THE PIANURA PADANA EMILIANA EARTHQUAKE

The main characteristics of May 2012 seismic sequence have been analyzed. The comparison of data from macroseismic surveys and historical information on the main events that struck the area in the past has shown that the present sequence was the most violent in the last 500 years, highlighting the possible criticality in this sector of the Italian territory seismic hazard assessment. Finally, the analysis of some accelerometric recordings has revealed that the response spectra close to the epicenter exceed technical code design provisions, while heavy damage is also present where response spectra are far lower than code provisions; some considerable damage to both civil and industrial buildings can be explained by the ground motion characteristics

The May 2012 seismic sequence in Pianura Padana Emiliana: hazard, historical seismicity and preliminary analysis of accelerometric records

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The seismic sequence started on May 20^{th}, 2012, 02:03:52 UTC with the main shock (M_L=5.9, 44.889N 11.228E, depth 6.3 km), close to Mirandola (Figs. 1a and 1b), without any seismic activity in the area in the previous months, except three events the day before (M_L=2.5, 4.1 and 2.2, respectively). In Fig. 1a, the historical earthquake and the known active faults are also represented. The activity that followed had a major aftershock, on may 29^{th}, 2012, at 07:00:03 UTC (M_L=5.8, 544.851N and 11.086E, depth 10.2 km). Source mechanisms are presented in Fig. 2. Note that M=M_W in this figure and the values are different from the previous ones.

Coseismic deformation has been evaluated through the satellite-based SAR (Syntetic Aperture Radar), that gives the interferometric representation of the differential motion between May 12^{th} and June 5^{th}, shown in Fig. 3.

By the shape of the interferogram it is possible to estimate that two almost parallel faults have been activated. Separated analyses of the two main events gave about 15 cm uplift for the first one, and 12 cm for the second one, respectively.

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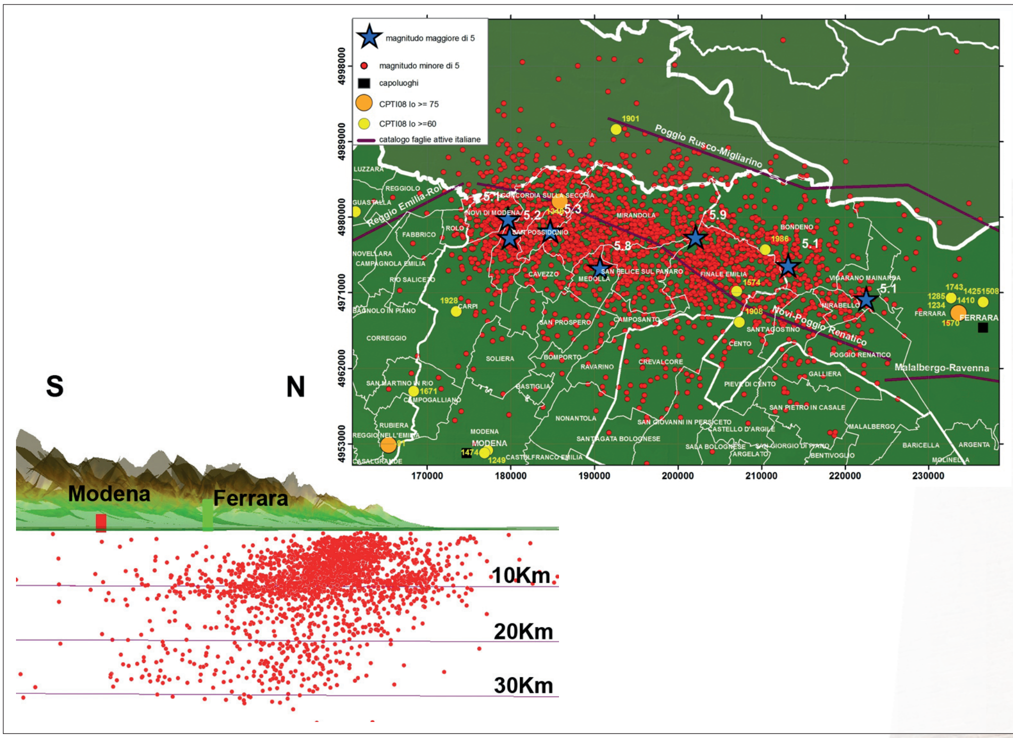

FIGURE 1 (a) The seismic sequence epicenters (up to 09/15/2012) and (b) NS section
Source: ENEA elaboration of INGV data

