EPICentre

The 20th May 2012 Emilia Romagna Earthquake

EPICentre Field Observation Report

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EPICentre Field Observation Report
No. EPI-FO-200512

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The Emilia (Italy) Earthquake of 20th May 2012

1.0 INTRODUCTION

A 5.9M_w earthquake hit the Emilia Romagna region of Italy on the 20th May 2012, resulting in 7 deaths, significant damage to historic structures, churches and industrial buildings, and 7000 people needing shelter.

On the 25th May 2012 the EPICentre team travelled to the earthquake affected areas, where they were joined on the 26th May by Professor David Alexander. The team spent two days in the field, making rapid observations on the performance of structures, infrastructure, emergency management and noting geotechnical features of the event. Four members of the team left the field on the 26th May, whilst 3 stayed onto make further observations.

The timely deployment of the mission meant that, despite the short length of the mission, it was possible to obtain a good overview of the earthquake effects before clear-up took place. On the 29th May 2012, at the time of writing this report, a second earthquake of magnitude 5.8M_w hit the region causing further damage and deaths. This report therefore presents an overview of the state of damage and earthquake effects after the 20th May 2012 earthquake. These can be regarded as intermediate observations of damage, and will be updated following a second EPICentre reconnaissance mission to Emilia Romagna to take place between the 2nd and 6th June 2012.

Updates of the report will be made available at www.epicentreonline.com , where a kml file of the georeferenced photos collected in the field can also be downloaded (for viewing on Google Earth).

2.0 THE MAY 2012 EMILIA ROMAGNA EARTHQUAKE

2.1 Earthquake Characteristics

At 02:03 UTC (04:03 local time) on Monday May 20th, an earthquake with magnitude M_W = 5.9 (INGV, 2012a) struck the region of Emilia Romagna in northern Italy with an epicentre approximately 30km west of Ferrara. The epicentre is shown in Figure 2.1. Depth estimates vary and range between 6.3km (INGV, 2012b) and 9.0km (USGS, 2012a). Over one week later at 07:00 on Tuesday May 29th, an earthquake of magnitude M_W = 5.8 occurred with an epicentre 15km to the west of the first main event. Both the USGS (2012a) and INGV (2012c) agree on a depth for this event of around 10km.

Figure 2.1 - Location of epicentre of May 20th earthquake.

These two earthquakes have occurred as part of a series since May 18th (INGV, 2012d). The daily distribution of earthquakes in this sequence by magnitude is shown in Figure 2.2. The spatial distribution of these earthquakes is shown in Figure 2.3.

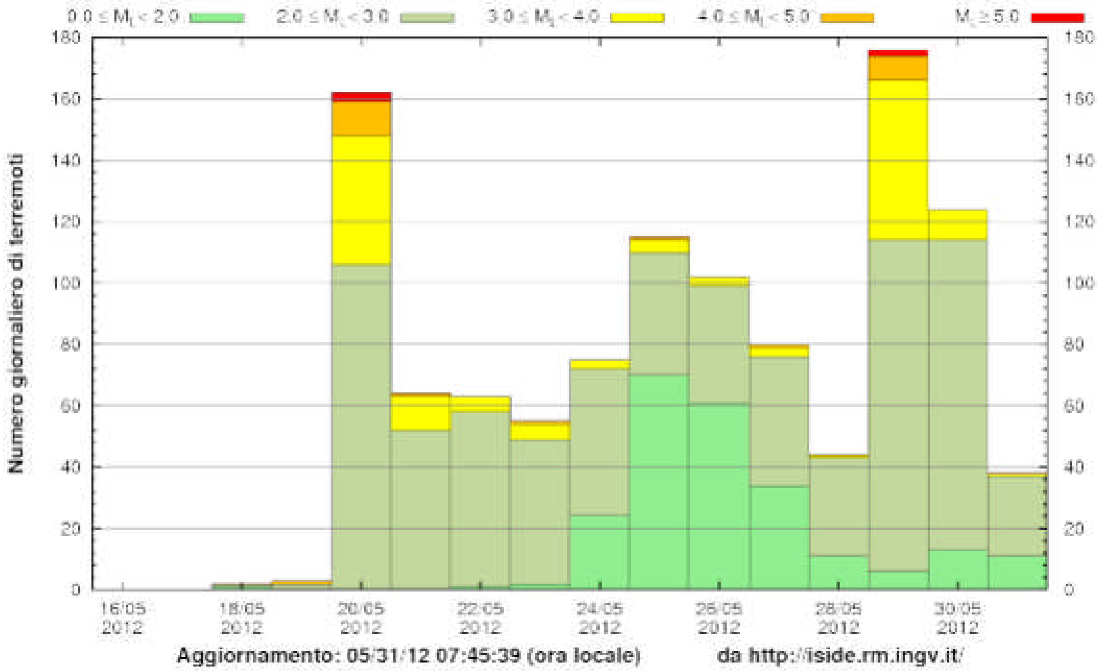

Figure 2.2 - Distribution of earthquake sequence by date and magnitude (INGV, 2012d).

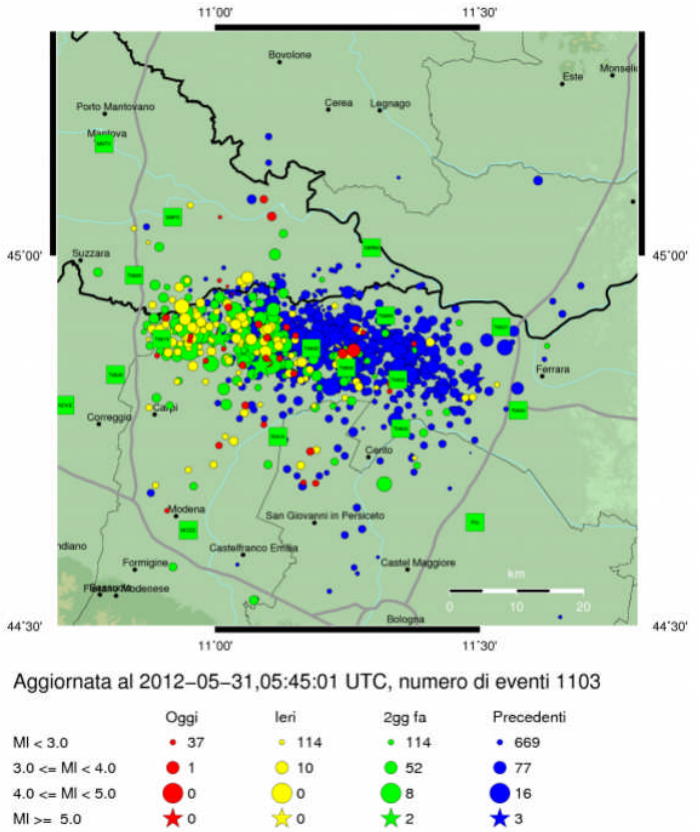

Figure 2.3 - Spatial distribution of earthquake sequence (INGV, 2012d).

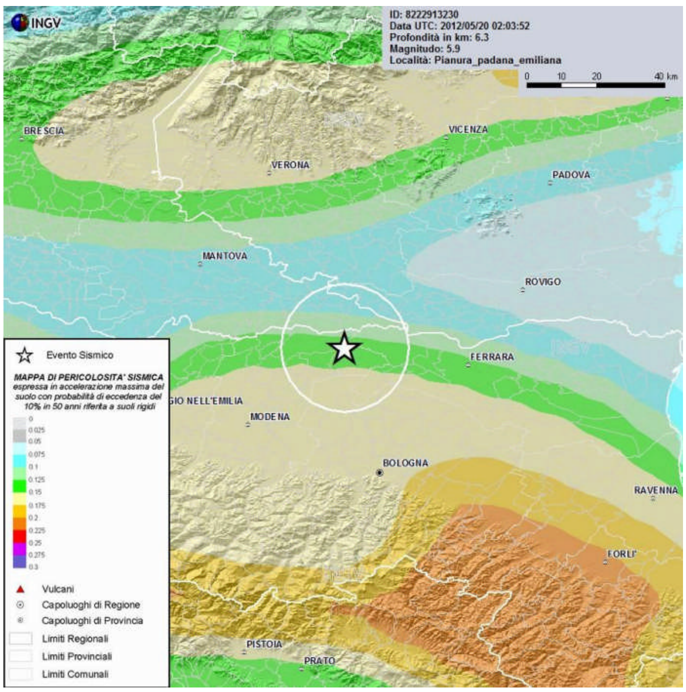

Figure 2.4 - Seismic design accelerations in Emilio Romagna (INGV, 2012a).

INGV (2012a) have identified the seismic risk across Italy based on a 10% exceedance probability of peak ground acceleration within 50 years. This risk for Emilia Romagna is shown in Figure 2.4. In the area around the epicentres of the recent events, the current design acceleration is between 0.125g – 0.15g. It should be noted that until 2003 the affected area was not classified as having significant hazard by Italian seismic hazard maps ($pga_{10\%\ in\ 50yrs}$<0.05g estimated). Hence, buildings in the area were not required to be designed according to the seismic code.

Acceleration contours estimated by INGV (2012a) for the May 20th and May 29th events are shown in Figures 2.5 and 2.6. The maps indicate peak ground accelerations at both epicentres of around 0.30g, approximately double the design acceleration identified by the INGV seismic risk map. Both earthquakes occurred due to thrust faulting (USGS, 2012a).

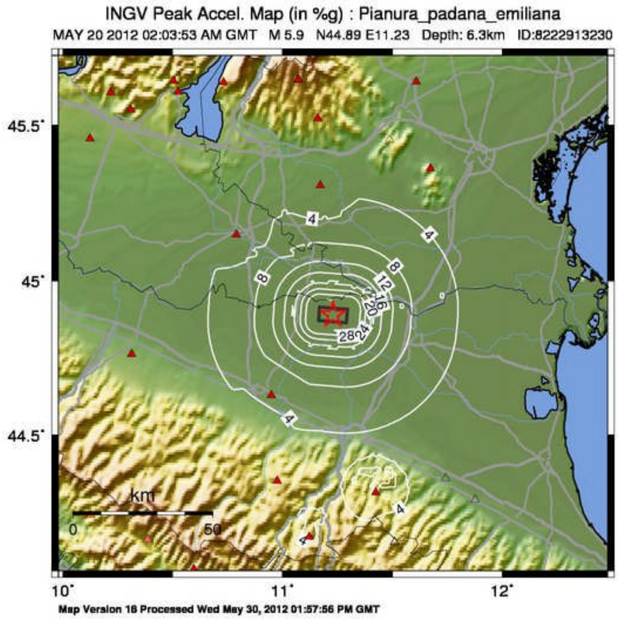

Figure 2.5 - PGA contour map for May 20th event (INGV, 2012b).

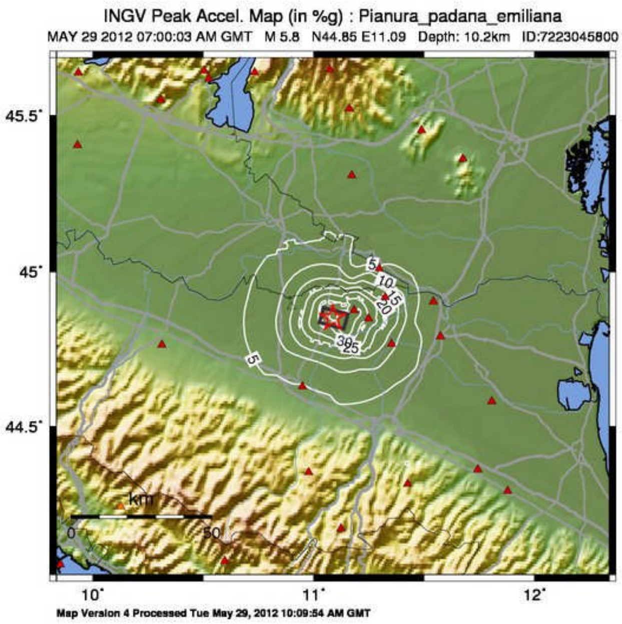

Figure 2.6 - PGA contour map for May 29th event (INGV, 2012c).

2.2 Tectonic Environment

The Mediterranean region is seismically active due to the northward convergence of the African plate with respect to the Eurasian plate at a rate of approximately 7mm per year. The specific geology in this area, the Po Valley, is dominated by compressional tectonics forming thrust-belt type structures such as the Appenine Mountains. (USGS, 2012a). The compressive tectonic phases have produced asymmetric folds and thrust and reverse faults verging north-northeast. The seismogenic structure of Mirandola, the cause of the recent earthquakes, has historical earthquakes associated with it. It has a maximum depth of 7.6km and is about 8.7km long and is shown in Figure 2.7. It is capable of generating an earthquake with M_W = 5.9 (INGV, 2012e). All earthquakes in the Po Valley are associated with shallow focal depths, long periods and small amounts of released energy (Boccaletti et al., 1985).

