING DAMAGE

7.1 Private Residential Buildings

7.1.1 Performance of Historical Urban Block in Downtown Mirandola

Civil Protection of the Piedmont Region in collaboration with the Department of Structural, Geotechnical and Building Engineering (DISEG) sent teams to perform technical activities in the Emilia region right after the earthquake. In particular, a team of engineers from the Politecnico di Torino worked in the historical center of Mirandola, with the goal of evaluating damage in the urban block between Via Milazzo, Via Volturno, and Piazza Garibaldi (Figure 7-1). They focused mainly on masonry buildings. The following figures show damage to the historical urban block in Via Volturno 37.

Figure 7-1 Historical building in Via Volturno 37

Figure 7-2 Team at work

The load bearing masonry walls had serious damage near the stairwell and the vaults of the stairs (Figure 7-3).

Figure 7-3 Damage to the vaults of the stairs

Shear cracks appeared on the load bearing walls as well as in the internal partitions and in the architraves (Figure 7-4).

Figure 7-4 Damage to architraves and internal partitions

In the courtyard, it can be seen that, due to different rigidity and symmetry, a portion of a recent building expansion suffered serious damage to its vertical structure. The cover is made of wood without curbs.

At the foundation level, there is a physical cut made in an attempt to eliminate moisture problems, but during the earthquake, it caused damage at the top of other house.

Figure 7-5 Physical cut at level of foundation

Figure 7-6 Lesions on load-bearing walls

Many pieces of furniture inside the buildings suffered rocking effect. In some cases, the overturning of the furniture itself was examined.

Figure 7-7 Overturning effects: This building has been classified as non-accessible

Overall, masonry buildings showed good behavior, often exhibiting minor damage apart from a few isolated cases that were most vulnerable. Most of the buildings were declared class F, meaning fit for use as soon as the danger of falling material from neighboring buildings was removed. In some cases of building renovation carried out with judgment and respecting the original design features, the seismic behavior proved to be satisfactory with only marginal damage.

7.2 Churches

7.2.1 General Characterization of the Churches in Emilia Romagna

Many churches suffered extensive damage during the earthquake; most were made of brick masonry. The following pages introduce the classical constructive scheme of these churches.

7.2.1.1 Masonry Wall Analysis

There are different brick masonry bonds in the masonry walls, as shown by the following figures. A typical masonry bond type is the single header bond with a classical block dimension of 28x14x3.5 cm.

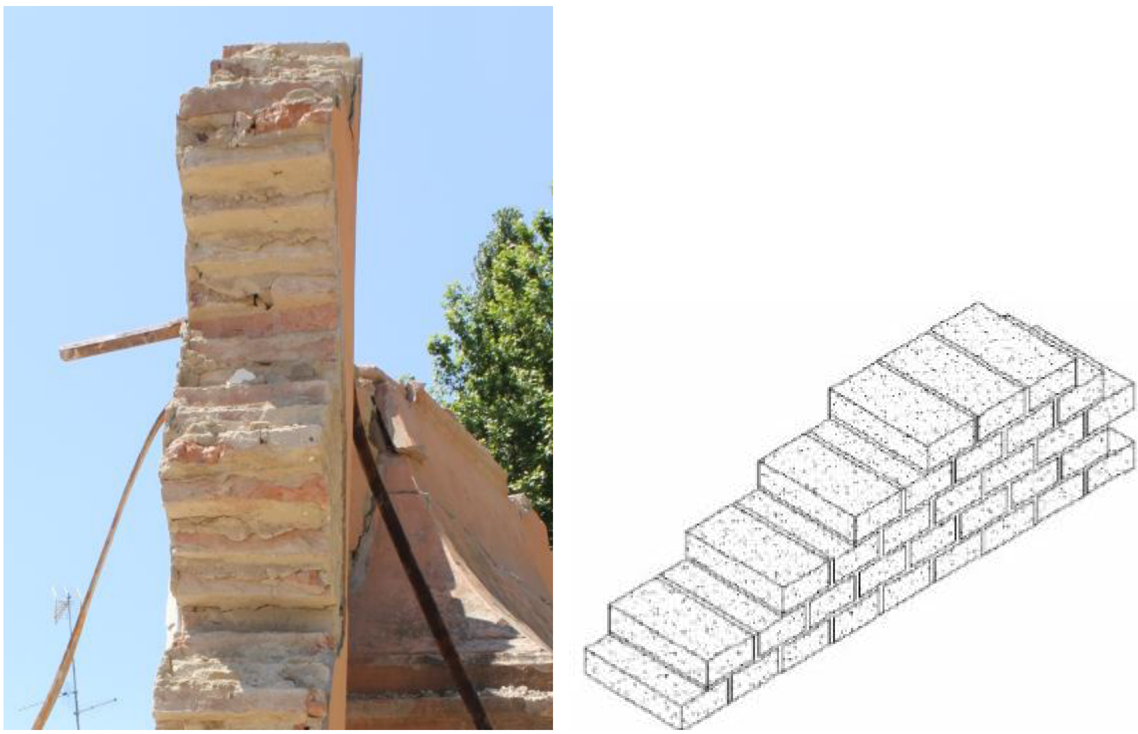


Figure 7-8 Single header brick masonry bond and sketch of the bond type adapted from Borri (2006)

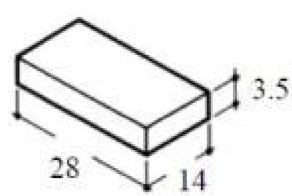


Figure 7-9 Brick dimension in cm

A very common bond type is the double header bond masonry, similar to the Flemish bond and widely used in the local architecture.

Figure 7-10 Double header brick masonry bond

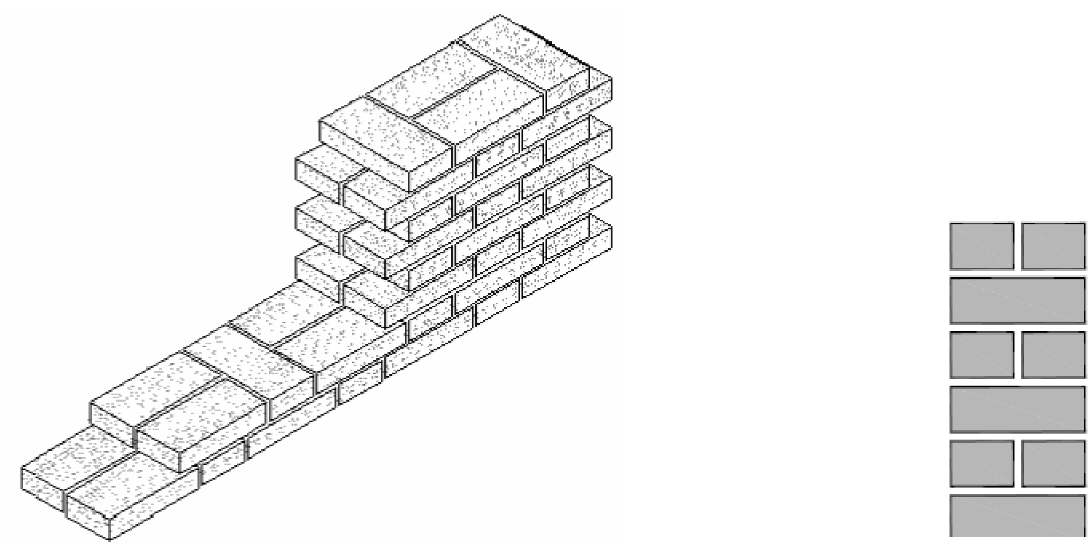


Figure 7-11 Sketch of the bond type adapted from Borri (2006) and sketch of the cross section view of the wall

Sometimes, in order to support a greater load, the previous walls were duplicates. This is usually observed in the support region of the timber truss. Generally, both walls are connected to the truss by timber or metallic elements.

Figure 7-12 Double wall made of double header brick masonry bond

Figure 7-13 Double wall supports a timber truss

Sometimes the bond type is made by a triple header masonry bond, but research shows that there is no precise rule for use of this type of wall. For example, the same walls are organized with specific regular patterns.

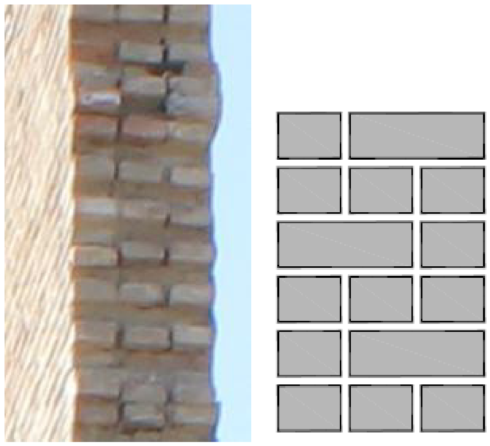


Figure 7-14 Triple header brick masonry bond and sketch of the cross section view

In other churches, the regular pattern is abandoned for an irregular one without a specific reason. Examples of this irregular triple header brick masonry are shown in the following figures.