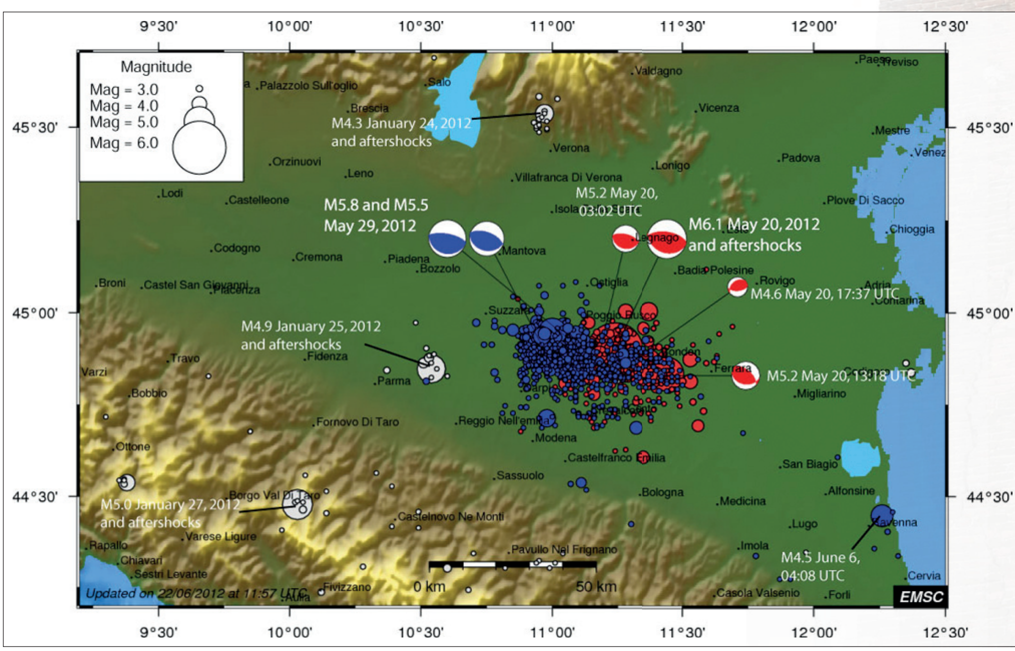

FIGURE 2 Source mechanism (blue after May 29th)
Source: ENEA elaboration of EMSC data