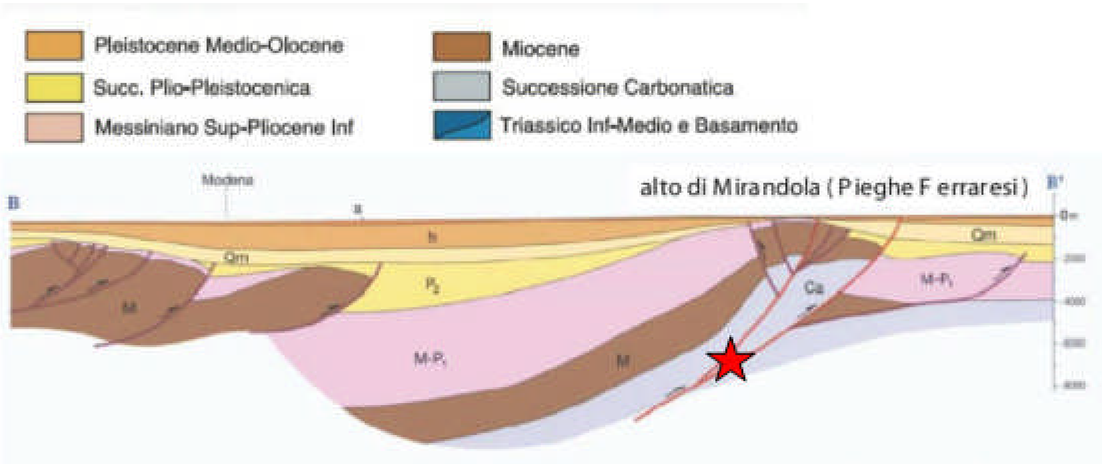

Figure 2.7 - Profile of seismogenic source of May 20th earthquake (INGV, 2012e).

2.3 Historical Seismicity

The INGV historical catalogue reports that no significant events have taken place within 30km of the epicentre of the May 20th event. However, there are a series of historic events of magnitude below 6.0, further south along the northern Apennines (INGV, 2012a). The historical catalogue is shown in Figure 2.8.

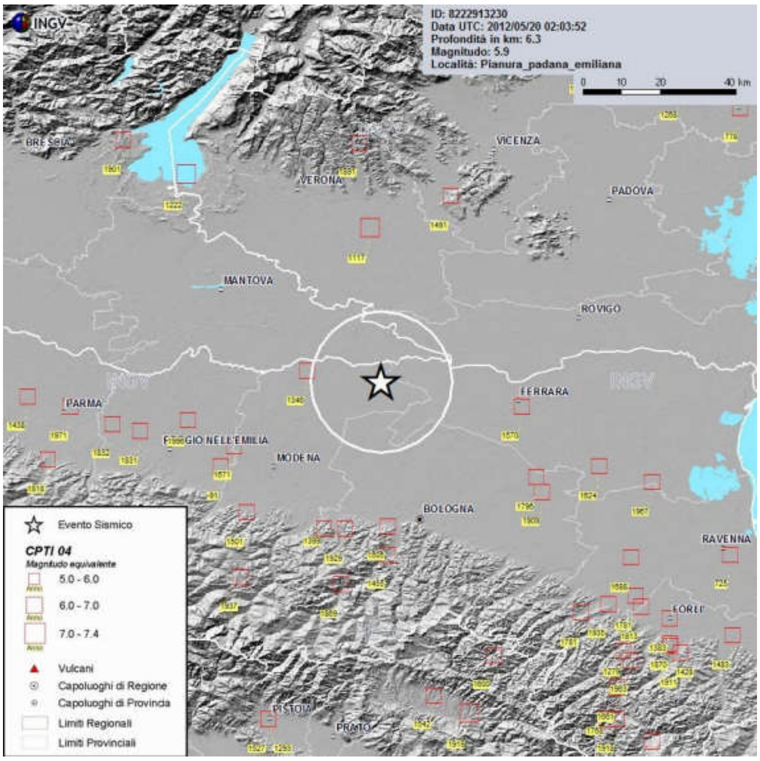

Figure 2.8 - INGV historical earthquake catalogue (INGV 2012a).

Toscani et al. (2008) identified specific seismogenic sources in Emilia Romagna. These are shown as yellow boxes in Figure 2.9, where Ferrara is marked as ‘FE’ and Bologna as ‘BO’. These relate to six notable 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 Forli.

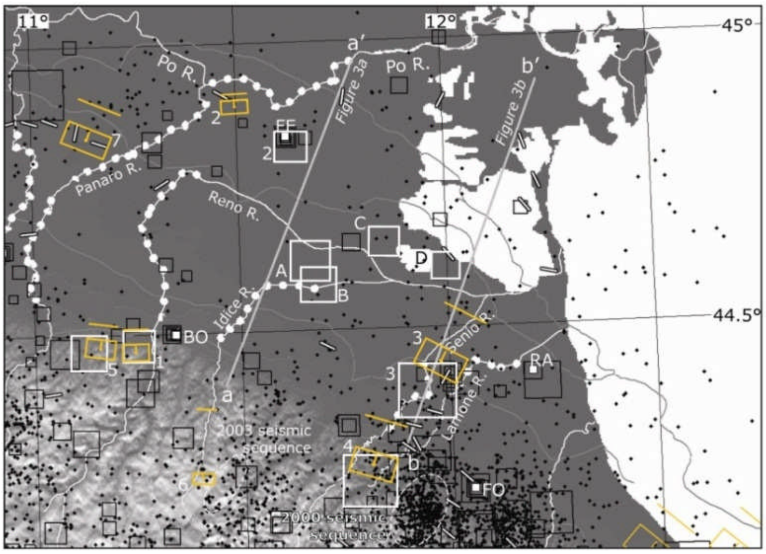

Figure 2.9 - Seismogenic sources identified by Toscani et al. (2008).

All of these events are identified by Toscani et al. (2008) as having $M_W > 5.5$. Around Ferrara, shocks with intensity of VIII MCS or greater have been recorded in 1467, 1570, 1624 and 1787. The 1570 event is notable as it was followed by a sequence of over 2,000 shocks over four years with intensities ranging from III to VIII (Boccaletti et al., 1985). Based on analysis of the historic catalogue, Toscani et al. (2008) suggest a maximum magnitude for future events in this region of around $M_W =$

5.8, slightly lower than the magnitude recorded by the USGS for the May 20th event. The more recent INGV instrumental catalogue is displayed in Figure 2.10 and shows that since 2005 there has been a belt of earthquakes along the northern Apennines although these are predominantly more than 50km from the May 2012 epicentres. These earthquakes have been of low magnitude and at shallow depth.

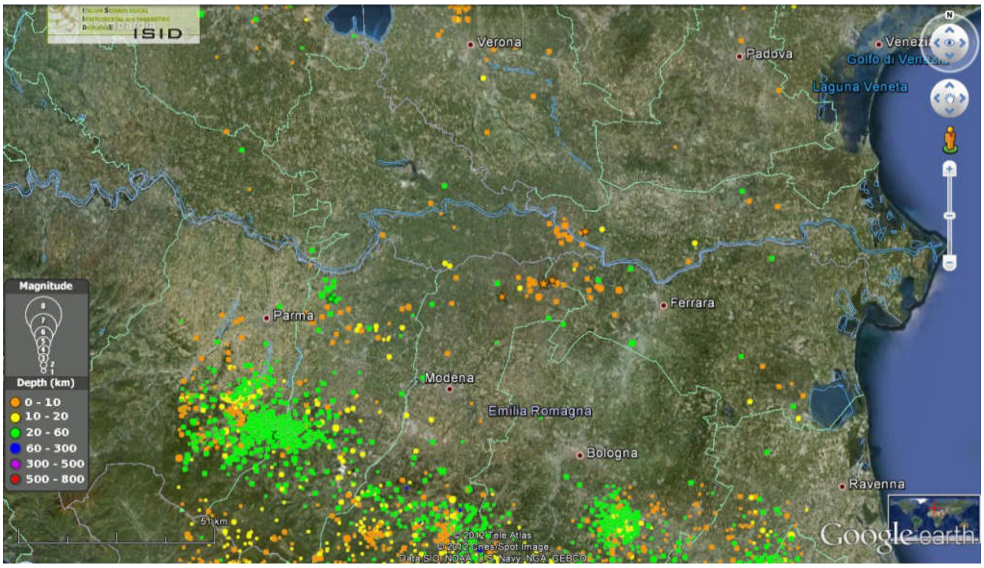

Figure 2.10 - INGV instrumental earthquake catalogue (INGV, 2012a).

The USGS NEIC catalogue (2012b) dates back to 1973 and is shown in Figure 2.11 for $M_W > 4.0$. Within a radius of 100km from the May 20th epicentre, there have been 141 such earthquakes in the last 39 years, most recently on January 27th 2012, about 40km southwest of Parma and over 100km from the May 20th epicentre. Just ten earthquakes in this period had $M_W > 5.0$. The most recent was on December 23rd 2008, 30km south of Parma, with $M_W = 5.4$.

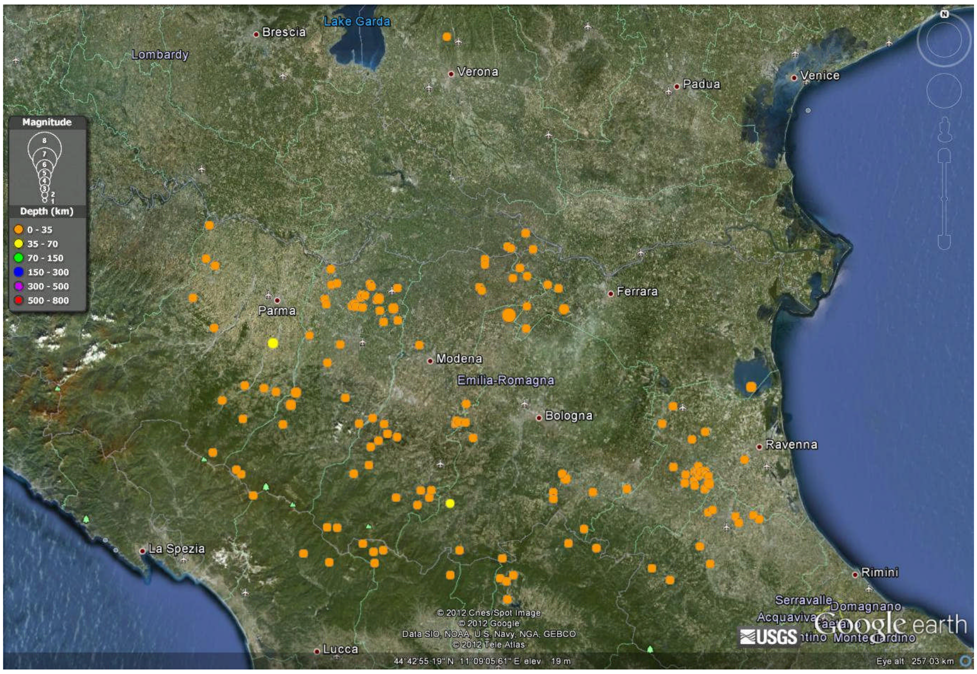

Figure 2.11 - USGS NEIC earthquake catalogue 1973-2012 for $M_W > 4.0$ (USGS, 2012b).

3.0 GENERAL OVERVIEW OF OBSERVED DAMAGE

The EPICentre earthquake reconnaissance started in the town of Vigarano Mainarda and finished in San Felice sul Panaro, with field observations made at Mirabello, S. Carlo, S.Agostino and Finale Emilia and along route (see Figure 3.1). Damage data was collected through rapid visual inspections of the exterior of buildings. The damage observations and observed geotechnical phenomena were recorded using GPS cameras and Leica GPS receivers. A kml file of the georeferenced photographs is available for download at www.epicentreonline.com .

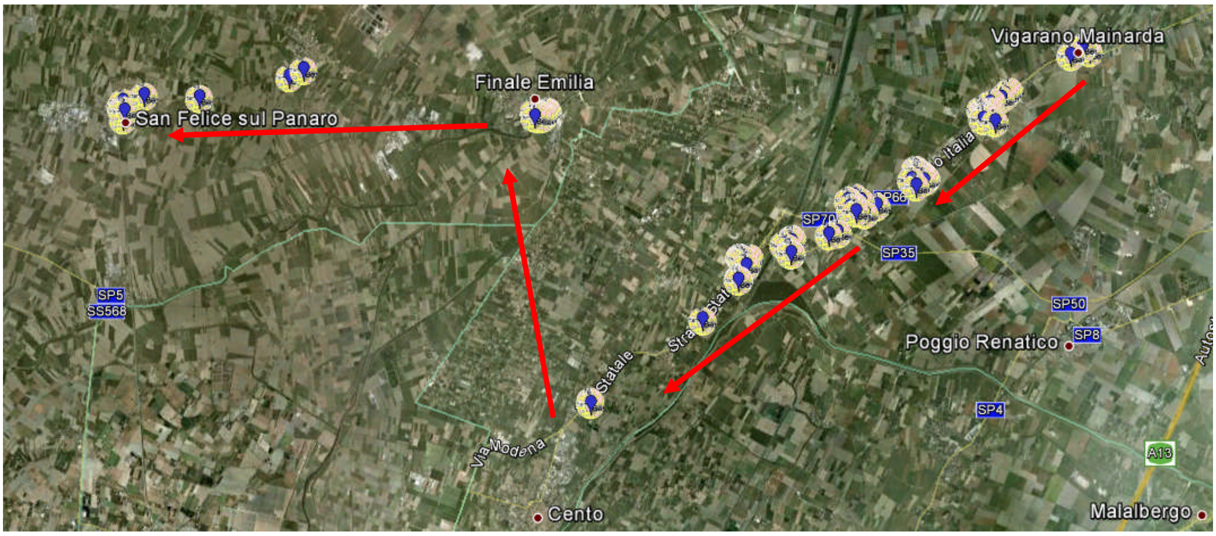

Figure 3.1 - Path taken by the EPICentre field reconnaissance team.