Figure 7-15 Irregular triple header brick masonry bond

Figure 7-16 Irregular triple header brick masonry bond and sketch of cross section

7.2.1.2 Roof Analysis

Generally, the roof structure of the churches consists of timber trusses.

Figure 7-17 Example of roof structure made of timber trusses

Timber battens run transversal to the trusses over which there is a roof made of masonry elements, either hollow or solid. The roof tiles are then fixed to this masonry sheeting by mortar.

Figure 7-18 Example of roof structure made of timber trusses

Figure 7-19 Example of roof sheeting made of hollow masonry elements and with solid masonry elements

Three kinds of vaults are the most common in the Emilia area churches:

- vaults made of brick masonry laid flatwise;
- reed mat false vaults hanging from the roof timber trusses;
- vaults made of timber elements imbedded in mortar/plaster.

Figure 7-20 Example of vault structure made of brick masonry laid flatwise

Figure 7-21 Example of reed mat false vaults

Figure 7-22 Example of vault made of timber elements imbedded in mortar/plaster

7.2.1.3 *Arch and Interior Columns Analysis*

Most of the arches are made of vertically stacked brick masonry.

Figure 7-23 Example of arches made of vertically stacked brick masonry

The interior columns are also usually made of brick masonry.

Figure 7-24 Example of an interior column made of brick masonry

7.2.2 Churches Surveyed

7.2.2.1 Chiesa del Gesu in Mirandola (Modena)

The seventeenth-century Chiesa del Gesù was built on the orders of Alexander the Pico on the occasion of his investiture as Duke of Mirandola. Unfinished in the façade, it contains beautiful works of the local carving school. The interior is a classical example of Baroque architecture.

Figure 7-25 Frontal and aerial view of the church complex before the earthquake

Figure 7-26 Internal view of the church before the earthquake

The earthquake caused severe damage to the church. The external wall presents numerous cracks and some buttresses have collapsed (Paupério et al., 2012).

Figure 7-27 External view of the church complex after the earthquake and some debris

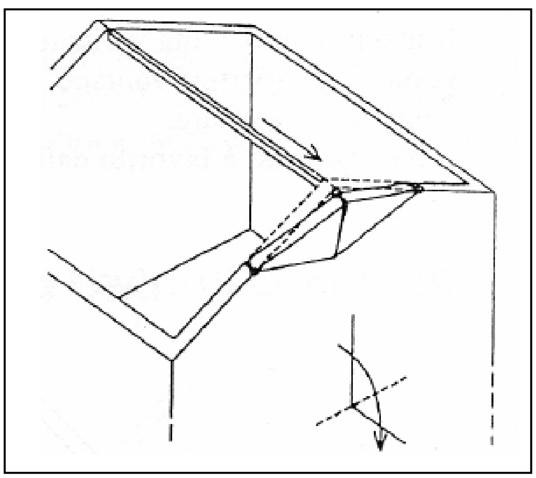


Figure 7-28 Mechanism to break through the wall of the tympanum

The mechanism that caused the collapse of the roof is shown in the Figure 7-28. The force generated by the timber trusses during the earthquake caused the collapse of the upper part of the façade. Without this support, the roof collapsed.

The internal vaults were made of brick masonry and totally collapsed, causing severe damage at the internal works.

Figure 7-29 External damage and collapsed buttresses

Figure 7-30 Collapsed roof

Figure 7-31 Collapsed vaults

The debris that fell from the roof also opened some subterranean crypts.

Figure 7-32 Subterranean crypt

Figure 7-33 Internal view of the church after the earthquake

7.2.2.2 Chiesa di San Francesco Church in Mirandola (Modena)

The Chiesa di San Francesco is one of the most ancient churches in Mirandola. Together with the neighboring Franciscan convent, it appears to be the very first urban structure dating from the thirteenth century. It is an example of Gothic art and one of the first Franciscan churches in Italy. The importance of the building is emphasized by the role of the "pantheon" of the Pico family: inside, in fact, are preserved the magnificent tombs of Galeotto (1499), Prendiparte (1394), Spinetta (1399), Giovan Francesco I and Giulia Boiardo (1467).

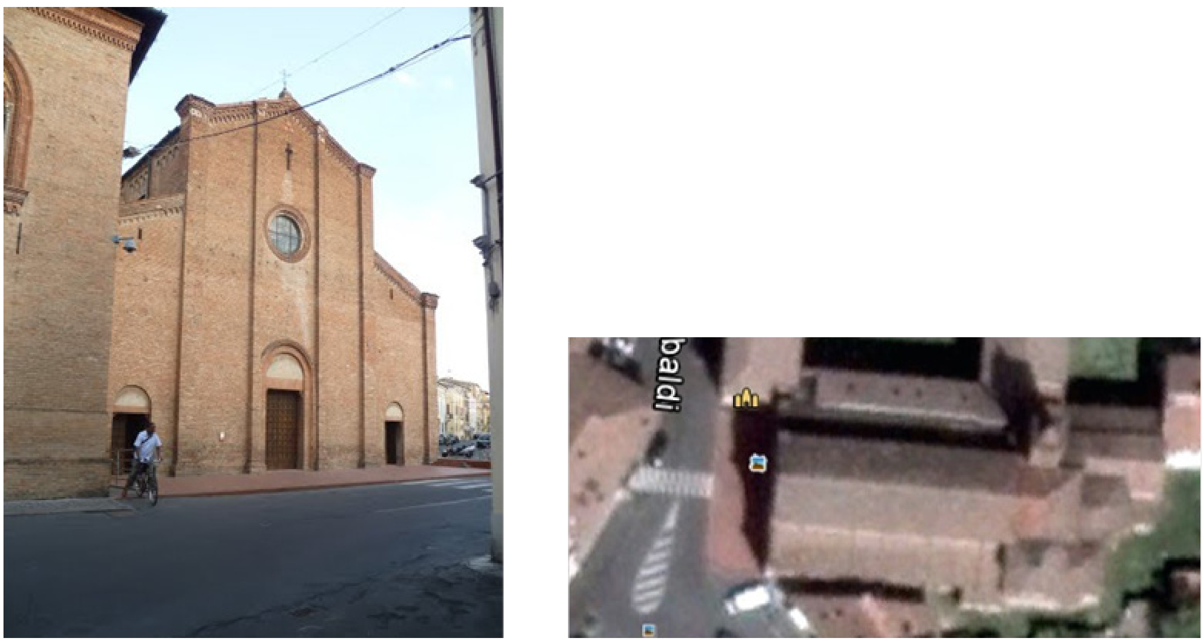


Figure 7-34 Frontal and aerial view of the church complex before the earthquake

Figure 7-35 San Francis Church in Mirandola before the earthquake

After the earthquake, the structure of the church was destroyed. The timber collapsed as well as the lateral walls. The cause of this collapse was the detachment of the façade, which is clearly visible in the following figure. In fact, the façade of this particular building is an important element in limiting the push on the side walls.

Figure 7-36 San Francis Church in Mirandola after the earthquake and critical mechanism

Figure 7-37 Façade damage

Figure 7-38 Internal view of the church after the earthquake

The first emergency interventions were shoring of walls with steel bars and the placement of wood shore at the openings.

Figure 7-39 Emergency interventions

7.2.2.3 Chiesa in Sant'Agostino

In Sant'Agostino, the church located in piazza Lupatelli sustained a partial collapse and was declared inaccessible.

The fall of a decorative statue from the roof may be the primary cause of the damage. The church also has some shear cracks in the north wall and the bell tower is leaning. A partial detachment of the façade is clearly visible.