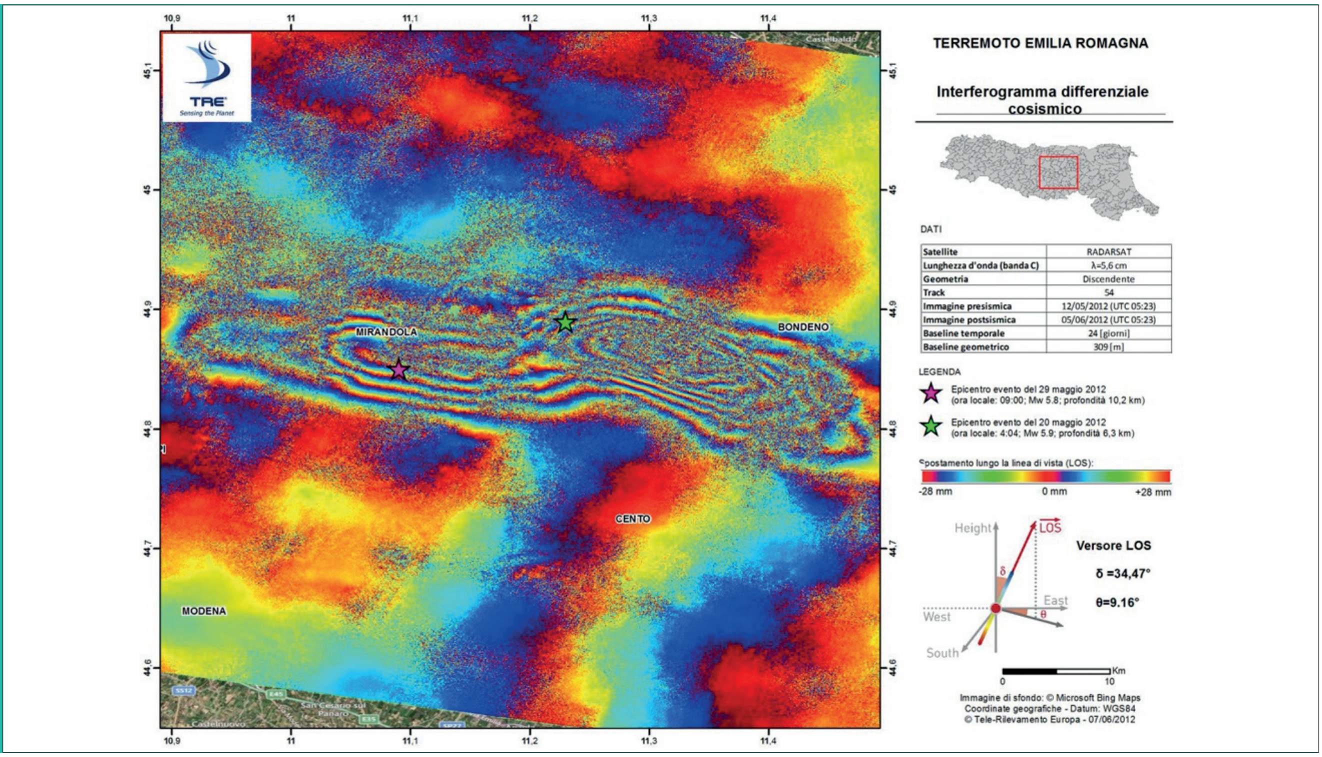

FIGURE 3 Interferogram 05/12/2012-06/05/2012
Source: GEO

Tectonic settings and earthquakes

Most seismic activity in central Mediterranean area is attributed to the Adriatic plate that is part of the African plate, as depicted in Fig. 4, moving towards N. Actually there are quite different points of view. With reference to Fig. 5 we report some of the main conclusions by Cuffaro et al. (2010): "*The northern Adriatic plate boundaries are deformed by the three belts, i.e., Apennines, Alps, and Dinarides. ... Northeast Italy is usually interpreted as an area affected by N–S compression due to the African-Adriatic indenter. However, this comes from a misleading kinematic approach, where local stress field is assumed to be an indicator of plate motion. The stress field rotates along oblique plate margins, and the WNW-ward motion of the Adriatic plate relative to Europe can generate right-lateral transpression and consequent NW–SE to N–S compres-*

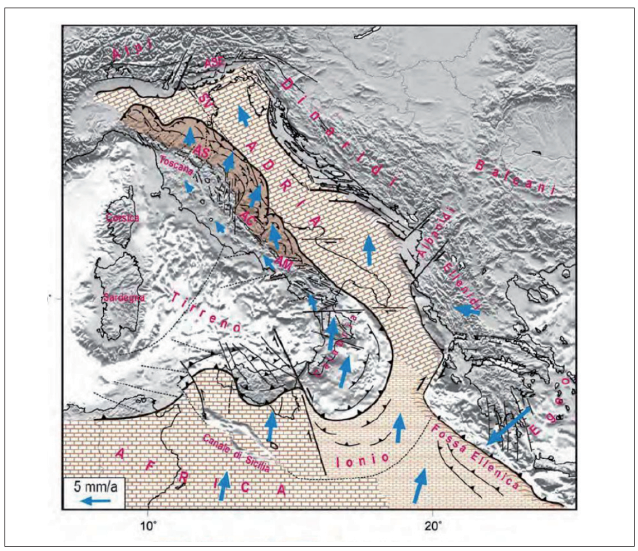

FIGURE 4 Sketch of general tectonic setting
Source: EERI

sion along the central-eastern Alps. ... Apart from local regional details, the main conclusions based on seismic reflection profiles and space geodesy data are that the three belts around the northern Adriatic plate are still converging and seismically active ...".

In the same figure, the Ferrara salient is the area of the Emilia earthquakes. In Cuffaro et al. (2010) Fig. 6 is also reported, and the following sentence expresses the possibility of earthquake in the area where they happened: "*The areas where the strain rate sharply decreases along a tectonic feature (e.g., the Ferrara salient, the Venetian foothills front) are proposed to be occupied by locked structures where stress is accumulating in the brittle layer and thus seismically prone*".