On May 25th, the team deployed in the towns of Vigarano Mainarda and Mirabello. In Vigarano Mainarda the church of Nativita' di Maria, in Piazza San Giovanni, reported a partial detachment of the main facade. Cracks to the external masonry walls were also visible. The clock tower presented shear cracks in the top half of the structure (Figure 3.2 and 3.3). Overall, damage to masonry and reinforced concrete low-rise residential housing and small local businesses was minor. Approximately 100 local people had been evacuated from their homes as a precaution but it was estimated by the captain of the fire brigade in Vigarano Mainarda that only 25 of these would need re-housing. 23 of the latter are immigrant worker families, who were living in older, poorly maintained and more vulnerable constructions (personal communication fire brigade captain in Vigarano Mainarda). The supermarket of Vigarano Mainarda reported just a few objects falling from the shelves, but no overturned shelves. There appeared to have been no significant business interruption.

Figure 3.2 - Damage to the Church of Nativita' di Maria and Clock tower in Vigarano Mainarda

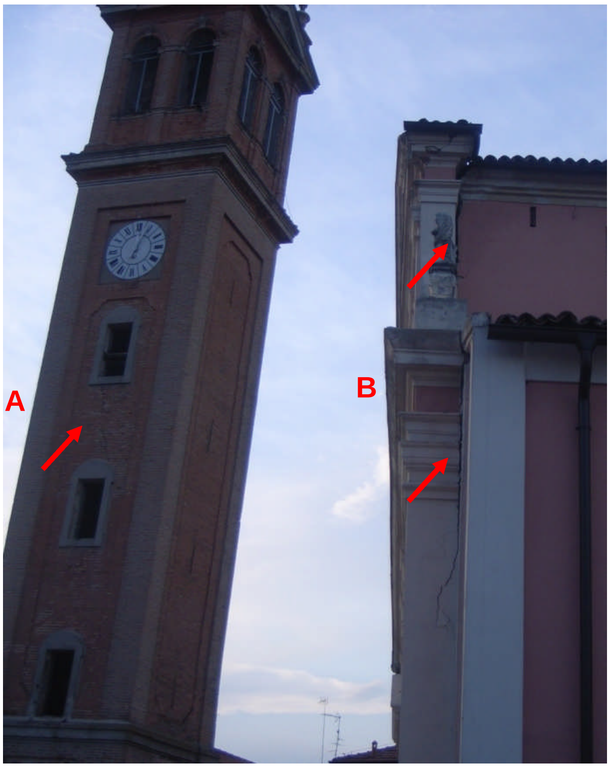

Figure 3.3 - Detail of the fractures lines in the top half of the clock tower (A) and detachment and rotation of the church facade (B).

In the town of Mirabello, the church sustained a partial collapse of the facade and total collapse of the transept and apse (Figure 3.4 and 3.5). The bell tower of the church did not sustain structural damage and was declared salvageable (Online Newspaper Estense.com – 23 May 2012 http://www.estense.com/?p=221642). Locals also reported that the bell tower foundations had been strengthened in the past.

In Mirabello, significant evidence of lateral spread due to liquefaction of soil at relatively shallow depth were found. These caused movement of buildings lining the main street as rigid bodies down-slope. This was visible as uplift of the pavement stones and the presence of separation cracks between the buildings moving down-slope and those attached to them further up-slope (Figure 3.6, 3.7 and 6.8). Measurement of the cracks indicated overall movements in the range of 0.5-2.5cm. Locals in the town of Mirabello told the team that the street interested by the lateral spreading was originally a small river (likely an affluent of Reno River). According to locals the river was running in the direction of S. Carlo and S. Agostino, where further evidence of lateral spread and liquefaction, were found. In Mirabello, damage to residential structures outside the main street, was minor and mostly concerned non-structural elements. New reinforced concrete low-rise residential houses were undamaged and were inhabited at the time of the mission. Locals reported there had been damage to gas pipes which would take a week to repair, and that electricity was unavailable for 4 hours after the earthquake. Despite the limited amount of damage to residential buildings, many locals were voluntarily sleeping in tents and in their own cars. Shelter was provided at the local school for people whose houses were damaged.

Figure 3.4 - Damage to facade of the Church of Mirabello (front view).

Figure 3.5 - Damage to cupola of the church of Mirabello (back view).

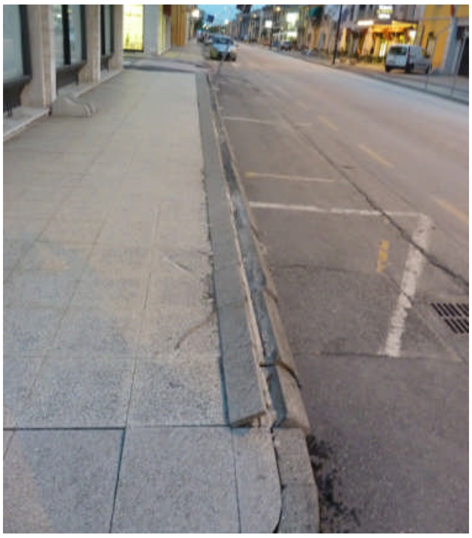

Figure 3.6 - Evidences of lateral spreading in the street of Mirabello.

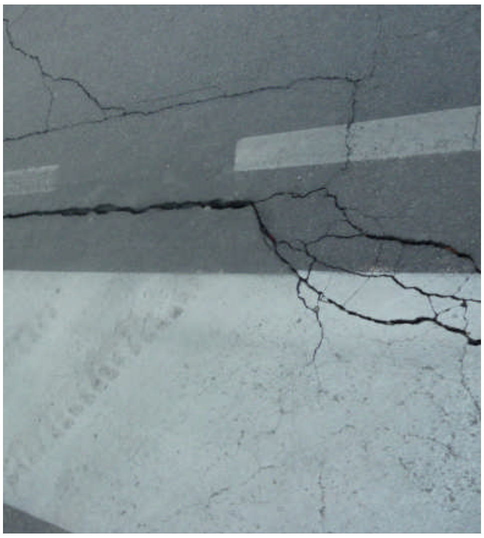

Figure 3.7 - Detail of lateral spreading in the street of Mirabello.

On May 26th, the team left Mirabello and moved in the direction of S.Carlo and S. Agostino. In S. Carlo instances of liquefaction were commonly seen and wide-spread (Figure 3.8). The overall damage to residential buildings was still minor but damage up to DS5 (EMS98) was observed in a small number of 3 storey masonry residential buildings located in the proximity of two streets (including Via Risorgimento) where liquefaction occurred. The elementary school in San Carlo was also reported to have sustained damage.

In S. Carlo, damage to industrial facilities was also observed (Figure 3.9.). All the collapsed structures were built with pre-cast reinforced concrete elements (see Section 4).

Figure 3.8 - Damage to a residential building in S. Carlo. The picture shows clear evidences of liquefaction.

Figure 3.9 - Damage to industrial facilities in S. Carlo.

In S. Agostino, both the Church and the Town Hall, located in Piazza Lupatelli – Corso Garibaldi, sustained partial collapse (Figure 3.10 and 3.11). The area had been cordoned off by fight fighters and the church declared inaccessible. (Online Newspaper Tempi.it 28th May 2012 - http://www.tempi.it/sisma-santagostino-fe-senza-chiesa-ma-i-fedeli-vogliono-ripartire#axzz1wHApePa6).

Figure 3.10 - Damage to the church of S. Agostino

Figure 3.11 - Damage to the town hall of S. Agostino. Detail A – Fallen column. Detail B – Collapse of the external wall.

More damage to industrial facilities was found in S. Agostino. The collapse of some of the warehouses of the S. Agostino Ceramic factory was observed, where two night-shift workers lost their lives. Close to the S. Agostino Ceramic factory another factory was damaged (Figure 3.10 and 3.11).

Figure 3.11 - S. Agostino Ceramic – Collapse of a warehouse for the storage of ceramic tiles.

Figure 3.12 - Another warehouse in the near proximity of S. Agostino Ceramic. Name and usage of the warehouse is unknown.

In Finale Emilia, the team found a larger number of displaced people, some of them were queuing at the fire brigade stand waiting to be escorted into the RED AREA to retrieve their belongings from the evacuated houses. At the time of the deployment, fire fighters were also inspecting the accessibility and liveability of private houses in order to re-house the displaced. Damage was greater for old and poorly maintained masonry structures but the majority of the residential buildings performed well (Figure 3.13).

Figure 3.13 - Different degree of damage to residential building were observed in Finale Emilia. Damage was particularly evident for old and poorly maintained masonry structures.

The damage in Felice sul Panaro followed the same pattern as in Finale Emilia. Residential buildings were either not damaged or slightly damaged. Monumental and historical buildings, including the old castle, sustained major damage (Figure 3.14). Industrial and commercial buildings suffered damage when conditions of structural vulnerability were present, but not all the industrial structures performed poorly.

Figure 3.14 - Damage to historical buildings in San Felice sul Panaro. The ancient tower is collapsed and the castle presents factures lines.

On the whole, damage to residential structures was judged minor, and the observed damage was concentrated in old and poorly maintained masonry structures. Monumental and historical buildings, in particular clock and bell towers, churches and town halls suffered disproportionate damage. The industrial sector sustained moderate damage, and the majority of this concerns a particular type of prefabricated reinforced concrete building (see Section 4.0).

4.0 OVERVIEW OF THE PERFORMANCE OF BUILDINGS

4.1 Reinforced Concrete (RC) Buildings

The first building code for reinforced concrete (RC) construction in Italy was published in 1939 (Royal Decree no. 2229). This was subsequently updated several times through a series of Government Decrees and Circulars. In 1974, Law no.64 and the subsequent Governmental Decree of March 1975, first introduced checks for seismic loads in the design of buildings, which used acceleration response spectra in the determination of the seismic forces. A series of revisions followed these codes, with major re-hauling of the seismic code taking place in 1986, 1996 and 2003. The seismic hazard maps for Italy were also revised in each version of the code. The areas affected by the 20th May 2012 Emilia Romagna earthquake were, however, not classified as a seismic area in Italian hazard maps until 2003. Hence, seismic design regulations were not mandatorily applied. From 2003 until now the area has been classified as Zone III, with characteristic $pga_{10\%\ in\ 50years}$ values ranging between 0.05-0.15g.

Residential RC buildings in the area were observed to be 2-3 storey moment resisting frames with infill made of thin-shelled hollow clay blocks. These were generally not damaged and only a few isolated cases of minor damage were observed. In general, the proportion of RC buildings in towns is lower than for masonry buildings and of fairly recent construction.

Figure 4.1 shows residential buildings in Mirabello without damage. Only pounding between the buildings was observed.

a) b)

Figure 4.1 Residential buildings in Mirabello: a) overview of the RC buildings; b) pounding observed between the buildings.

Residential RC buildings without damage in Sant Agostino are shown in Figure 4.2. Figure 4.3 shows a residential RC building in Finale Emilia with damage to its facade. The damage is non-structural and concerns the hollow clay brick infill, which failed in compression and shear.

Overall, little damage was observed in residential RC buildings.

Figure 4.2 Residential buildings in Sant Agostino.

Figure 4.3 Residential building in Finale Emilia with damage in the hollow clay brick infill.

4.2 Masonry Buildings (Residential)

Approximately 30 low-rise masonry buildings, typically unreinforced and without seismic design, have been surveyed in five different locations affected by the earthquake. Ordinary buildings in Italy have typically mixed occupancy, i.e. the ground floor is for commercial use and the above storeys for dwellings. The main observations are presented below.

In Vigarano Mainardo, very few buildings were inspected. The most seriously damaged was a three storey masonry building which sustained damage at one corner of the ground storey and was fitted with a stabilization system of steel ties (see Figure 4.4). This building had also suffered a dislodged chimney (see Figure 4.5). The remaining buildings were located very close to the church of Nativita' di Maria and were found to have suffered only light cracking to their façades (see Figure 4.6).