Figure 7-40 Chiesa in Sant'Agostino

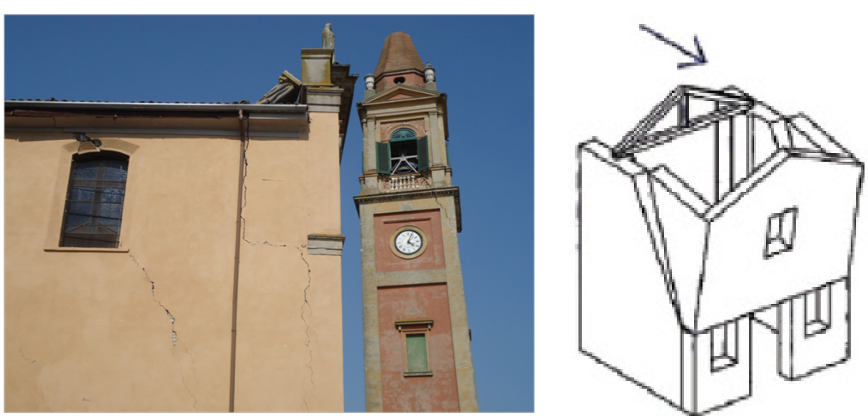


Figure 7-41 Partial detachment of the façade and relative mechanism

Figure 7-42 Collapse of the statue located at the roof level

Figure 7-43 Shear cracks to the bell tower

7.2.2.4 Chiesa di San Martino in Buonacompra

After the earthquake, the structure of the church was destroyed. The timber collapsed as well as the lateral walls. The major cause of this collapse was the use of poor materials; in fact, the damage spread throughout the whole structure.

Figure 7-44 San Martino Church before the earthquake

Figure 7-45 San Martino Church after the earthquake

Figure 7-46 San Martino Church after the earthquake: lateral view

Figure 7-47 Collapsed roof

Figure 7-48 Close up of San Martino Church

After the earthquake, the bell tower was very unsafe. Some shear cracks in the middle of the tower caused a sliding surface. In order to avoid an unsafe collapse, it was demolished.

Figure 7-49 San Martino bell tower after the earthquake and before the demolition

Figure 7-50 San Martino bell tower after the earthquake and after the demolition

Figure 7-51 Shear fracture was the reason for the demolition

7.2.2.5 Duomo in Finale Emilia

One of the most beautiful churches in Finale Emilia is the Duomo in the center of the town. The classic style of the façade is an element of continuity with the surrounding environment. Inside the church, the classic style is enriched with baroque altars. The vaults are rich in frescos.

Figure 7-52 Internal view of the church before the earthquake

The earthquake caused severe damage to the structure of the church. The roof was partially collapsed, as was the top of the façade. The mechanism involved in this collapse is the same one that afflicted the Chiesa del Gesù in Mirandola.

Figure 7-53 Duomo in Finale Emilia after the earthquake

Figure 7-54 Collapsed roof

Figure 7-55 Close up of Duomo in Finale Emilia

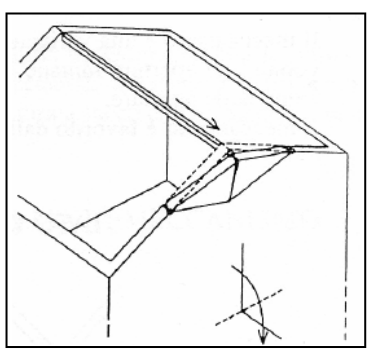


Figure 7-56 Mechanism to break through the wall of the tympanum

7.2.2.6 Chiesa di San Paolo in Mirabello

Figure 7-57 Church of San Paolo before and after the earthquake

The church of San Paolo in the town of Mirabello sustained a partial collapse of the façade and a total collapse of the transept and apse. The bell tower of the church was declared salvageable because it did not sustain structural damage. Locals reported that the bell tower foundations had been strengthened in the past.

Figure 7-58 Partial collapse of the top façade and collapse of the cupola

Figure 7-59 Shear crack on lateral wall

Figure 7-60 External view of the back of the church

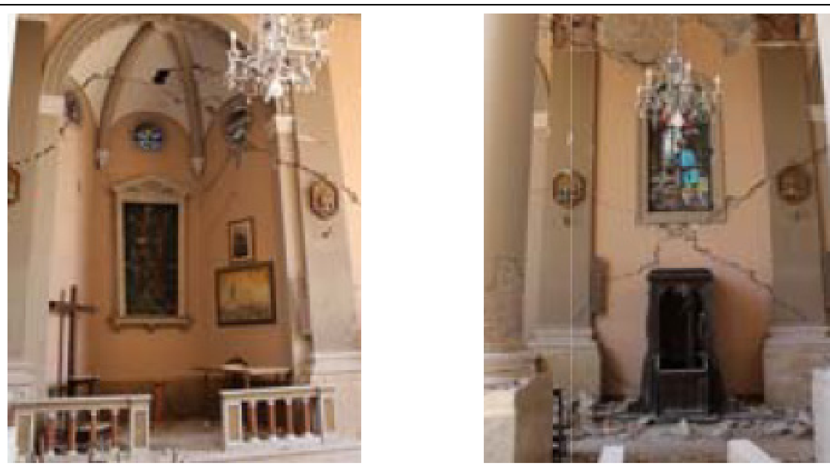


Figure 7-61 Internal view of the church

As shown in the previous figure, the main cause of the collapse of the structure was the use of poor materials. Some figures also show the presence of reinforced concrete elements that may have been used for some restoration.

Figure 7-62 Collapse of reinforced concrete element

7.3 Public Historical Palaces

7.3.1 City Hall of Sant'Agostino

In Sant'Agostino, the city hall is located in piazza Lupatelli – Corso Garibaldi. It is made of unreinforced brick masonry with timber floors. During the earthquake, this structure suffered severe damage to its structural components. A middle column of the façade's portico collapsed.

The external wall suffered partial collapse due to insufficient out of plane resistance. The reason for this behavior was probably the small thickness of the wall.

Figure 7-63 City hall of Sant'Agostino – Fallen column and collapse of external wall

There are extensive diagonal cracks in both side walls, and the connection of the side walls with the front wall seems to be destroyed. This forms a wedge which caused the out of plane failure of the portico. On the lateral wall, the collapse mechanism is shown in Figure 7-56. It is a mechanism of vertical deflection, with a very complex calculation scheme; this is due to the complexity of the shapes of the wall and to the difficult identification of the masses.

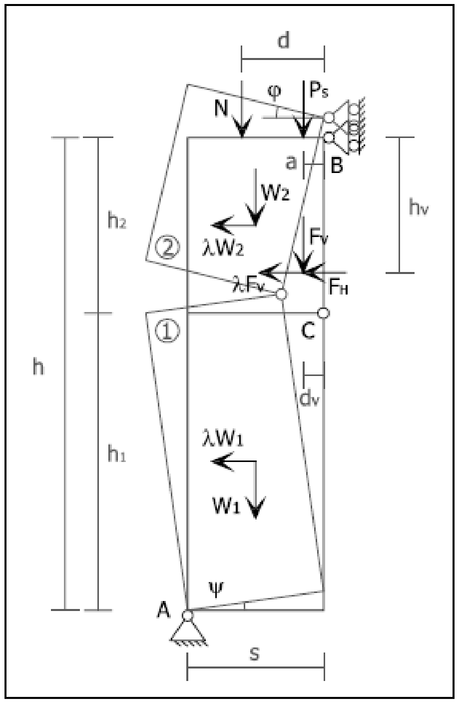


Figure 7-64 Calculation scheme

Figure 7-65 Partial collapse of the side wall and loss of the connection to the external wall in the front

Figure 7-66 Structural details of the roof ceiling

Figure 7-67 Large and extensive crack in a side wall

7.3.2 City Hall of Mirandola

The City Hall of Mirandola is made of unreinforced brick masonry with timber floors. During the earthquake, this structure suffered severe damage to its structural components.

Figure 7-68 Front view of the City Hall of Mirandola before the earthquake

The building was immediately declared unusable. The first emergency interventions were shoring of the portico with steel bars and installing lateral wood buttresses.

Figure 7-69 First emergency interventions

Very dangerous cracks on the external walls are visible and the interior of the structure was also severely damaged. Some floors have collapsed and the whole structure was very unsafe.

Figure 7-70 Shear crack on the external walls

Figure 7-71 Colonnade

A floor located over a vault of the colonnade collapsed and caused a dangerous situation in the vault below.

Figure 7-72 Vault damaged by floor failure

Figure 7-73 Cracks on internal walls

Figure 7-74 Partial collapse of the floor

Figure 7-75 Sliding phenomena

Figure 7-76 External damage

7.3.3 City Hall of Finale Emilia

The City Hall is located near the Duomo of Finale Emilia. The tower in the façade of this structure suffered a partial collapse. The fallen debris damaged the roof of the structure.

Figure 7-77   City Hall of Finale Emilia

Figure 7-78 Details of the City Hall of Finale Emilia

7.3.4 Castello delle Rocche (Rocca Estense) in Finale Emilia

Figure 7-79 Rocca Estense before the earthquake

Located along the ancient course of the waterway (Panaro della Lunga), the castle of the Rocche (also known as Rocca Estense) is one of the most famous castles of Emilia Romagna. It is a jewel of military architecture of the fifteenth century; however, some parts date back to a time more ancient, from the thirteenth century. At that time, the city of Modena built the Tower of the People, now known as the Clock Tower, and raised the keep of the castle. It was then used as a part of the defensive walls of the town, as confirmed from the vault of passage found at its base. The first fortified settlement, which then went on to capture the stronghold, thus eliminating the primitive function of entrance tower, was built in the early fourteenth century, but few remains have been unearthed during recent excavations.