Seismic hazard

In Italy, since the beginning of '900, the seismic hazard has followed the main seismic events through a

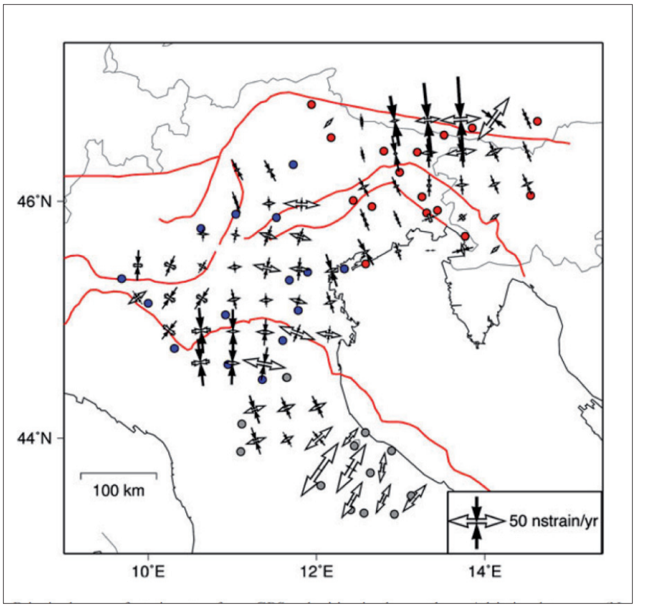

FIGURE 6 Strain rates in the northern Adriatic plate
Source: Cuffaro et al., 2010

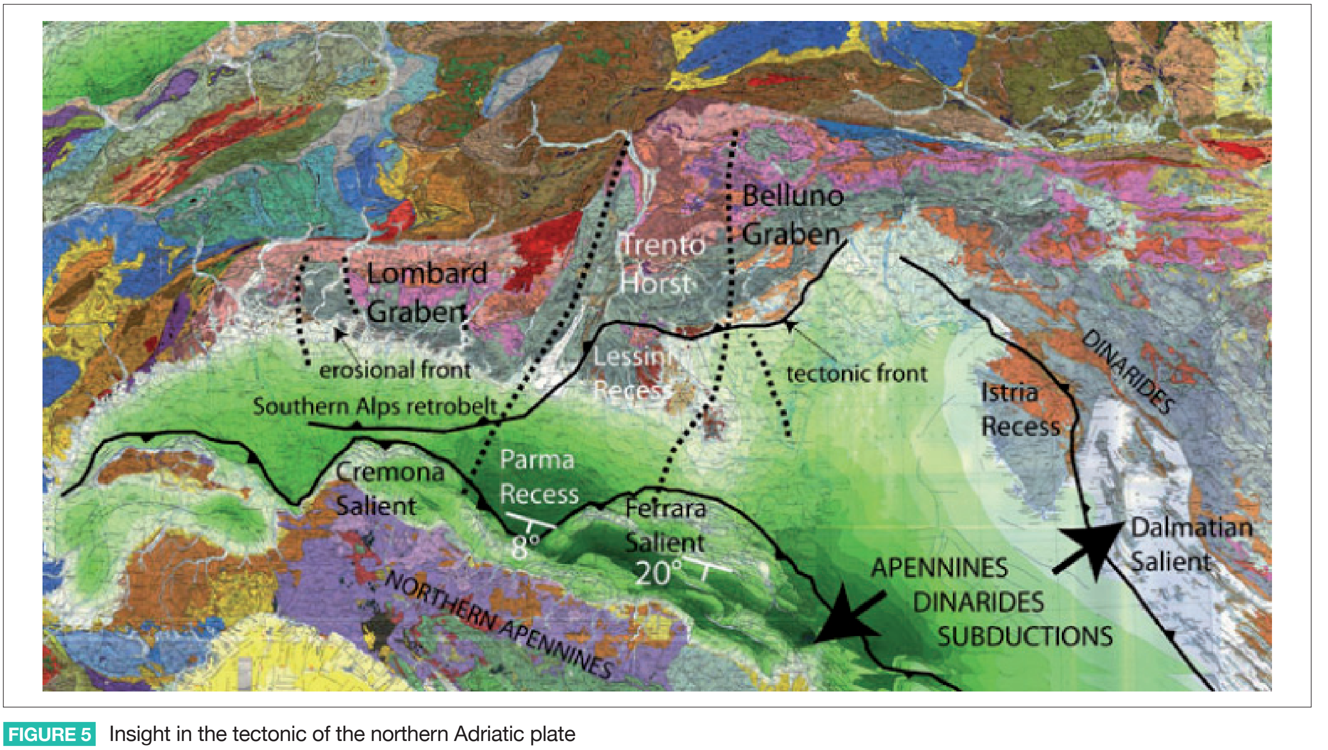

FIGURE 5 Insight in the tectonic of the northern Adriatic plate
Source: Cuffaro et al., 2010