Figure 4.4 - Stabilisation of a commercial/residential building in Vigarano Mainardo.

Figure 4.5 - Dislodged chimney of a commercial/residential building in Vigarano Mainardo.

Figure 4.6 - Light damage of a commercial/residential building adjacent to the church of Nativita di Maria.

In Mirabello, a few brick masonry residential buildings located near the church of San Paolo were inspected. They were found to have suffered mostly vertical cracks (see Figure 4.8 and see Figure 4.9) which in a couple of cases was seen to be extensive (Figure 4.7), on their external walls and in some cases dislodged chimneys (DS1-DS3 in EMS-98). The cracks appear to have been caused by separation of the buildings due to the movement down-slope of one building relative to the other triggered by lateral spread of the ground. A bank building was also inspected. It was found to have suffered major damage (DS4 in EMS-98), indicated by an extensive and long crack on the middle of the arch which extended to the side wall, indicating out-of-plane failure of the corner on one side.

Figure 4.8 - Large and extensive vertical cracks on a residential house near the church of S. Pavlo in Mirabello.

Figure 4.9 - Long crack on a residential house near the church of S. Pavlo.

Figure 4.10 - Long cracks on a residential house near the church of S. Pavlo.

Figure 4.11 - Stabilisation to prevent overturning of the corner of a masonry building in Mirabello.

The top of the column in Figure 4.11 seemed to have swayed away from the building and a stabilisation system was fitted under the arch to prevent its collapse.

In San Carlo, the extensive liquefaction near the school caused significant damage on two adjacent buildings. In Figure 4.12, a 3 storey unreinforced brick masonry building located next to the school is shown to have suffered large cracks on its front façade. A similar building with timber roof (see Figure 4.13) located in a different street was also found to have suffered moderate damage (DS3 in EMS98) with large cracks in its two walls. The damage seems to be concentrated to this building since adjacent buildings (see Figure 4.14) of similar size were not damaged.

Figure 4.12 - Large and extensive cracks due to differential settlement on a residential house in San Carlo.

Figure 4.13 - Moderate damage of a commercial/residential building in San Carlo.

Figure 4.14 - Undamaged building adjacent to the building of **Error! Reference source not found.** in San Carlo.

Finally, most brick masonry buildings were inspected in Finale Emilia. In the Giuseppe Mazzini square, where the church of St Bartholomew is located, the unreinforced masonry buildings suffered slight damage mainly caused by dislodged chimneys and slight cracks on the wall (see Figure 4.16). Slight to moderate levels of damage was suffered by most masonry buildings inspected (see Figure 4.16 and Figure 4.18). A notable exception is the partial collapse of the commercial unreinforced masonry building with timber roof located in via Cesare Frassoni (see Figure 4.17). The collapse pattern appears to be similar to the failure pattern of the wall of the town hall in S. Agostino, i.e. the out of plane bending of the thin and tall wall led to its collapse. The adjacent buildings seemed to sustain slight to moderate damage. The long and extensive crack on the wall of the adjacent building in Figure 4.17 could have been caused by the poor connection of the two walls.

Figure 4.15 - Light damage of a commercial/residential building in plazza Giuseppe Garibaldi in Finale Emilia.

Figure 4.16 - Cracks on the wall of the 3rd floor in a residential building via Cesare Frassoni.

Figure 4.17. – Dislodged ceramic tiles from the roof and Shear crack on the wall of a residential building in Finale Emilia.

Figure 4.18. - Partial collapse of a commercial building in via Cesare Frassoni in Finale Emilia.

Overall, observations made of the performance of residential brick masonry buildings showed that most buildings suffered light damage due to the horizontal earthquake loads. This could be partially attributed to the poor soil conditions, which induced lateral spread and differential settlements that caused significant damage to the inspected buildings. Two cases of extensive damage were noted: the partial collapse of the commercial building in Finale Emilia as a result of the removal of an internal floor and the overturning of the corner of the bank in Mirabello.

4.3 Historical Buildings

The monumental structures inspected include 9 churches, 4 bell towers, 2 clock towers, the 'Rocca Estense' Castle, the Castle in Finale Emilia and San Agostino's tower hall. In many cases, the structures could not be assessed from all sides, and in all cases these observations are based on visual inspections made externally to the building.

Almost all inspected historical structures appeared to be of unreinforced brick masonry. Notable exceptions were the church of San Paolo in Mirabello and the castle in San Felice sul Panaro, which appeared to have been retrofitted with reinforced concrete, and both suffered partial collapse. Overall, most historical structures sustained moderate or higher levels of damage, and partial collapse was not uncommon. In churches, damage was frequently caused by the out of plane failure of the church façade. This type of failure was also suffered by the portico of the town hall. Dislodged architectural decorations were the most frequent type of non-structural damage noted in churches and bell towers.

Most churches suffered slight to moderate damage. The least damage seemed to have suffered by the church of San Bartholomew in Finale Emilia, built in 1504. The church sustained dislodged decorations from its façade (see Figure 4.19a). Moderate damage was sustained by the church of San Agostino, the church of Nativita' di Maria in Vigarana Mainarda, the church of Georgio Martiri in Corpo Reno and a church outside San Felice sul Panaro. The structural damage sustained by these churches was due to the out-of-plane failure of the façade (see the vertical cracks in the connection of the side wall to the façade in Figure 4.20b, 4.21b, 4.22b, 4,23b). Shear cracks were noted on the north wall of S. Agostino (see Figure 4.22b) and on the south transept of the church outside San Felice (see Figure 4.3c). Dislodged decorations were a common non-structural damage to the facade. The fall of a decorative statue on the roof may be the cause of damage in S. Agostino (see Figure 4.22a). The bell towers were noted to have suffered non-structural damage, i.e. dislodged decorations (see Figure 4.21, 4.22d, 4.23c). Shear cracks were also noted in the leaning bell tower of San Agostino (see Figure 4.22c) and notably of the Nativita di Maria, whose foundations have been recently strengthened. The decorations at the top of the bell tower of San Agostino seemed to have landed on a church building (see Figure 4.22d) causing localised damage on its north wall such as the collapse of part of the roof and the and an extensive vertical crack on the supporting wall.

Figure 4.19 - Dislodged decorations of the façade in the church of S. Bartholomew in Finale Emilia.

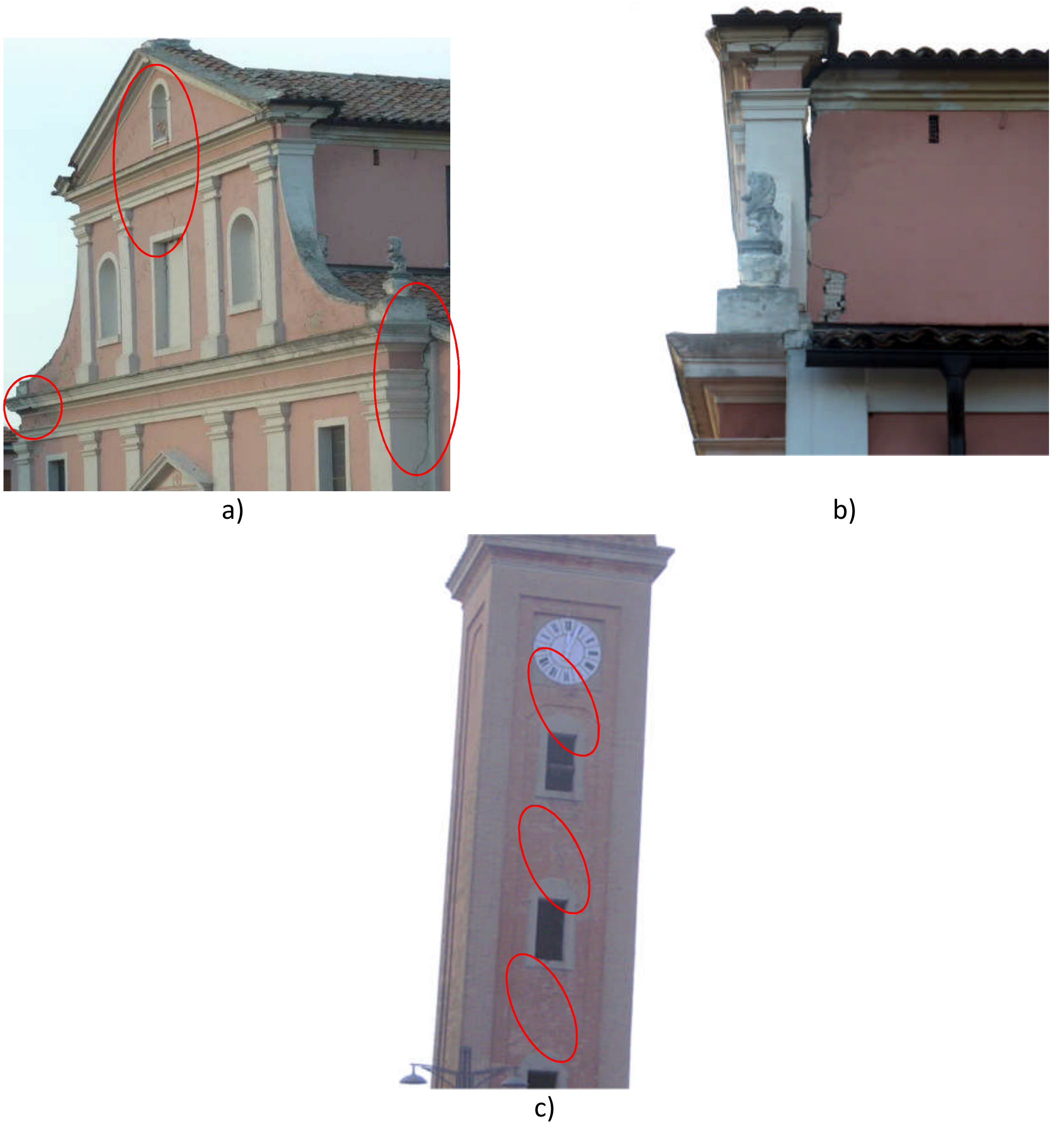

Figure 4.20 - Church of Nativita di Maria in Vigarano Mainardo: a) long crack on the facade and some dislodged decorations; b) failure of the external connection of the facade with the south wall; c) shear failure of the masonry wall between the openings on the bell tower.

a)

b)

c)

Figure 4.21 - Church outside San Felice sul Parano: a) dislodged decorations; b) crack on the external wall of the facade and the south wall; c) long crack on the south transept.

a)

b)

c)

d)

Figure 4.22 - Church of S. Agostino in S. Agostino: a) dislodged decorations and cracks on the plaster of the facade; b) long cracks on the north wall; c) large and extensive cracks on the leaning bell tower; d) localised collapse of the roof and long cracks on the north side.

a)

b)

c)

Figure 4.23 - Church of Divo Georgio Martiri Dicatum in Corpo Reno: a) dislodged decoration and a large crack on the facade; b) out of plane failure of the façade; c) dislodged cross on top of the leaning bell tower.

A brick masonry church with roof made from a steel frame with infill brick masonry and cladded with tiles, located in via degli Estensi, suffered moderate damage. In **Error! Reference source not found.** and **Error! Reference source not found.**, the façade sustained a degree of separation from the rest of the building, and suffered out-of-plane failure at the top. In addition, a long and extensive vertical crack on the south side was noted (see **Error! Reference source not found.**) which could be attributed to the poor construction of the masonry wall. The large crack (see **Error! Reference source not found.**) near the connection of the wall of the south transept and the wall of the sacristy.

The remaining four churches suffered moderate to substantial damage. The collapse of the top-part of the façade was a common damage pattern for these churches (see Figure 4.24a, 4.25, 4.26a, 4.27). Moderate damage was suffered by the church in via degli Estensi outside San Felice sul Panaro. This damage consisted of a long vertical crack which could be the result of poor construction of the masonry. Another extensive crack near the connection of the wall of the south transept, shown in Figure 4.24c, could be attributed either to the failure of the connection of these two walls or failure of the support of the roof. It was not possible to walk around the Duomo di Filippo and Giacomo in Finale Emilia for a good damage assessment. Figure 4.25 depicts the collapse of the top end of the façade which was reconstructed in 1807. The church of San Paolo in Mirabello and the church of DOM in San Felice sul Panaro suffered partial collapse. With regard to the bell towers, the tower of San Pavlo, whose foundations had been strengthened, did not suffer damage (see Figure 4.26c).In the tower of the church in San Felice sul Panaro, spalling of the plaster and brickwork was observed along the lower portion of the structure.

Partial collapse was also noted for the two church buildings used by the D.O.M. (Figure 4.28). The smaller building's failure mechanism seems to involve the formation of two large diagonal cracks, which led to the overturning of the corner, resulting in the collapse of the structure. Similarly, the collapse of part of the first floor of the larger building seems to have also been caused by the overturning of the corner (also induced by diagonal cracks). The walls of the ground floor for this building, however, seem undamaged.

a) b)

c) d)

Figure 4.24 - Church on via degli Estensi in San Felice sul Panaro: a) Collapse of the top façade of the church on via degli Estensi; b) Cracks on the external wall of the façade and the south wall of the church on via degli Estensi; c) Large and extensive crack on the north side of the church on via degli Estensi; d) Spalling at the bottom of the bell tower of the church on via degli Estensi.