The castle, as seen today, was built in the fifteenth century. It is characterized by the irregularity of the planimetric and by the anomalous position of the keep in comparison with other towers. Around 1430, the unadorned original fort underwent a transformation into a luxurious mansion. At that time, the ducal apartments were constructed and loggias that overlooked the courtyard and graced the top of the tower were added. Connecting bodies with graceful sports and colorful decorations also became part of the complex. The existing Ghibelline battlements were transformed into a sinuous and elegant shape. The castle interior preserves precious remains of fifteenth-century pictorial ornamentation. The south façade of the castle was renovated in 2011.

From a structural point of view, the castle is an unreinforced brick masonry structure with four towers. The earthquake caused extensive damage to the castle. Three towers partially collapsed and the fourth sustained significant large and extensive diagonal cracks.

Figure 7-80 Collapse of the tower of the castle in Finale Emilia

Figure 7-81 Partial collapse of the east side of the castle

Figure 7-82 Partial collapse of the two towers and severe damage to third tower

7.3.5 The Library and Archives of Mirandola

Next to the Chiesa del Gesù in Mirandola are the ancient city archives and the library. These are located in the same structure and were severely damaged by the earthquake. The structure under consideration is made of masonry like the adjacent church and dates from the same historical period.

Figure 7-83 Frontal view of the library in Mirandola

The earthquake caused severe damage to the structure. Although, from the outside of the structure, it is possible to see only some cracks, the damage found inside is quite significant.

Figure 7-84 Entrance to the library (left), and archive entry (right)

A more detailed external analysis has shown that the attic suffered a seismic swarm. As shown in the following photos, some walls that supported the roof collapsed. This is probably due to some openings in the wall under the roof, as well as the use of poor quality materials.

Figure 7-85 Walls under the roof

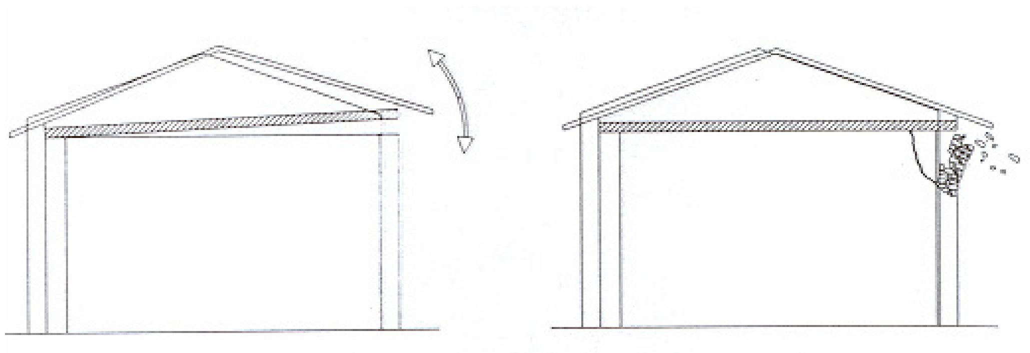


Figure 7-86 Vertical hammering of the roof

The cause of interior damage may also be due to a vertical hammering of the roof.

As shown in Figure 7-86, this mechanism may be associated with the cracks found on the internal vaults. Some vaults also suffered partial collapse.

Figure 7-87 Damage to the vaults

Figure 7-88 Partial collapse of the roof

Tie rod anchorage in some parts of the structure is present, but the large force involved caused crushing of the masonry.

Figure 7-89 Masonry crushing at the tie rod anchorage

The entire property is not secure and many bookshelves fell over.

Figure 7-90 Overturning phenomena

7.3.6 Stadium of Mirandola

The stadium "Libero Lolli" of Mirandola was declared unsafe after the earthquake. Some architectural elements of the façade were unsafe and were removed.

Figure 7-91 Stadium Libero Lolli

Figure 7-92 Façade of the stadium

Figure 7-93 Unsafe architectural elements

7.3.7 Ex-kindergarten "Govetto"

This structure was a kindergarten, but for some years now has not been used as a school. During the earthquake, the structure suffered significant damage and is now unsafe.

Figure 7-94 Ex-kindergarten Govetto

Figure 7-95 Crack on external walls

Figure 7-96 Shear crack on internal walls

7.4 Commercial Activities

7.4.1 Cheese Factories

The Po Valley is famous for the production of one of the most famous Italian cheeses: Parmesan. To produce a cheese of good quality, it is necessary to store it for many months at a precise temperature with controlled humidity. This process takes place in large sheds where the cheese is placed on special shelves. The earthquake overturned these slender shelves, causing enormous economic losses to the cheese factories.

Figure 7-97 Collapse of shelves filled with Parmesan cheese

Figure 7-98 Shed with shelves filled with Parmesan cheese

7.5 Historical Palaces

7.5.1 Il Barchessone Vecchio

Figure 7-99 The Barchessone Vecchio before the earthquake

The Barchessone Vecchio was built in 1824 to shelter horses. It is a construction with a polygonal plan having a diameter of about 28 meters. Two rows of columns arranged in a ring around the central column supports a radial wooden roof. The central pillar and the inner row of columns support the upper floor, which was made into an apartment.

Figure 7-100 Sketch and model of the Barchessone Vecchio

The floor was rebuilt as the original during the renovation of the building. It is made of brick laid in a herringbone pattern, and the same type of coverage can be found outside the structure, where the equestrian activities took place. After the renovation, the lower level of the Barchessone Vecchio was set up as a conference room with 120 seats and an exhibition hall.

Figure 7-101 Internal view of the Barchessone Vecchio before the earthquake

After the earthquake, the connection between the external walls and the roof was corrupted and the structure was declared unsafe. Some cracks are clearly visible on the external walls. These cracks were caused by the pushing force of the strut coverage.

Figure 7-102 Cracks on the walls of the Barchessone Vecchio after the earthquake

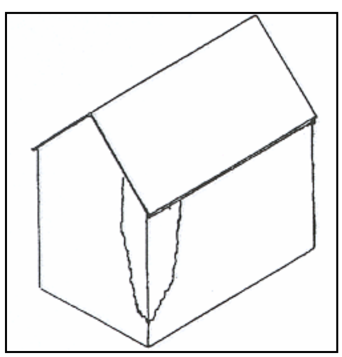


Figure 7-103 Cracking phenomena triggered by the pushing of the strut coverage

Figure 7-104 Internal view of the Barchessone Vecchio after the earthquake

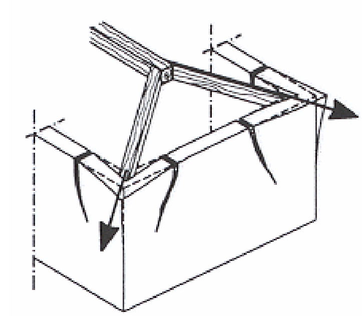


Figure 7-105 Pushing of the strut coverage

SECTION 8
SEISMIC PERFORMANCE OF CONCORDIA

8.1 Post-earthquake Analysis of Monumental Buildings of Historical Interest in Concordia

A research group from the Polytechnic of Torino worked in the municipality of Concordia Sulla Secchia. This is a small town in the province of Modena, full of historical sites, ancient churches and monuments.

Post-earthquake analysis was conducted on a sample of buildings inside the historic fabric of Concordia Sulla Secchia that were reported as being of architectural and/or historical interest by the Municipal Technical Office. Then, for each building, a module which reviews the history of the building and the damage that occurred was prepared.