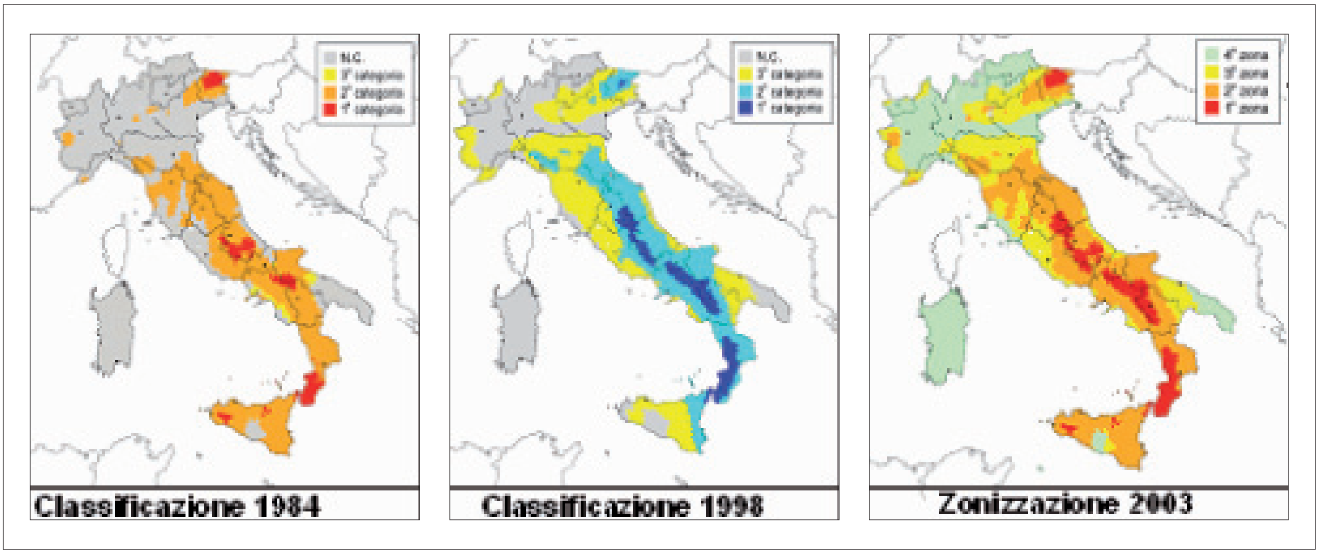

FIGURE 7 Evolution of seismic classification
Source: INGV

"classification" by seismic zones, for which the seismic codes have provided the rules for new constructions. In Fig. 7, the evolution in the last decades is summarized.

All the structures built until the end of last century appear to have no seismic provision.

After the 2003 zoning, the building code (NTC2008) has provided the basis for new buildings as a design spectrum base shape, to be scaled according to the expected PGA, the local soil condition and the structural type. The expected PGAs for the examined area are shown in Fig. 8.

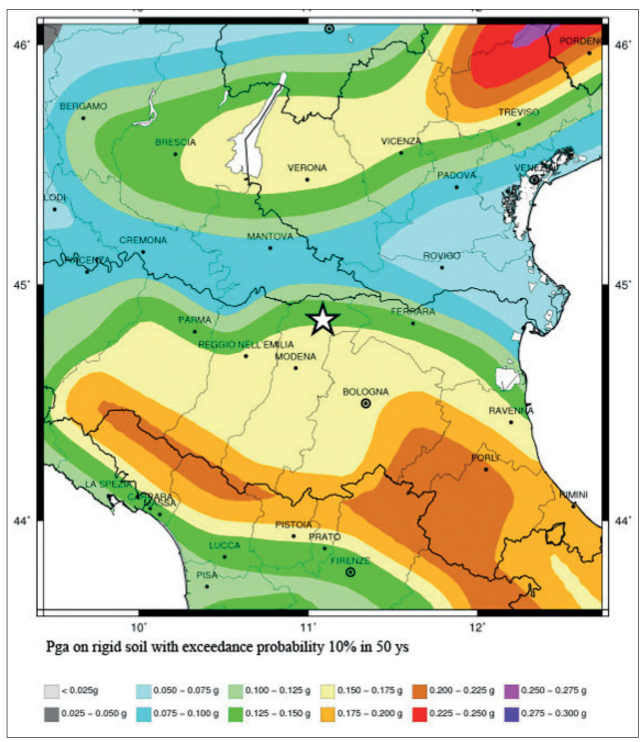

FIGURE 8 Design basis PGAs
Source: INGV

Historical vs. today's seismicity

The May 20th 2012 earthquake (5.9 M_L) struck the towns of Finale Emilia, San Felice sul Panaro and Sant'Agostino, involving a wide, adjacent area.