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Figure 4.25 - Collapse of the top end of the facade of the Duomo in Finale Emilia.

a)

b)

c)

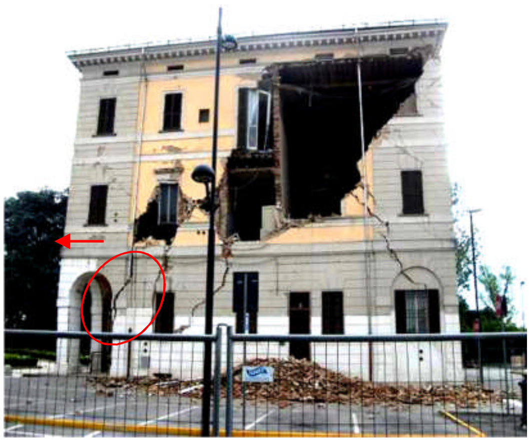
Figure 4.26 - Church of San Paolo in Mirabello: a) partial collapse of the; b) out of plane failure of the facade; c) collapse of east side and part of the north transept.

Figure 4.27 - Partial collapse of the façade of the church of D.O.M. in San Felice sul Panaro.

Figure 4.28 - Partial collapse of the church buildings next to the church of D.O.M.

The town hall of San Agostino is made of unreinforced brick masonry with timber floors. This building suffered severe damage to its structural components. Figure 4.29a shows the collapse of a middle column from the façade's portico. In Figure 4.29b, the external wall suffered partial collapse due to insufficient out-of-plane resistance. This can be attributed to the small thickness of the wall, i.e. one brick thick, which extends to two floors without being supported by a floor slab. There are also extensive diagonal cracks in both side walls (see Figure 4.29b,c) indicating the loss of connection of the side walls with the front wall. This forms a wedge which caused the out-of-plane failure of the portico.

a)



b)

c)

Figure 4.29 - Town hall in S. Agostino: a) Collapse of the middle column of the facade; b) partial collapse of a side wall and loss of connection of the external wall in the front; c) large and extensive cracks in a side wall.

The portico of the Oratorio in Corpo Reno, built in 18th century, was found to have suffered slight damage by the earthquake. A dislodged decoration from the facade and slight damage in the arches were noted (see Figure 30).

Figure 4.30. – Slightly damaged façade of the Oratorio in Corpo Reno.

The three inspected unreinforced brick masonry towers in Finale Emilia performed very differently. In particular, the unreinforced brick masonry tower in via Giovanni Zuffi suffered slight damage. The damage consisted of dislodged marble plates, which cladded the wall above the door (see Figure). The bell-clock tower in Figure suffered the partial collapse of one column which supported the roof, perhaps due to excessive compressive loads. The brick masonry clock tower in piazza Alfredo Baccarini in Finale Emilia (see Figure) collapsed.

Figure 4.31 - Dislodged decorative marble plates from the brick masonry tower in Finale Emilia.

Figure 4.32 - Collapse of a column supporting the bell on a clock tower in Finale Emilia.

Figure 4.33 - Collapse of a brick masonry clock tower in piazza Alfredo Baccarini in Finale Emilia.

The Castello delle Rocche in Finale Emilia, built in 1000 AD, suffered partial collapse. Figure depicts the collapsed east side.

The "Rocca Estense" Castle in San Felice sul Panaro was also inspected. The castle, built in the 15th century, is an unreinforced brick masonry structure with four towers. The castle suffered extensive damage due to the earthquake: three towers partially collapsed (Figure and Figure) and the fourth (see Figure) sustained significant large and extensive diagonal cracks, suggesting loss of connection between the walls. From the debris of a collapsed tower in Figure it can be concluded that one tower at least has been retrofitted with RC beams.

Figure 4.34 - Partial collapse of the east side of the Castello delle Rocche in Finale Emilia.

Figure 4.35 - Partial collapse of the two towers and severe damage in the third tower of the Rocca Estense Castle.

Figure 4.36 - Partial collapse of the fourth tower of the Rocca Estense Castle.

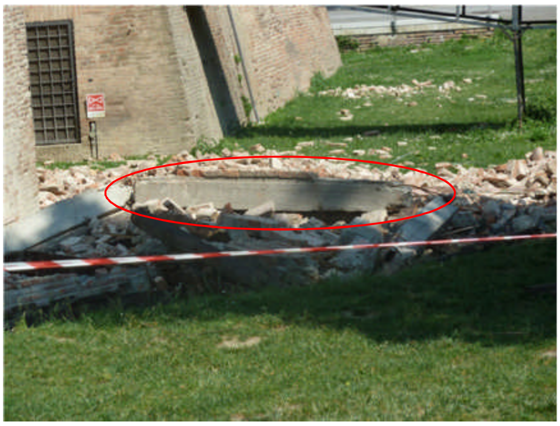


Figure 4.37 - Debris from the partial collapse of the tower of the Rocca Estense Castle.

4.4 Industrial Facilities

The main industrial structures observed in the affected region consisted in precast RC, pre-stressed precast concrete, steel frames, masonry or masonry with reinforced concrete or timber frames. The majority of the structures were constructed using RC and pre-stress precast techniques. Since the structures have large spans, and since most of the elements are pin connected, they may have longer fundamental periods of vibration. As described in Section 6 the ground conditions amplify considerably the ground shaking particularly at smaller frequencies, and hence industrial warehouses are characterised by large accelerations. These types of structures were observed to be mostly affected and damaged by the earthquake. In the next sections each typology will be discussed separately accounting for the damage observed.

4.4.1 Pre-cast reinforced and pre-cast pre-stress concrete industrial structures

The structures mainly consist in a series of single bay portal frames. The transverse frame consists in precast RC columns, supporting pre-stressed long span beams. 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. In absence of shear keys, the transverse beam is connected to the column by means of a system of steel plates and bolts. Many columns have also corbels in the transverse plain to support a bridge crane. 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 with the former using metal plate connectors and bolts. Other structures had masonry infill instead of RC precast panels. For most of the structures, the roof consisted in double T-precast pre-stressed slabs spanning in the longitudinal direction. In other cases, the roofing consisted in pre-cast pre-stressed hollow slabs also spanning in the longitudinal direction. For a particular case, the roof consisted in a series of slabs made of a RC ring beam and a thin steel fibre reinforced concrete shell. In another case, the roof consisted in a RC shell spanning over RC columns supported over columns having an inclination on the upper part.

The lightly connected beams and columns are equivalent to a pin/roller connection at the upper part of the structure, and it is only the column to foundation connection that prevents the structure from having a mechanism under static load conditions. 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 in the rotation of columns in opposite directions such that the transverse and longitudinal beams slipped off the column connection and collapsed. Plastic hinges were also observed at the base of the columns. In most cases, the shear key also failed. It is observed that the latter was not adequately detailed with reinforcement, and no redundancy provisions were provided to make a monolithic connection. Figures 4.38 to 4.41 show this mechanism. Figure 4.45a,b shows 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. 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 4.41 shows two industrial structures in an industrial zone close to Corpo Reno. In Figure 4.41a,b the structure exhibits the mechanism described. However, the second structure only exhibits minor damage even though it has the same structural system as the former. The only difference consists only in the latter having longitudinal spans approximately half that of the collapsed structure. The undamaged structure is more integral.

a)

b)

Figure 4.38 - Industrial buildings close to Mirabello: a) overview of the pre-cast structure; b) joint detail.

a)

b)

Figure 4.39 - Industrial building in Fondo Sabbione: a) overview; b) joint failed detail.

a)

b)

Figure 4.40 - Industrial building in Sant Agostino: a) overview; b) joint failed detail.

a)

b)

c) d)

Figure 4.41 - Industrial building close to Corpo Reno: a) overview; b) joint failed; c) pre-cast structure without damage; d) joint with few deformation.

a) b)

Figure 4.42 - Industrial building close to Sant Agostino: a) overview; b) joint failed.

The pre-cast RC panels attached to columns with steel plate connectors were observed to fail in Sant' Agostino ceramics factory (Figure 4.43), in an industrial hanger close to Mirabello (Figure 4.44) and in a factory close to Finale Emilia (Figure 4.45). Another industrial structure close to Mirabello, with enclosing panels were made of clay bricks, also had an out of plane failure (Figure 4.38). The precast RC panels supported between I-section columns were observed to slip off. In all the cases no fixity mechanism apart from the groove action formed by the I-shaped columns was observed. This was particularly observed in the damaged industrial building close to Corpo Reno (Figure 4.41a,b). However, this was not observed in the adjacent factory with shorter spans (Figure 4.41c,d) and in the damaged factory in Fondo Sabbione (Figure 4.39).

Many roofs of the industrial facilities collapsed as a consequence of failure of the transverse and longitudinal beams supporting them. This was observed in the abandoned factory in Sant' Agostino (Figure 4.40), where double T-beams collapsed together with some of the transverse precast RC beams, and in the factory close to Corpo Reno (Figure 4.41) were precast pre-stressed hollow slabs collapsed together with transverse and longitudinal beams. The precast roof of the modern factory observed close to Finale Emilia had a similar collapse mechanism (Figure 4.45a,b). In the older part of the factory, the RC shell roof which was monolithically attached with the RC beams spanning transversely across the column, collapsed with the former (Figure 4.45).The slabs made of a RC ring beam and a thin steel fibre reinforced concrete shell forming the roof of the factory close to Mirabello (Figure 4.38) had a similar failure mechanism to the former. In the industrial structure at Fondo Sabbione, the double T-beam roof structure slid over the transverse beams, causing collapse in some areas and permanent slippage of the slabs in other areas (Figure 4.39). Figure 4.43 shows that the roof did not collapse in the RC and pre-stress pre-cast structure at Sant' Agostino ceramic factory. The height of the structure is however shorter when compared with the other structures with damaged roofs.

a) b)

Figure 4.43 - Industrial building close to Sant Agostino: a) overview; b) panel connection failed.

Figure 4.44 - Industrial buildings close to Mirabello: lateral panel failure.

a) b)

c) d)

Figure 4.45 - Industrial building close to Finale Emilia: a) overview of new factory; b) plastic hinge on the column; c) overview of old factory; d) collapse of roof.

4.4.2 Steel industrial structures

The only steel industrial facility in which we observed damage was the storage warehouse at Sant Agostino ceramics factory (Figure 4.46). The warehouse was a large shelving facility for boxes of ceramic tiles. From visual inspection at a distance, the structure of the shelves also appears to have been the superstructure of the building. There were in total 12 singular rows of shelves. Each shelf seems to have consisted in 2 parallel multi-level frames. The parallel frames were connected transversally with a diagonal truss system. The parallel shelves appear to be connected in the transverse direction with each other at the foundation level and by a truss system at roof level. The structure was enclosed on the sides and the roof by sandwich insulation panels connected directly to external shelving steel frames or to a truss system in the longitudinal direction, which was only at various intervals.

Approximately 70% of the structure collapsed. In the longitudinal direction. 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 this direction. In the transverse direction, the truss system of each individual shelves provided some lateral resistance. Nevertheless, each individual shelve is very slender in this direction, and since the whole system seems only to be connected at the base and roof level, the lateral resistance also appears to be very small in the transverse direction. In the portion of the warehouse still standing, it was observed that only the upper levels of the shelves were filled with heavy boxes of tiles, and hence might have contributed to a larger base shear 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. The diagonal elements were rectangular in section and welded with the vertical elements, and not observed to experience local damage in many of the sections. Nevertheless, the vertical and horizontal elements consisted in U-shaped sections and in many sections were observed to experience warping failure effects particularly at intersections with other elements.