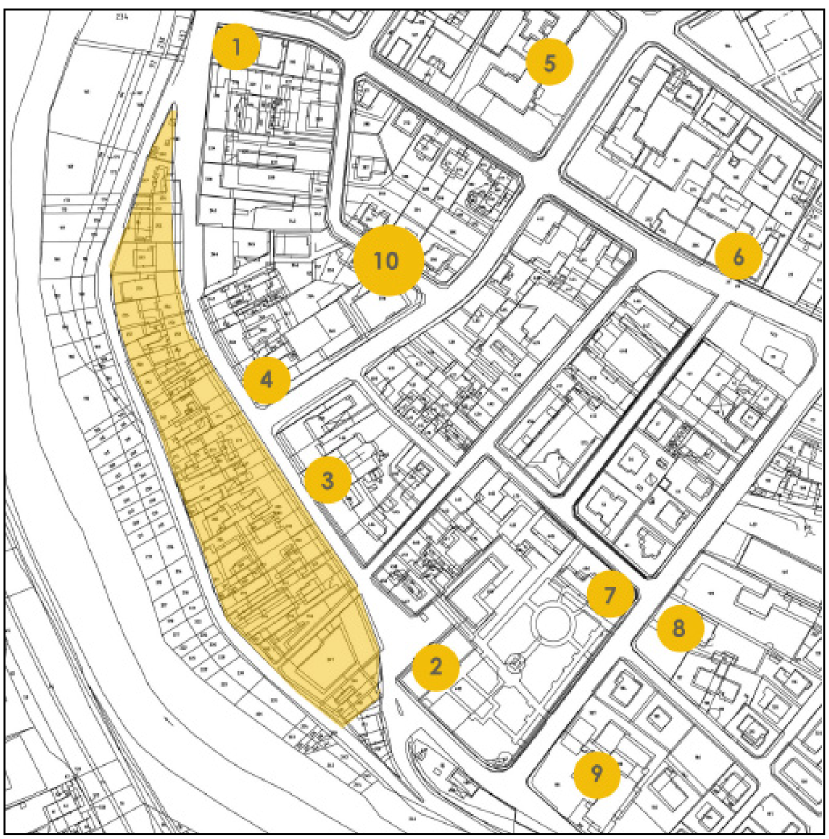


Figure 8-1 Map of Concordia

The following buildings were analyzed:

1. Teatro del Popolo
2. Corbelli Palace
3. Church of St. Paul
4. Post office building
5. School S.Neri
6. Malavasi Palace
7. Police station
8. Mazzuchelli Palace
9. Ex-mill Papotti
10. Villini of Via Decime

A detailed photographic survey was conducted on buildings in Via della Pace and Via Don Minzioni (highlighted area in Figure 8-1), as the present gothic structure enabled the team to recognize the oldest urban settlement in this area, created at the time the church was dedicated to the Conversion of St. Paul.

The following paragraphs contain a summary of the architectural analysis, emphasizing the structural and strategic importance of the buildings.

8.1.1 Teatro del Popolo

The structure under consideration is a theater called the Teatro del Popolo. It stands on the site of a former theater and was built in 1933; at that time, it was called Teatro Littorio. The façade consists of a colonnade supporting a large tympanum. The central body is supported by cruciform piers.

In 1945, the façade was restored and the theater was renamed Teatro del Popolo.

Figure 8-2 Façade of Teatro del Popolo and damage to the roof

The earthquake caused the collapse of the eastern part of the roof. The perimeter walls are damaged and off-axis.

8.1.2 Corbelli Palace (ex-Municipality)

Corbelli Palace was built for the first time in the seventeenth century and later enlarged after it was acquired by the Zanoli family in the second half of the eighteenth century. In 1861, the building was chosen as the seat of the municipality of Concordia. In the twentieth century, an additional floor was built on both sides of the structure. The façade was restored after the Second World War.

Figure 8-3 Façade of Corbelli Palace and cracked walls

After the earthquakes, the third floor of the building partially collapsed, and the walls of the façade cracked slightly.

The historical archives of the town are located in the most damaged area.

8.1.3 Church of St. Paul

The Church of St. Paul was founded in 1396. It has three aisles and a wooden roof resting on masonry vaults. The façade is reminiscent of the late Renaissance period. The bell tower is made of masonry load-bearing brick. The inside of the church is full of paintings which were restored in 1996.

Figure 8-4 Church of St. Paul and its damage

Coverage collapsed in the earthquake; the façade separated from the church and the bell tower was seriously damaged.

8.1.4 Post Office Building

The post office building consists of a brick bearing wall and a wooden roof. The windows on the façade are full of decorative elements.

Figure 8-5 Damage to the post office building

There was a collapse of the roof and some outside walls.

8.1.5 School S. Neri

The building was inaugurated in 1936. It consists of a C-shaped central body bounded by a wall consisting of columns enclosed by wire mesh.

The façade was restored by changing the original design, and a ramp was added adjacent to the main entrance.

The boundary wall suffered a reversal during the earthquake.

Figure 8-6 Reversal of boundary wall

8.1.6 Malavasi Palace

The present Malavasi Palace building stands on the site where the convent and the Church of the Capuchins once stood. There is a neo-gothic tower next to the main building. Originally, the floors were made of wood and brick, and with subsequent work, have been replaced by concrete slab. The ground floor is supported by bearing walls. Inside, there are many frescoes.

The building was partially restored with the replacement of horizontal structures and consolidation work on the turret.

Figure 8-7 Malavasi Palace and damage to the roof

Figure 8-8 Cracked wall and Malavasi's tower

After the earthquakes, the tower separated from the rest of the structure; the cover partially collapsed and the inner walls cracked.

8.1.7 Police Station

The police station was inaugurated in 1934 and converted into a barracks in 1955. It consists of a main body with two floors above ground level, to which is attached a 5-story tower of masonry brick.

Figure 8-9 Damaged cornice

Figure 8-10 Police station

The tower partially collapsed and was partially demolished. Also, part of the cornice in Via Carducci collapsed.

8.1.8 Mazzuchelli Palace

The Mazzuchelli Palace was built in the twentieth century. It is composed of a main building with two floors and a tower of three floors. It is currently intended for residential use.

The structure held up well in the earthquakes.

Figure 8-11 Mazzuchelli Palace

8.1.9 Ex-mill Papotti

The ex-mill Papotti was opened in 1885 as a steam mill, and later transformed into an electric mill. A chimney that no longer exists can be seen in historical photos. The building has a rectangular plan.

It is currently used as a library and is home to numerous cultural associations.

During the earthquake, it did not suffer any major damage.

Figure 8-12 Ex-mill Papotti and some plaster problems

8.1.10 Villini of Via Decime

The name of this building refers to the ancient palace of Decime, the residence of Pico, which was destroyed in 1704. In the twentieth century, villas with different architectural styles were built. The buildings are regular in plan with load-bearing masonry brick.

The protruding sections were severely damaged.

Figure 8-13 Villini of Via Decime

SECTION 9
INFRASTRUCTURE DAMAGE

9.1 Lifelines

9.1.1 Water, Gas, Electric Power, and Telecommunications Performance

The electric company that provides electric energy in the region affected by the earthquake (ENEL) was active in the hours immediately after the earthquake. Electric power was shut down for buildings that were severely damaged or collapsed.

The *gas network* was closed in less than two hours following the earthquake in order to avoid explosions and fires. Then, in the following days, all the gas valves outside residential buildings were closed as well. In less than three months, the gas network was restored and it was possible to restart gas distribution for all end-users with a safe home. The only gas pipes that were damaged were in Mirabello and were rapidly repaired.

The *water distribution system* has a network of large pipes with pressure between 30-50 bar and is stored in tanks. The distribution network is composed of cast iron and steel pipes with pressures ranging between 6-8 bar. No damage was observed to the main water distribution system. Water provision was restored gradually in different zones in order to prevent flooding in damaged buildings.

Damage to the *telecommunication network* was very limited, because it was only out of service for two hours right after the earthquake. Cell phones are the major communication system in the region. Firefighters and police used their own radio system as the primary means of communication.

9.1.2 Performance of Water Storage Towers

9.1.2.1 Performance of Water Tower in San Carlo

Some vertical cracks were observed in the water tower at San Carlo. The tower is made with a reinforced concrete circular core and six columns connected by reinforced concrete diaphragms at various intervals.

Figure 9-1 Water tank in San Carlo and localized crack in the interior reinforced concrete core

9.1.2.2 Performance of Water Tower in San Felice sul Panaro

The structure of the water tower in San Felice sul Panaro is an octagonal reinforced concrete frame, with masonry infill panels and only one reinforced concrete horizontal diaphragm. As seen in Figure 9-2, various masonry panels fell out of plane. At the two lower levels of the frame, some shear failure is visible. Some plastic hinges are visible in some of the columns at the bottom.

Figure 9-2 Water tank in San Felice sul Panaro and plastic hinges in the beam

9.1.3 Performance of Gas Storage Facilities

There are 12 gas storage sites in Italy. Rumors were spread among the population that the earthquake was caused by excavations to detect gas. Based on a complex study, the area for gas storage was selected for low seismic risk; therefore, a gas storage facility with 3.7 billion cubic meters of natural gas located at 2,800 meters depth in Rivara was created. The place is located 14 km from the epicenter and no damage to the storage site was detected.

There are two gas storage facilities in Emilia and two in the Lombardy region, but damage from the earthquake was not detected at these sites.