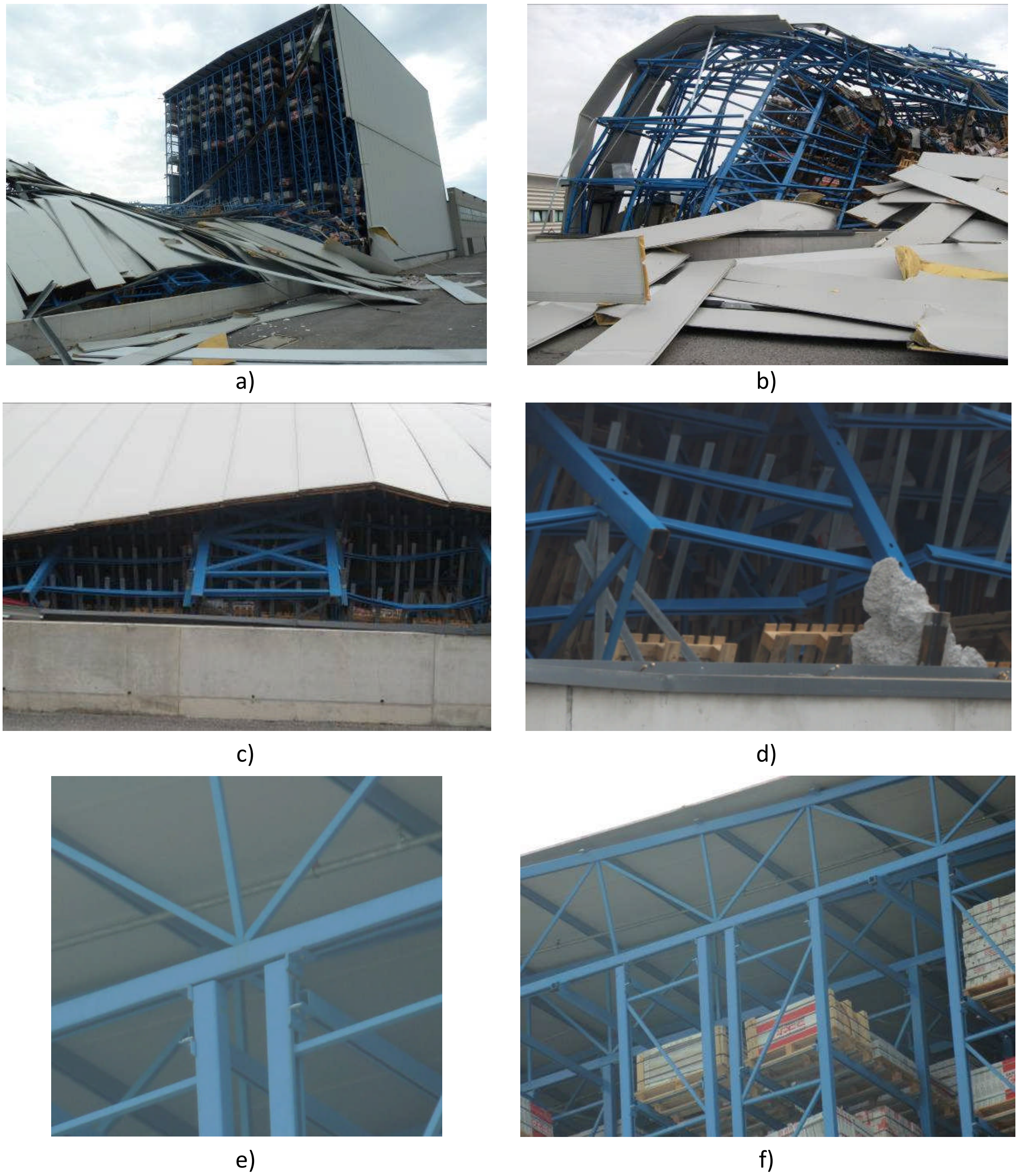


Figure 4.46 - Factory close to Sant Agostino: a) and b) overview; c) longitudinal frame; d) connection between the frames and the foundation; e) detail of the connection between the frames and the roof truss; f) general detail of the frame system.

4.4.3 Masonry industrial structures

A small warehouse in Vigarano Mainardo was observed to suffer shear diagonal cracks on the facade (Figure 4.47). An abandoned industrial warehouse along a water canal outside Massa Finale experienced partial collapse (Figure 4.48). The structure consisted in masonry walls with RC reinforcements. The roof structure consisted in a wooden truss. A small masonry bridge connecting the two banks of the canal on either side, had a transversal crack in the middle of its arch, hinting that there was minor lateral displacement of the canal bank that may have contributed to the collapse of the warehouse.

a)

b)

Figure 4.47 - Industrial building in Vigarano Mainardo: a) overview; b) shear failed on the front facade.

a)

b)

Figure 4.48 - Industrial building close to Massa Finale: a) overview; b) reinforced concrete frame failed.

4.4.5 Reinforced concrete structures - Water towers

Two water towers were observed. The first one was at San Carlo, consisting in a RC circular core and 6 columns, connected by RC diaphragms at various intervals. In this structure, various vertical cracks were observed on the RC core (Figure 4.49). The other water tower observed in San Felice sul Panaro had more damage (Figure 4.50). The structure consisted in an octagonal RC frame, with masonry infill panels, and only 1 RC horizontal diaphragm. Various masonry panels were observed to have fallen out of plane. Shear failure was observed in various beams at the lower 2 levels of the frame. Plastic hinging was also observed in some of the columns at the bottom.

a) b)

Figure 4.49 - Water tank in San Carlo: a) overview; b) crack in the interior reinforced concrete core.

a) b)

Figure 4.50 - Water tank in San Felice sul Panaro: a) overview; b) plastic hinge in the beams.

5.0 OVERVIEW OF THE PERFORMANCE OF INFRASTRUCTURE

This section provides an overview of the performance of infrastructure. Observations are limited to locations visited by the Epicentre team. Overall, there was minimal damage to infrastructure.

5.1 Roads

The main roads connecting the affected towns were not damaged by the earthquake. Several roads to the west of Ferrara were closed. The centres of Mirabello, San Carlo, Sant Agostino, Finale Emilia and San Felice sul Panaro were cordoned off to prevent injury from the collapse of unstable or damaged buildings.

Roads in the centre of San Carlo were damaged by liquefaction of the underlying soil and ground movement. On the main street of Mirabello, lateral movement caused cracking in the road surface and damage to the footpath (Figures 5.1). According to locals, the main street was constructed on the site of an old river. The ground in the damaged area appears to be settlement prone. Settlement cracks which existed prior to the earthquake are evident in roads, car parks and buildings, and were exacerbated by the earthquake.

a) b)

Figure 5.1 - a) Damage to the footpath in Mirabello due to lateral spreading; b) Typical cracking in roads in Mirabello due to lateral spreading.

5.2 Buried Services

No instances of damage to buried services due to ground movement were observed by the Epicentre team. Although locals in Mirabello reported there had been damage to gas pipes in the town that was estimated to take 7 days to repair.

6.0 GEOTECHNICAL OBSERVATIONS

In general, the soil surrounding the area where most damage was observed is characterised by unconsolidated ground layers. This may have contributed to the amplification of ground acceleration. These conditions have triggered damage in infrastructure and buildings due to settlement. Moreover, the region was susceptible to liquefaction since in general the ground is characterised by a clay material overlaying layers of sand, possibly saturated due to the flood plain region and other underlying clays. This resulted in observations of building damage due to liquefaction-induced differential settlement and lateral movement of the ground underlying the structures.

All the observations presented in this section relate to the route taken by the EPICentre team, and it is not excluded that other damage or other phenomena also occurred in areas that were not visited by the team. Reference is made to ground problems and associated damage observed in the structures. It is not excluded that other structural problems may have contributed to the overall development of damage.

6.1 Geological Lithology, Stratigraphy and Ground Amplification

The lithography of the area stretching between Modena and Ferrara consists mainly in clay or clay prevailing material, with areas of clay sand or sand as shown in Figure 6.1 and Figure 6.2. The area is quite flat and has a long history of flooding from various rivers mainly the Po and Reno. As a result, the ground consists mainly in an alluvial plane, stratified with alternating layers of fine sand often also containing silt. Intermediate alternating layers of silt, sandy silt and clay silt are also present and vary in thickness. In some areas, at the base of this series of layers, local medium to coarse sands and intercalating layers of clay are also present; the latter generally roofing the former.

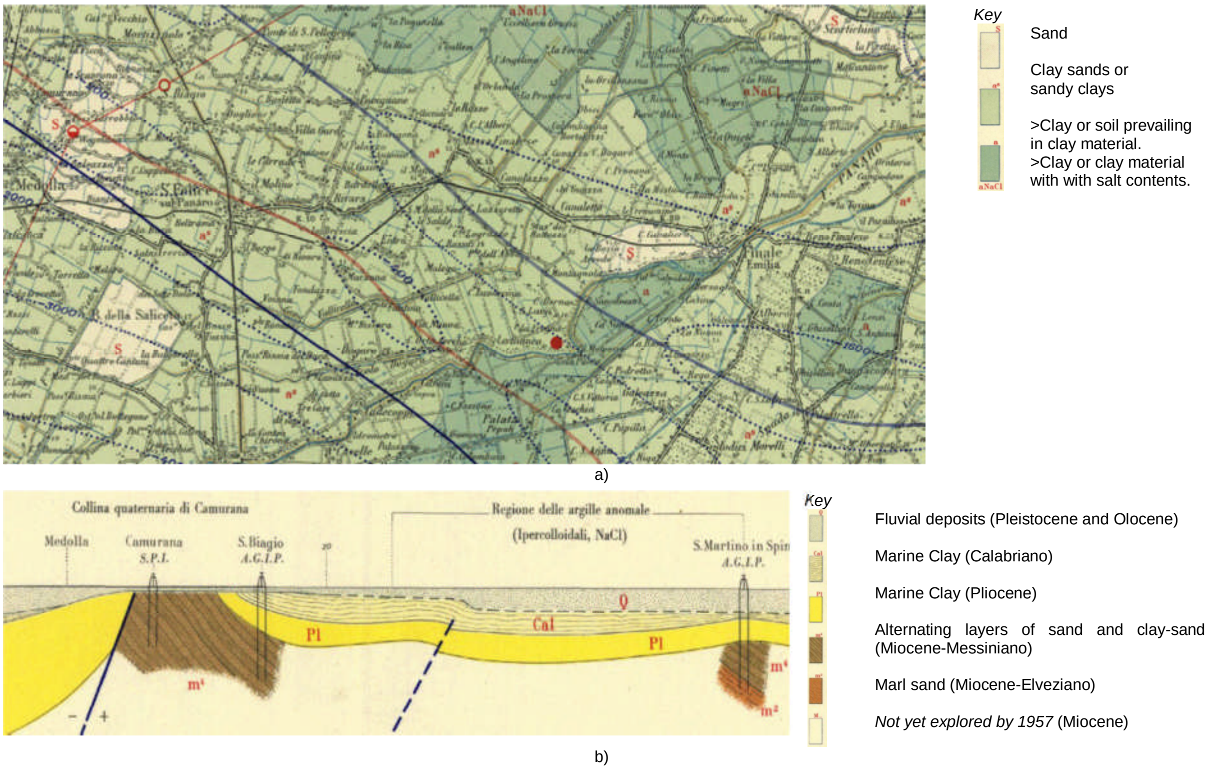
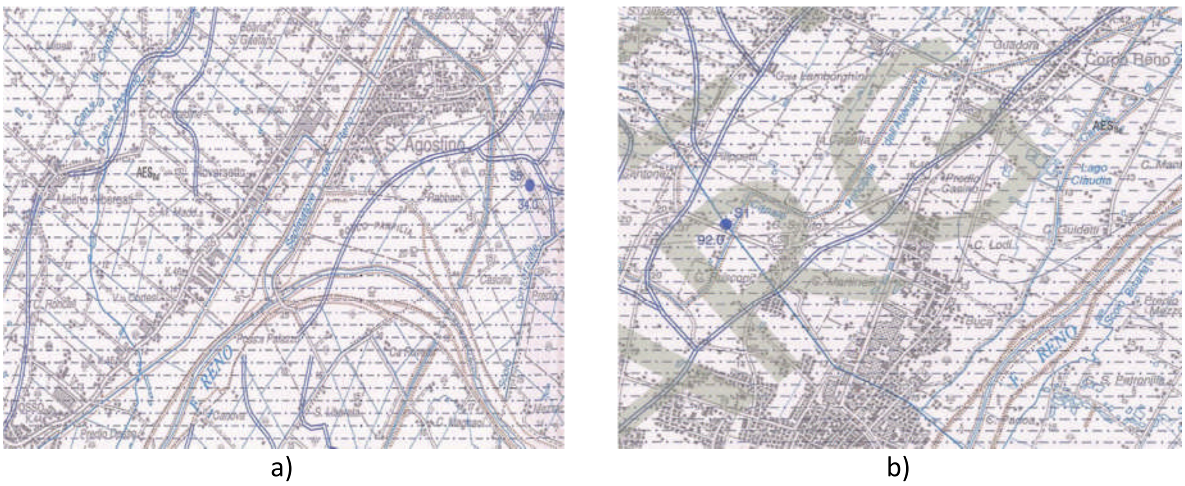
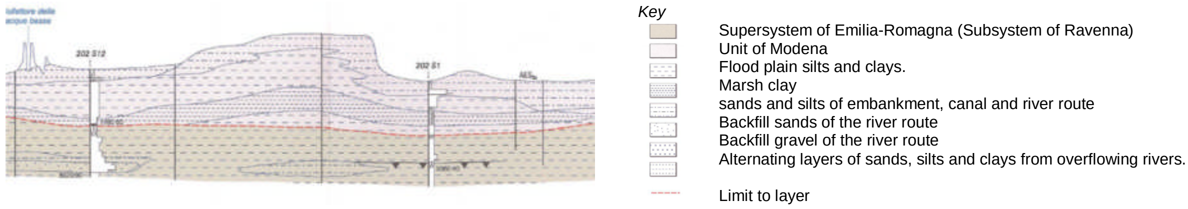


Figure 6.1 - Geological map at a scale of 1:100,000: a) Surface lithology of Finale Emilia and San Felice; (b) Stratigraphy Close to San Felice sul Panaro.

The stratigraphy is divided into 2 main parts: the top part of the sub-system of Ravenna, underlying the unit of Modena as the superstructure of the Emilia-Romagna region. Figure 6.1 and Figure 6.2 show a typical stratigraphy of the region and the lithology of Finale Emilia, San Felice sul Panaro, Sant Agostino and Corpo Reno. These are based on 2 geological Italian maps of the area. One is at a scale of 1:100,00 completed in the 1950’s (Law 2/2/1960) and the other is a more detailed map at a scale of 1:50,000 (CARG, 2007).





c)

Figure 6.2 - Geological map at a scale of 1:50,000: a) Surface lithology of Sant Agostino; b) Surface lithology of Corpo Reno; c) Stratigraphy between Cento and Corpo Reno.

The unconsolidated ground and its stratigrafic structure described above give rise to large seismic acceleration amplifications. Table 6.1 shows the peak ground acceleration (PGA) according to the latest Italian seismic code, and the maximum horizontal acceleration generated by the earthquake according to USGS and RNA (Protezzione Civile, 2012). In Figure 6.3, elastic response spectra for various soil conditions at 5% damping and complying with DM14/01/2008 (Italian seismic code 2008), are compared with the response spectra derived from the acceleration history measured in perpendicular directions at Mirandola (Protezzione Civile, 2012). From the description of the ground stratigraphy, the ground condition may be expected to vary between types C, D and E. As a matter of fact the code spectra for ground types D and E seem to match the spectra of the earthquake. Nevertheless, the corresponding measured PGA was higher than the corresponding code value.

According to much earlier Italian seismic codes (MLP 14-07-1984) the region was not classified as a seismic region. In 2003 it was assigned to Seismic Zone III, i.e. having minimum seismicity. As a result, it is not excluded that geotechnical issues associated with dynamic loading and soil structure interaction may have not been considered in the design and construction process, mainly for structures built before the start of the new millennium. The ground amplification factors indicate that geotechnical aspects play an important role in definition of seismic hazard and hence seismic risk of the region.

Table 6.1 - Comparison of measured and projection values of ground acceleration

	Projection - DM 14/01/2008 **			Maximum Computed PGA (USGS)	Recorded PGA at Mirandola (RNA)
				Event: M=5.8; 20-05-2012	
	agh –[g]	agv – [g]	Se – [g]	Se – [g]	Se – [g]
San Felice – Vigarano Mainarda Region	0.14 - 0.15	0.078	0.2-0.225	0.24	0.31
** Based on 10% probability of exceedance in 50 years with a return period of 475 years.					

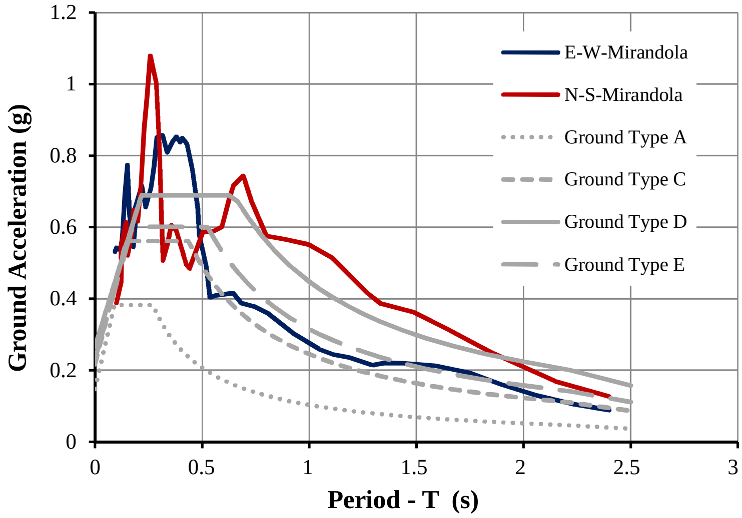


Figure 6.3 - Comparison of the response spectra at 5% damping for different ground typologies with the response spectra derived from the acceleration history measured at Mirandola.

6.2 Liquefaction

Ambraseyes (1988) indicates that for a 5.8 magnitude shallow earthquake, sites may be susceptible to liquefaction up to a distance of about 25km from the epicentre. Table 6.2 below shows the visited villages and the corresponding approximate distance from the epicentre of the main event on the 20/05/2012. Considering also the statigrafic structure described in section 6.1, and associated soil properties generally characterising such materials, the sites can be assessed as susceptible to liquefaction. Liquefaction was indeed observed in Mirabello, San Carlo and San Felice sul Panaro.

Table 6.2 - Approximate distance of the visited sites from the epicentre.

Town	*Distance (km)*
Vigarano Mainarda	21
Mirabello	18
San Carlo	14
Sant Agostino	10
San Felice sul Panaro	9
Finale Emilia	8
Corpo Reno	6

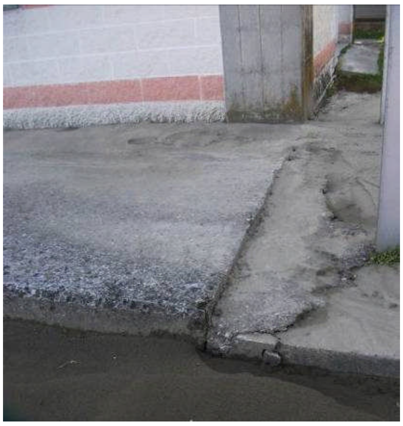
6.2.1 Liquefaction in rural environments or ground

Liquefaction was observed inside the small San Felice sul Panaro football stadium (Figure 6.4). Various patches of liquefied soil of considerable diameter were observed on the pitch. Liquefaction was also observed along the perimeter of the enclosure, lifting a small concrete ground slab. Liquefaction was alsofurther observed around the dressing rooms. Nevertheless, the superstructure of the enclosure looked undamaged from an external visual inspection. Liquefaction also surrounded the athletics track, lifting the rubber track at various intervals. Liquefaction was also observed along the discus, putting the shot and long-jump tracks. A tennis court separating the stadium from the main road did not experience any liquefaction. Nevertheless, liquefaction was observed on the main road.

Liquefaction was also observed close to the embankment of the national road 225 leading from Mirabello to San Carlo (Figure 6.5a). Further Liquefaction was observed in the agricultural fields that separate the two villages (Figure 6.5b). Wide surface cracks in the clayey agricultural soil were observed possibly due to ground movement and settlement also associated with liquefaction effects and the densification of lower strata of soil (Figure 6.5c,d).

(a)

(b)



(c)

(d)

(e)

(f)

Figure 6.4 - Liquefaction in the San Felice Stadium: a) Liquefaction on the pitch; b) Liquefaction on the pitch; c) Liquefaction surrounding the foundation of the enclosure; d) Liquefaction surrounding the dressing rooms; e) the superstructure of the enclosure; f) liquefaction around the athletics track.

a) b)

c) d)

Figure 6.5 - Liquefaction in rural areas: a) Liquefaction close to the national road 225; b) Liquefaction in agricultural fields outside Mirabello; c) Surface cracks in agricultural soil outside Mirabello; d) Detail and dimention of the surface crack.

6.2.2 Liquefaction around industrial facilities

Liquefaction was observed around two industrial facilities off the 255 national road. In the first facility (Figure 6.6a) most of the liquefaction was observed around a concrete platform at the rear of the warehouse. This caused differential movement of the platform relative to the superstructure. This was also the case for the second facility. Furthermore, ground rupture and liquefaction occurring in the service road, extended along the pavement, and inside the industrial facility (Figure 6.6c,f). A small gap was observed between some RC panels and the RC column due to differential movement of the ground (Figure 6.6g). Liquefaction was also observed along the service road leading to the 2 facilities (Figure 6.6b). However, it was also observed that the subgrade of the road was not constructed according to any standards.

6.2.3 Damage in buildings due to liquefaction

Most of the damage in buildings directly caused by liquefaction effects was mainly observed in masonry buildings. This was very prominent along “Via Risorgimento” in San Carlo (Figure 6.7). Liquefaction fissures were observed along the transverse section of the road, and extending to the foundations of buildings. Consequently differential settlement, uplift, or lateral spread were contributors to damage. Masonry structures were more prone to damage caused by liquefied ground movements, since under such conditions the structure does not behave monolithically, particularly if the foundation is not so. For one particular house, relative displacement caused by liquefaction resulted in the dislocation of the house from the third party wall separating it from its neighbouring house (Figure 6.7b). In another case, the liquefaction fissure passed close to an aperture causing differential movement to the superstructure supporting the building on either side of the aperture, resulting in severe damage to the whole structure (Figure 6.7c).

a)

b)

c)

d)

e)

f)

g)

Figure 6.6 - a) Liquefaction around platform; b) Liquefaction and settlement on the service road; c + d) damage to the ground pavement from differential settlement; e) Effects of differential settlement on the industrial facility; f) Cracking of the ground slab inside the industrial facility; g) Damage to the

RC panels of the industrial facility.

a)

b)

c)

Figure 6.7 - Liquefaction along Via Risorgimento in San Carlo: a) Separation of façade from third party wall; b) detail of the differntial displacement between the façade and third party wall, including ground settlement; c) Liquefaction fissure through an aperture of a masonry building.

6.3 Damage in Buildings due to Ground Settlement, Differential Settlement and Lateral Spread

It is very difficult to establish the nature of the ground failure relying only on observations, and without the conduction of proper field investigation. The descriptions provided are based on the observations made, and underground liquefaction and plain failures may not be excluded.

The ground on either side of Via Italia in Mirabello gently slopes towards the main road, where once a stream of the river Reno passed. A masonry house along the alley next to the San Paolo church experienced lateral differential displacement due to lateral spreading of the ground. Settlement was also observed. The masonry structure sustained various shear cracks (Figure 6.8a,b). The failure plain was observed to extend to the adjacent house which experienced differential displacement at foundation level (Figure 6.7c).

Figure 6.8 - Lateral spread in Mirabello: a) Lateral spread of ground under a building; b) lateral spread of foundation. c) damage in masony building due to differential movement; d) Lateral spread extending into a parapett wall; e) Lateral spread of ground extending into a building in Via Mazzini; f) Lateral spread extending into a house in Via 25 Aprile; g) Lateral spread of ground extending into San Paolo church; h) Densification of soil subgrade.

a) b)

Figure 6.9 - Lateral spreading of the ground parallel to the road a) Via Italia b) behind “Numero 1 Pizzeria”.

Lateral spreading was also observed to extend transversely from Via Risorgimento in Mirabello, into a parapet wall. Lateral spreading of the ground was observed in Via Mazzini and Via 25 Aprile (Figure 6.7e,f) Lateral spreading extended transversely from the road into the buildings causing damage due to differential ground displacement.

Ground rupture showing lateral spread parallel to the road and the façade of buildings was observed in Via Italia and behind the “Numero 1 Pizzeria” (Figure 6.9). This caused uplifting of part of the pavement and kerbs as the ground below the buildings moved against the subgrade and sub-base under the road. Settlement was also observed. Various pot holes were formed along Via Italia showing the densification and possible flowing of soil below ground level.

A rupture in the car-park adjacent to San Paolo church also extends into the structure (Figure 6.8g). Figure 6.10 shows an overall view of the surface ruptures, cracks and lateral spreads that were observed during the trajectory followed in Mirabello. Lateral spread observed at various locations in Mirabello indicate a possible trend forming lateral spread of ground that extends through the centre of the village, and that may have possibly contributed to the partial collapse of the San Paolo church. The damage experienced by the church is further described in Section 4.3.