9.1.4 Performance of Transportation Systems

The earthquake did not damage the main roads connecting the affected towns. Many roads in residential areas were closed to prevent injury from the collapse of unstable or damaged buildings. Soil liquefaction and ground movement caused the road damage in the center of San Carlo. On the main street of Mirabello, some cracks occurred in the road surface and damage to the footpath was observed, both of which were mainly due to the lateral movement of the ground. According to the local population, this street was built on the site of an old river.

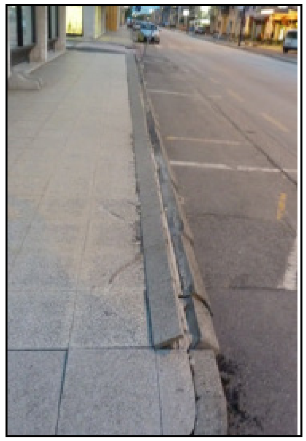


Figure 9-3 Damage to the footpath in Mirabello due to lateral spreading

Figure 9-4 Cracking phenomena in a road in Mirabello

9.1.4.1 Railroads

The train company (Trenitalia) temporarily interrupted traffic in the region affected by the earthquake in order to check damage to the rails. Due to the aftershocks that followed, some railroad bridges were inspected in the region, interrupting traffic, but the rail links were restored as soon as possible.

9.1.5 Lifeline Considerations on Emergency Response

It can be concluded that the lifeline network was not as severely damaged as the residential and monumental buildings; therefore, emergency management personnel were able to provide a rapid and resilient response.

SECTION 10
SOCIETAL IMPACTS

10.1 Management of the Emergency Response in Emilia

On May 20 and 29, 2012, two earthquakes of 5.9 M_w and 5.8 M_w struck the Emilia Romagna region of Italy, causing 27 deaths and widespread damage. The earthquakes can be classed as an inter-regional disaster – that required coordination at the national level – because it involved more than 80,000 people distributed across 40 municipalities (16 in the Province of Modena, 7 in Mantua, 7 in Bologna, 6 in Ferrara, and 4 in Reggio Emilia) and damaged historic buildings in the larger towns (Ferrara, Mantua, Modena and Bologna). The civil protection agency of the Emilia-Romagna region is one of the best equipped and organized in Italy, with a large headquarters in Bologna and many vehicles, personnel, equipment and supplies. Moreover, it was one of the first Italian regions to introduce the TETRA system (TErrestrial Trunked Radio) that creates an alternative emergency communication network if the existing one is damaged.

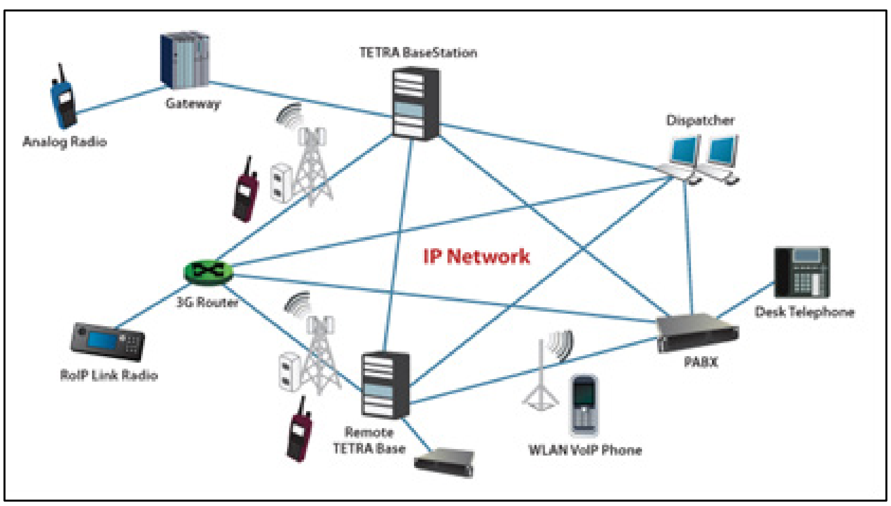


Figure 10-1 TETRA system (Terrestrial Trunked Radio)

The largest emergency response issue in Emilia was the regeneration of industry and employment. The evacuations were limited to brief exits at the time of the earthquakes, but about 20,000 people were in need of shelters distributed across the impacted region as follows: 62% in Modena, 30% in Ferrara, 5% in Bologna and 3% in Mantua. The damage to housing was slight, but the houses free of damage inside the red zones – areas such as town centers that were cordoned off in order to maintain public safety – were inaccessible. These buildings needed a first-level damage report to assess their safety.

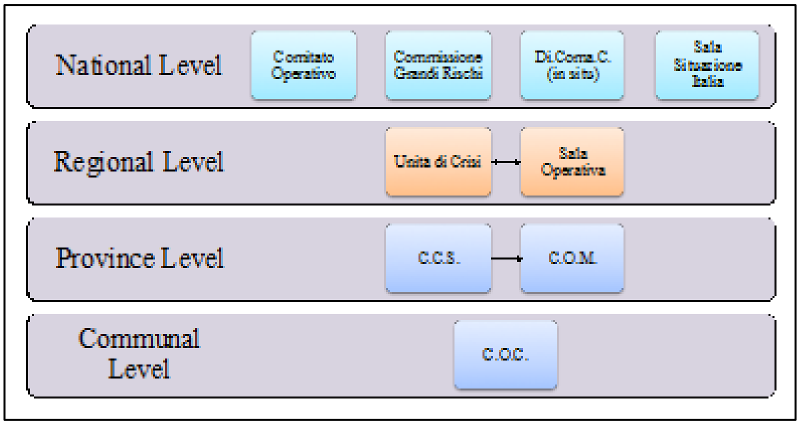


Figure 10-2 Italian system of coordination

Figure 10-2 shows the Italian system of coordination in which resources are managed by sectors from a national level (Di.Coma.C.), through a regional level (Unità di Crisi) to the larger (C.O.M.) and then to smaller local settlements (C.O.C.). One of the competencies managed by the national Department of Civil Protection is the coordination of technical assessments of the stability and habitability of residential buildings.

Volunteer technicians from various regions reported on damaged residential buildings during the emergency response by using AeDES hardcopy forms (certificates of occupancy), making 38,726 inspections (3,665 in Bologna, 8,827 in Ferrara, 24,144 in Modena, and 2,090 in Reggio Emilia) from the 21st of May until the 30th of August (101 days). In addition, the group from the Department of Structural, Geotechnical & Building Engineering of the Politecnico di Torino participated by collaborating with the Piedmont Civil Protection Agency, and made about 500 inspections.

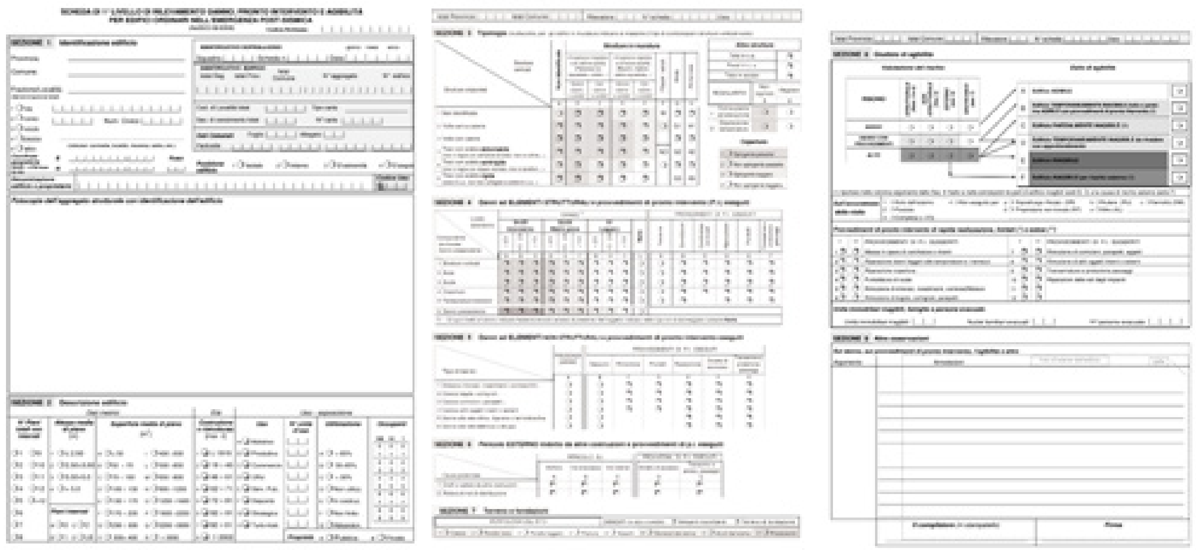


Figure 10-3 Certificate of occupancy (AeDES form)

Figure 10-3 shows the certificate of occupancy (AeDES form) that was used in Emilia, which defines six outcomes of building usability: (A) building usable, (B) building temporarily unusable (all or part) but usable with measures of emergency, (C) building partially unusable, (D) building temporarily unusable pending a more in depth review, (E) building unusable, and (F) building unusable due to external risk. Moreover, it has nine sections: (1) identification of the building, (2) characterization of the building, (3) structural typology, (4) structural damage and emergency measures, (5) nonstructural damage and emergency measures, (6) external risk from other structures and emergency measures, (7) soil typology and damage, (8) judgment of usability, and (9) other observations.

The results at the national level of certificates of occupancy for the investigated residential buildings are as follows: 14,112 (36.4%) of A, 6,827 (17.6%) of B, 1,644 (4.2%) of C, 208 (0.5%) of D, 13,825 (35.7%) of E, and 2,110 (5.4%) of F.

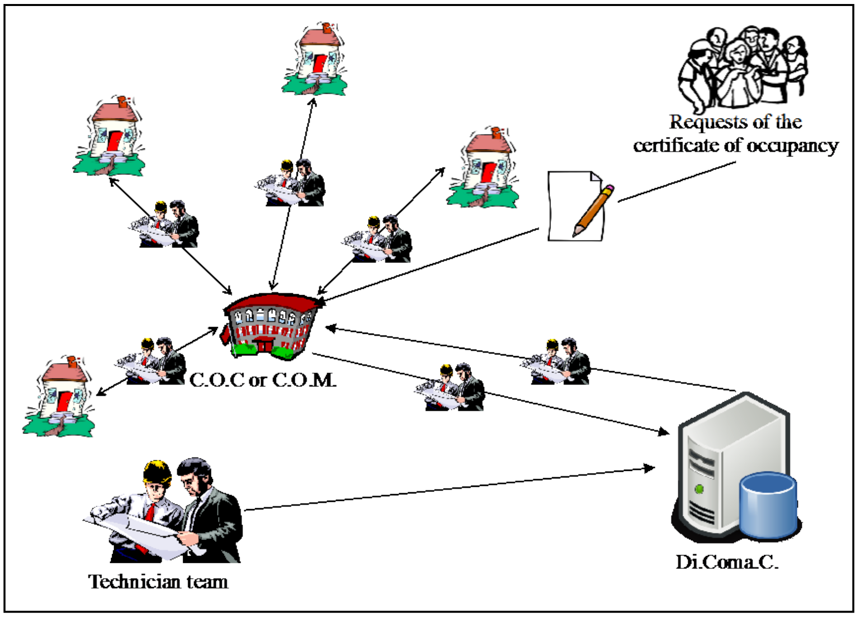


Figure 10-4 Standard procedure to make the certificates of occupancy during the Emilia earthquake

As discussed above, a series of technician teams carried out an assessment of building damage. The standard procedure to produce certificates of occupancy during the emergency was the following:

- Requests of certificates of occupancy in hardcopy form made by citizen in the C.O.C. or C.O.M.;

  For each technician team:

  - Registration at the Di.Coma.C. (Bologna) of the team;

    For each day:

    - Get the list of buildings to be investigated at the C.O.C. or C.O.M.;

      For each building:

      - Reach the building to be investigated;
      - Fill out the AeDES form (certificate of occupancy).
    - Compile a summary form for the C.O.C. or C.O.M.;
    - Reach the accommodation.
- Correction of the AeDES forms at the Di.Coma.C. (Bologna).

Usually, the average time to fill out an AeDES form was about 45 minutes, while the average time to reach a building to be investigated was about 15 minutes (considering detours and missing appointments). Moreover, the lost time in bureaucratic procedures for a technician team on average was 30 minutes to register the team at the Di.Coma.C., 35 minutes to get the list of buildings to be investigated, 1 hour to compile a summary of the day, 4 hours to correct the AeDES forms at the Di.Coma.C., and 55 minutes to travel between Di.Coma.C. and C.O.C. or C.O.M.

In conclusion, each certificate of occupancy took about 1 hour and 46 minutes, of which 30 minutes were lost due to bureaucratic procedures. This means that 28% (29 days) of the time spent to perform the certificates of occupancy of the damaged residential buildings was lost due to bureaucratic procedures, without considering the lost time to get the list of buildings to be investigated at the C.O.C. or C.O.M.

Table 10-1 Timing of the standard procedure to make certificates of occupancy during the Emilia earthquake

Days recording the AeDES forms	101	days			
Time to fill an AeDES form	0,75	hours/form			
Time to reach the investigated building	0,25	hours/form			
Time to reach C.O.C. from the acomodation	0,58	hours/day/team			
Time to fill the summary of the day	1	hours/day/team			
Working hours per day	8	hours/day/team			
Forms per day by a single team	5,6	forms/day/team			
Days spended compiling forms by a team	5	days/team			
Registration of the team at the Di.Coma.C.	0,5	hours/team			
Correction of the forms at Di.Coma.C.	4	hours/team			
Province	Modena	Bologna	Ferrara	Reggio Emilia	Total
Average time to reach the Di.Coma.C. (Bologna)[hours]	1	0,25	1	0,75	0,92
Forms produced by a single team during the first day[forms/day/team]	4,67	5,42	4,67	4,92	4,75
Forms produced by a single team during the last day[forms/day/team]	1,17	1,92	1,17	1,42	1,25
Time to produce an AeDES form [hours/form]	1,77	1,66	1,77	1,73	1,76
Bureaucratic time to produce an AeDES form [hours/form]	0,51	0,42	0,51	0,48	0,50
Avarage forms per day by a single team[forms/day/team]	4,52	4,82	4,52	4,62	4,55
Avarage number of teams per day[teams/day]	52,9	7,5	19,3	4,5	84,3
Total forms per day[forms/day]	239,0	36,3	87,4	20,7	383,4
Total forms[forms]	24144	3665	8827	2090	38726

10.2 Smartphone Applications during Emergency Response

Since the use of smartphones is becoming more common, the team decided to implement Smartphone technology in its standard procedure for issuing certificates of occupancy of the damaged residential buildings during the Emilia earthquake. During the emergency response, when assisting the Piedmont Civil Protection, a Smartphone application to compile and send the AeDES forms that works on Android technology was developed (Arcidiacono and Cimellaro, 2013, Cimellaro et al., 2014b).