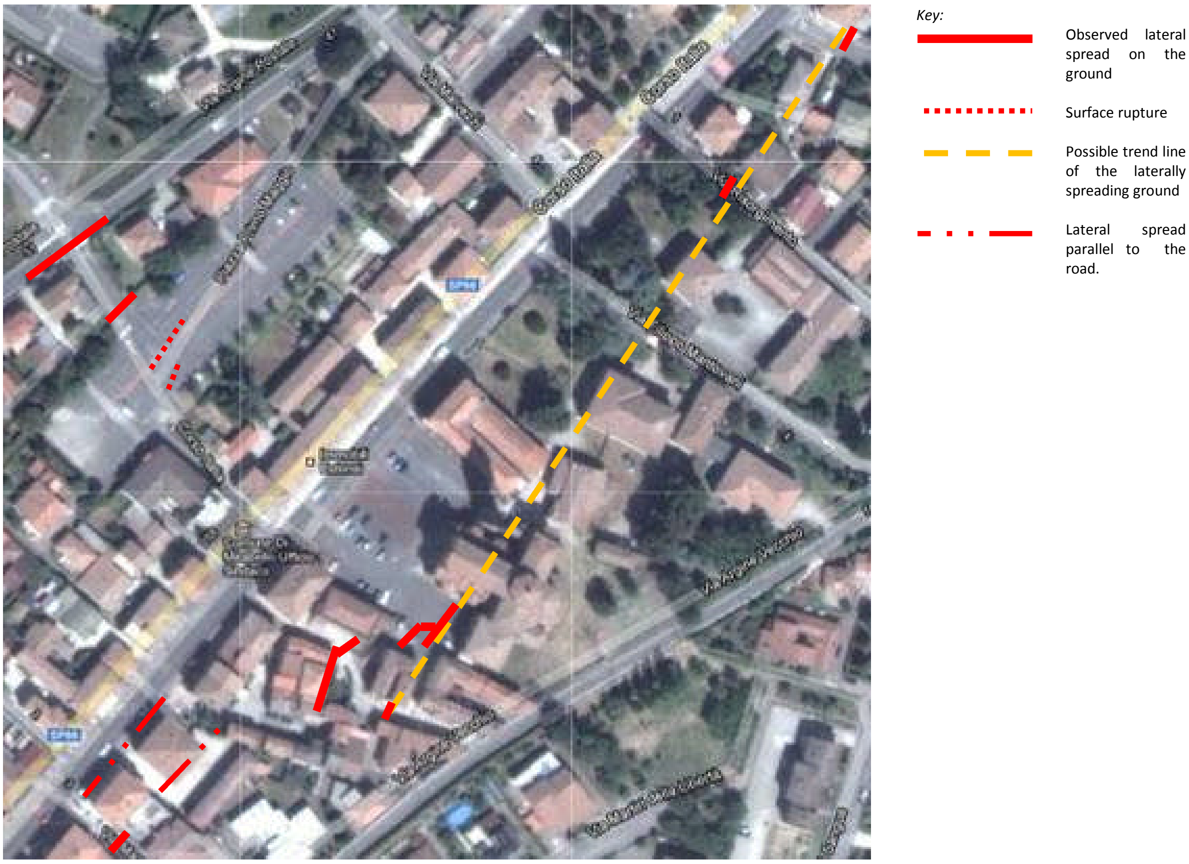


Figure 6.10 - Observed ground surface cracks at Mirabello.

In Via Primo Maggio, San Carlo, a masonry structure having access on two levels was observed to sustain damage due to pounding with the road substructure, causing the pavement in front of the house to fail completely (Figure 6.11). The house sustained minor permanent displacement. The road in front of building also experienced damage due to possible failure of the subgrade. Nevertheless, a buttressed RC diaphragm wall adjacent to the house did not sustain any damage.

a)

b)

c)

Figure 6.11 - a) Damage of house having access from 2 levels; b) Retaing wall adjacent to the house; c) detail of the damage of the pavement infront of the house.

a)

b)

c)

d)

Figure 6.12 - a) Lateral spread and settlement in Via Argine Postale, Mirabello; b) lateral spread and settlement in Corso Italia, Mirabello; c) Surface fracks and damage to trench in Via Primo Maggio, San Carlo; d) Collapse of sub-base and subgrade, San Carlo.

6.4 Geotechnical Issues and the Performance of Infrastructure

As described in the previous sections 6.2 and 6.3, various roads inside the towns of Mirabello and San Carlo experienced damage due to liquefaction, lateral spread and settlement of the ground substructure. Furthermore, lateral spread cracks were observed in Via Argine Postale and Corso Italia in Mirabello (Figure 6.12a,b). Over 3cm of settlement was observed. The storm water culvert was also damaged. Longitudinal cracks along the asphalt surface exposed the underlying subgrade. According to locals in Mirabello, the gas pipe system in Via Italia was damaged by the earthquake, and closed down for repair. According to the residents, they were given an estimate of 7 days from the event for the repair works to be completed. In the car park in Piazza Primo Maggio, various new cracks were observed on the asphalt surface (Figure 6.10).

Further to what was discussed earlier, Via Primo Maggio in San Carlo was partially closed due to lateral spread. Substantial cracks along the perimeter of service trenches were observed, indicating differential movement or settling. The subgrade and sub-base of part of the road experienced sliding collapse. It is evident that the retaining system was very weak (Figure 6.12c,d).

6.5 Conclusions

Geotechnical failures and issues have contributed directly to the damage of buildings, structures and infrastructure. Many roads, car-parks and concrete pavements are characterised by cracks failure, that were already there before the earthquake. Such failure is generally associated with poor sub-base or deep poor ground conditions. This hints that the general ground conditions were not optimal and required particular attention in the design and construction process. The soft nature of the soil is also evidenced by the common feature of leaning bell-towers observed throughout the region. As a result it is not excluded that geotechnical aspects also played a role in the development of damage to other structures and monuments. This is also due to the large amplification of ground shaking by the soil stratigraphy. The response spectrum also indicates that structures with long fundamental periods such as warehouses and industrial facilities may have been characterised with a large horizontal acceleration.

7.0 OBSERVATIONS ON DISASTER MANAGEMENT

7.1 Casualties

Seven people died in the 20th May 2012 earthquake, as follows:

- a 29-year-old male worker died in the collapse of the Uru polystyrene factory at Bondeno (Province of Ferrara).
- two male workers (aged 35 and 50 respectively) died in the collapse of parts of the Sant Agostino Ceramics factory.
- a 55-year-old male worker died in the collapse of the Tecopress aluminium pressings factory at Dosso, Sant'Agostino Ferrarese.
- at Sant Agostino a 103-yr old woman died when the roof of her house fell in.
- a 37-year-old woman died of a heart attack at Sant Alberto di San Pietro in Casale (Province of Bologna).

- at Vigarano Mainarda (Province of Ferrara) an 86-year-old woman died from a stroke.

About 50 people were injured, mostly lightly. However, a fireman was seriously hurt when he fell from a wall at Finale Emilia.

Thus five of the seven deaths resulted from the sudden, spontaneous collapse of non-seismically designed factory buildings affecting workers on the night shift. Most of the other buildings that collapsed were abandoned farmhouses, churches or ancient monumental buildings (towers and castles), none of which had any inhabitants. As damage to vernacular housing was light or absent, there were few problems of entrapment, rescue and injury associated with these processes. Nevertheless, in one such case, the collapse of the Palazzo dei Veneziani at Finale Emilia trapped 11 local residents who had to push a wall down to get out. Given that there were various cases in which vehicles were crushed by falling masonry, and numerous examples of façade elements of buildings crashing down into streets, there was a significant propensity for a larger number of casualties (Figure 7.1).

7.2 Disaster Management

The Emilia earthquake can be classed as a sub-regional disaster that solicited a reaction from national and regional forces. It involved 8-10 municipalities, all of them the locations of small towns, in four provinces (Modena, Ferrara, Bologna and Mantova), and a total population of about 80,000 people.

As is usual in Italian earthquakes, the National Fire and Rescue Service (Corpo Nazionale dei Vigili del Fuoco) took the initial lead role in responding to the emergency, assisted by medical emergency services. Within days some 1,400 volunteers were at work in the area, three quarters of whom were from the civil protection services of Emilia Romagna Region and its provinces. Two hundred were from the Italian Red Cross and 137 from national sources. There were 700 firemen and 2,000 other emergency responders.

Figure 7.1 - Car crushed by falling chimney, Finale Emilia.

A week after the disaster some 5,262 people were in need of shelter, either through reluctance to return home or because their houses were inside areas that had been cordoned off and interdicted in order to maintain public safety. The breakdown by province was as follows: 62 per cent from Modena, 30 per cent from Ferrara, 5 per cent from Bologna and 3 per cent from Mantova. Damage to housing was slight (except for the case of the liquefaction areas at Sant Agostino Ferrarese and its outlying settlement San Carlo), but people remained acutely fearful of aftershocks. Hence, the number of residents who would not or could not return home rose over the week after the earthquake to about 7,000. Many of these were accommodated in second homes, with family members, or in camper vans or local hotels. Communal shelters were set up in the main affected settlements, followed by tent camps. In addition, tents were pitched in an ad hoc manner on small green spaces outside the cordoned areas.

The Region of Emilia-Romagna (area 22,446 km^2, population 4.4 million) is frequently affected by floods, landslides and minor earthquakes. In civil protection terms, it is one of the best equipped and organised in Italy, with a well-developed response system headquartered in Bologna and developed at the level of the nine provinces and many of its 348 municipalities. Like other regions, and the national forces, it has constituted a regional relief column, composed of the vehicles, manpower, equipment and supplies that are needed in a significant emergency. It was one of the first Italian regions to introduce TETRA radio communications.

The response to the earthquake emergency was coordinated and directed by a combination of national and regional forces. The Autonomous Province of Trento coordinated the regional relief columns and the main input came, logically, from Emilia-Romagna. Tent camps were set up by the regional civil protection services of Emilia-Romagna, Tuscany, Friuli Venezia-Giulia, Marche, Umbria, Molise and Lazio, and in addition by ANPAS (Public Assistance) and the National Alpine Regiment, both of which are nationally constituted volunteer organisations. Locations are shown in Figure 7.2 Each tent camp module is designed to accommodate 250 people and includes wash rooms, toilets, a canteen and social and health-care facilities. Nine days after the earthquake 53 schools and gymnasia were being used as rest centres, along with 17 hotels and 19 tent camps.

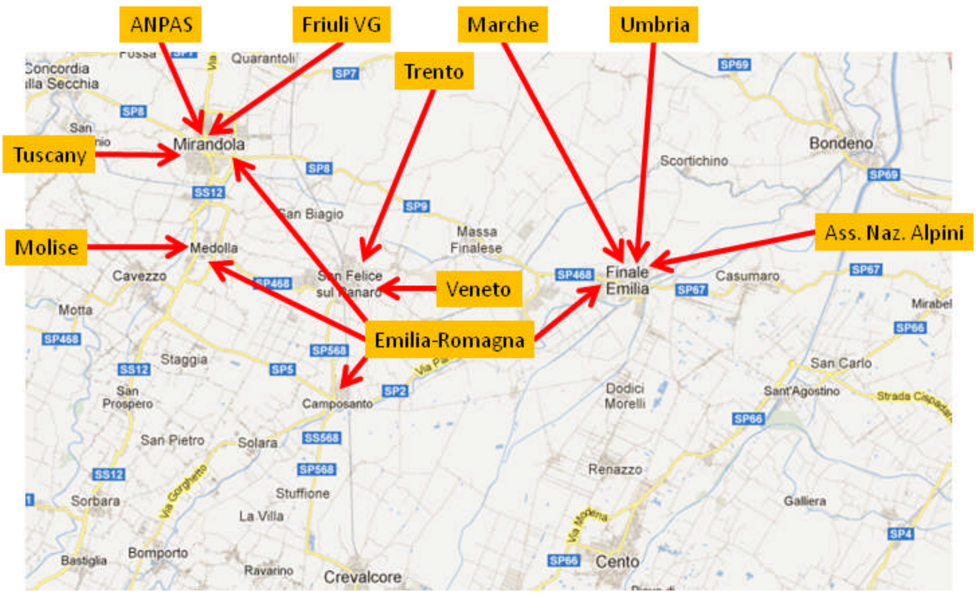


Figure 7.2 - Division of competencies for tent camps.

The main affected towns, such as San Felice, Sant Agostino and Finale Emilia rapidly became the locations of mixed operations centres (Centri Operativi Misti), using the Italian system of coordination in which resources are managed by sector according to support functions and are cascaded from national, through regional, levels to the larger and then smaller local settlements.

One of the competencies managed by the national Department of Civil Protection is to coordinate technical assessments of the stability and habitability of residential buildings. Technicians from various regions conducted this time consuming operation. The greatest need was found to be in Mirandola, Finale Emilia and Sant Agostino, i.e. in the areas of greatest damage and most significant liquefaction. Meanwhile, in nine days, firemen had conducted 7,500 building inspections, many accompanied by buttressing or dismantling of architectural details.

On 27 May at Bonderno (Ferrara) a 45-metre-high factory chimney was safely demolished by military engineers. Firemen worked throughout the affected area to remove precarious architectural elements and buttress buildings. Lastly, in Ferrara 500 prisoners were evacuated for precautionary reasons.

In synthesis, the Emilia earthquake was small and geographically circumscribed enough not to present exceptional challenges to the Italian civil protection system. The same management strategies were used as in the L'Aquila earthquake of 6th April 2009; namely, to cordon off the centres of damaged towns and maintain a guard on them. Residents and others were allowed inside the cordon only when accompanied by fire department personnel, and when wearing hard hats. Overall, resources were perfectly sufficient to manage needs generated by the emergency, which were mainly the accommodation of people rendered temporarily homeless, the maintenance of cordons around damaged areas of urban fabric, the inspection of damage and the emplacement of preliminary buttressing.

8.0 SUMMARY

This report presents an overview of the 20th May 2012 Emilia Romagna earthquake, the damage it caused, geotechnical features and disaster management issues made by a team from UCL EPICentre.

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