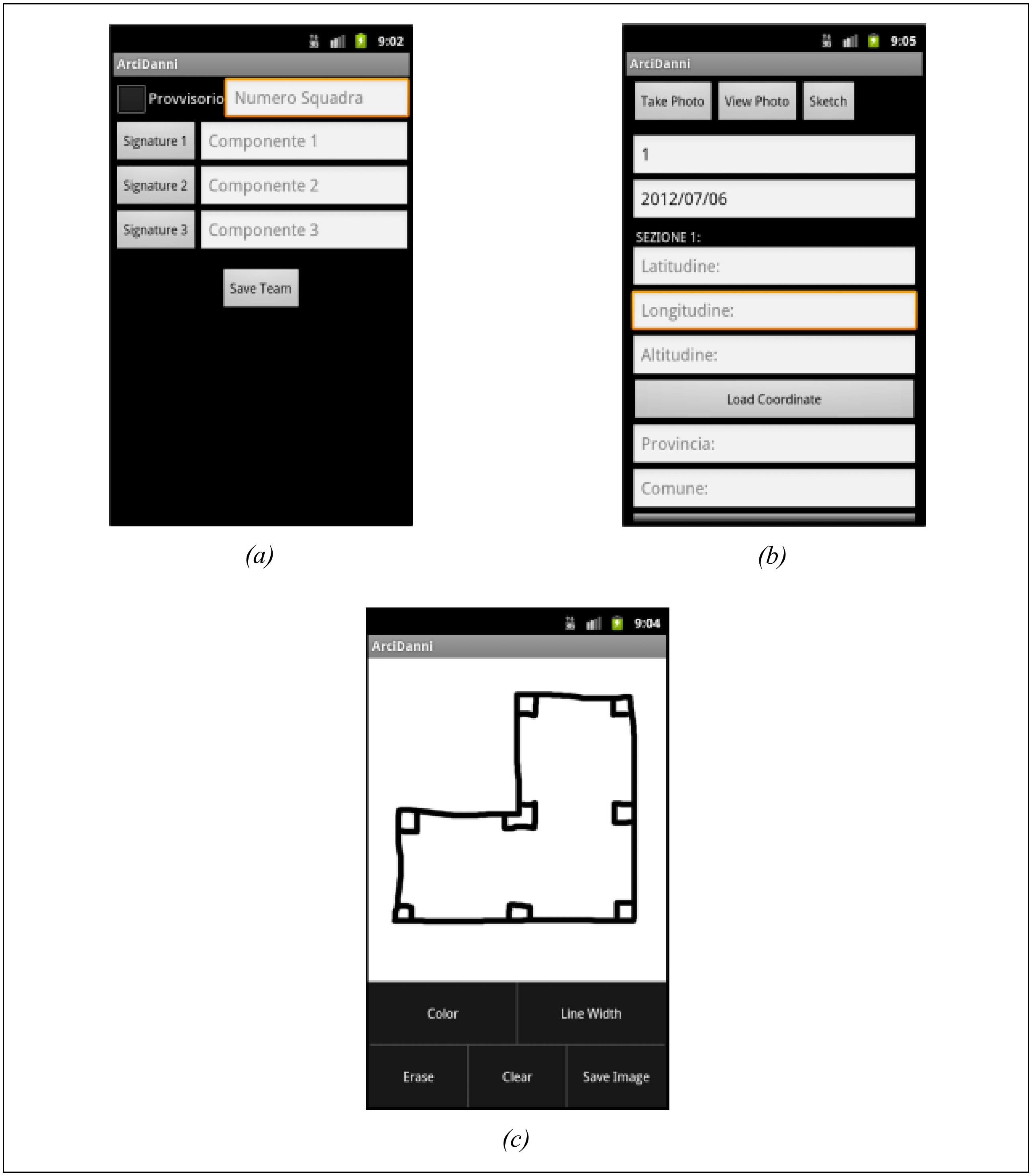


Figure 10-5 (a) Team registration form, (b) Digital AeDES form, (c) Sketch of a building section

As shown in Figure 10-5, the application, called Danni, requires identification of the technician team (team number, components, and signatures, (a), before completing and sending the AeDES form (b). Moreover, the form is prefilled – to speed up the acquisition process – and geo-referenced – through the GPS localization of the Smartphone. Therefore, the certificates of occupancy are sent to the operative center (in our case, the Politecnico di Torino) directly in PDF format together with photos and sketches of the investigated building (c).

Figure 10-6 Building investigated with the Danni application

This application was tested during the emergency response of Emilia earthquake in the recording of 70 investigations. It showed that the time to fill out an AeDES form was reduced to 40 minutes.

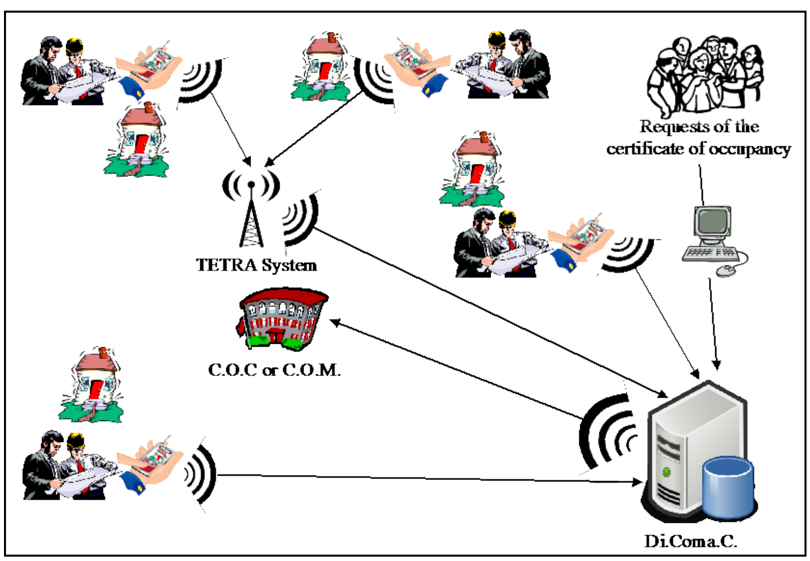


Figure 10-7 Proposed procedure to make the certificates of occupancy

Therefore, this research intends to propose a new ICT procedure to efficiently make certificates of occupancy during emergencies by: (1) integrating the TETRA system (robust network that permits the use of ICTs); (2) removing all bureaucratic procedures; and (3) reducing detours and missed appointments. The proposed procedure is as follows:

- Requests for certificates of occupancy in digital format are made by citizens;

  For each technician team:
  - Download application;
  - Register the technician team on the Smartphone;

    For each day and each building:
    - Select the building to be investigated on the application;
    - Reach the building to be investigated;
    - Fill out the AeDES form with the Smartphone, which is corrected by the application
    - Send the AeDES form to the Di.Coma.C. via Internet connection (TETRA system);
    - Reach the accommodation.

Table 10-2 Timing of the ITC procedure

Timing of Proposed Coordination

Days recording the AeDES forms	54,7	days			
Time to fill an AeDES form	0,67	hours/form			
Time to reach the investigated building	0,17	hours/form			
Time to reach the investigated area from the acomodation	0,5	hours/day/team			
Working hours per day	8	hours/day/team			
Forms per day by a single team	8,4	forms/day/team			
Province	Modena	Bologna	Ferrara	Reggio Emilia	Total
Avarage number of teams per day[teams/day]	52,9	7,5	19,3	4,5	84,3
Total forms per day[forms/day]	444,6	63,3	162,5	37,7	708,1
Total forms with Smartphone App.[forms]	24316	3461	8890	2059	38726
Total forms (from the reality)[forms]	24144	3665	8827	2090	38726

In conclusion, each certificate of occupancy takes 57 minutes to complete, considering that the average time to fill out an AeDES form is about 40 minutes; the average time to reach a building to investigate from a previous inspection is about 10 minutes, and from the technician's accommodations is about 30 minutes. Hence, the ICT procedure would save 46 days compared to the standard procedure.

SECTION 11
CONCLUSIONS

11.1 Summary and Conclusions

The reconnaissance team collected a substantial amount of data from field investigations in the area affected by the two earthquakes, which caused 27 deaths and widespread damage. Five of the deaths were caused by the collapse of recently constructed factory buildings.

Several historical structures (e.g., churches, palaces, castles, etc.) were damaged or destroyed. There was also significant damage to factories and agricultural land in the region. Production of Grana Padano and Parmigiano-Reggiano hard cheese was significantly affected; approximately 300,000 wheels of cheese, with an estimated value of 200 million euro, were destroyed. The information collected by the team will be useful in the analysis of the resilience of a community following extreme events and can be used to understand how to rebuild a new resilient community by avoiding the mistakes of the past (Cimellaro et al., 2010, Renschler et al., 2010).

11.2 Rebuilding Strategies

The rebuilding strategy for the area affected by the earthquakes is very complex. The importance of commercial activities in the area has necessitated concentrating efforts in the reconstruction of industrial sheds. Thus, the first reconstruction efforts focused on the infrastructure of the industrial and agricultural sectors. These efforts contributed to reducing possible industrial relocation and facilitated a quick restart of industrial activities.

One of the most probable causes of collapse of industrial sheds during the earthquake is that they were built without following seismic design criteria. However, the area was not classified as having high seismicity; therefore, the engineers who designed the warehouses were not obliged to connect plinths at the foundation level or beams with columns. In order to prevent the collapse of these structures in the future, the designer must keep in mind that all of Italy is susceptible to earthquakes. Therefore, it is highly recommended that seismic criteria be used even when the area is classified as being one of low seismicity. Precast structures should be designed by looking at the connection between the beams and columns as well as between the columns and foundation plinths. Connections should be able to reduce deformation of the structures through cantilever systems and/or transversal braces and/or passive connections. A hyperstatic scheme should be preferred with respect to the isostatic scheme.

People who have been left homeless are an important part of the emergency response. The camps provided by Civil Defense officials provided shelter for 2,000 people, but the majority of those displaced at the time of this report were still without accommodation. There are also many companies that are at risk of closing down for good. The recovery of the Emilia region must make it a safer place where the built environment is more resilient to future disasters of any kind. This is a key issue to keep in mind while revitalizing the area, which will necessarily call for some significant changes. A seismic and geological map of the area as well as of the infrastructure and materials in place before the earthquake can guide decisions on where to intervene. Before starting the reconstruction process, it is important to map these characteristics using available data and, when necessary, new techniques. Reconstruction processes, however, should also consider the subjective aspects of revitalization, especially the value of the memories of places that are the source of cultural and human attachment to them.

SECTION 12

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University at Buffalo, The State University of New York
Red Jacket Quadrangle ▪ Buffalo, New York 14261
Phone: (716) 645-3391 ▪ Fax: (716) 645-3399
E-mail: *mceer@buffalo.edu* ▪ WWW Site *http://mceer.buffalo.edu*

University at Buffalo *The State University of New York*

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