This event was followed by a series of significant aftershocks, such as the May 29th (5.8 M_L) event in the surroundings of Novi di Modena, which caused even more severe and extensive damage on a larger area.

The seismic sequence occurred on an area traditionally considered as characterized by low seismicity, where the population is – or rather, was – not very accustomed to earthquakes and where, unfortunately, the anti-seismic techniques were applied to a marginal portion of the housing. In fact, the area was included in the low seismic level category only in 2003 (OPCM 3274/03), but only in 2005 designing with anti-seismic techniques became mandatory.

In the past, the area between Ferrara and Novi di Modena had already been affected by seismic events. Some of these were destructive, such as the 1570 earthquake, while others, though causing less damage, aroused deep feeling in the population; in both cases the events left their traces in the chronicles of the time.

In the days immediately following the Emilia earthquake, the group Quest (Quick Earthquake Survey Team) of the National Institute of Geophysics and Volcanology (INGV) visited some of the affected areas and produced a report of damage and environmental effects caused by the earthquake (Arcoraci et al., 2012a-b). Contemporarily, the Italian Department of Civil Protection performed a macroseismic survey of the area (Galli et al., 2012).

In the present work, analysing the damage described in the Quest report, it is possible to obtain a comparison with the damage occurred during two historical earthquakes, namely November 17th, 1570, and October 22nd, 1796, in selected localities.

The 1570 earthquake

"Tutta questa notte s'è stato vegghiando ed aspettando nuovi terremoti, sì come hanno seguitato sempre, sebben più deboli e seguitano tuttavia" ("This whole night was spent watching and waiting for new earthquakes, just as they have always continued, albeit weaker and still they continue", Passeri, 1570).

All contemporary accounts agree in remembering how the day before the destructive shock was marked by a long series of shocks. The main shock, at 3 a.m., shook buildings already weakened partly.

Pirro Ligorio, who at that time lived in Ferrara as court antiquarian under duke Alfonso II d'Este, in his book *Libro di diversi terremoti* describes the early phase of the seismic sequence (Ligorio, 1570). According to him, the buildings' vulnerability was also affected by the damage caused by a previous earthquake occurred on November 24, 1561. In this regard, he stresses that several buildings, as the Castle Estense, do suffer heavy damage to those structures that had not been correctly repaired.

The greatest damage occurred mainly in Ferrara: the Castle, the Cathedral and some great palaces (e.g., Tassoni, Paradiso and Este palaces) were severely damaged as well as the monasteries. Essentially all buildings, public and private, suffered damage and needed shoring. The damaged area was in a radius of 15-20 km.

The replicas were numerous. Baratta (1901), citing sources, reported that the replicas lasted nine months and for some authors, according to others, until February 1574.

The affected area, according to historical sources was very extensive. North up to Milan, East up to Venice and South down to Pesaro. The historical sources of the same period also report the phenomenon of soil liquefaction in Ferrara and nearby towns.

Regarding the soil liquefaction, the description reported in Ligorio (1570) is very interesting. It refers to Ficarolo (RO), where the successive quake on November 24th caused 11 victims in the collapse of a building: "*…filled some wells with sand, so that putrid water came out of the ground*" and again on December 1st in Ficarolo, where "*… ruined some ploughed fields, and dried some wells by directing all water out; where stagnating water was reclaimed by man, the soil cracked and sand leaked out of it*". Be noted that the descriptions match up perfectly with the observations that the evidence gathered in this earthquake (including the smelly water leaking from the ground). Last but not least, in spite the above detailed descriptions, the seismic history of Ficarolo reported in DBMI11 (Table 1) does not include the earthquake of 1570.

A phenomenon that, as shown by the engraving in Fig. 9, has characterized the recent earthquake. Table 1 shows the places mainly affected by the earthquake of 1570.

Fc

Locality	MCS
Ferrara	VIII
Cona (FE)	VII-VIII
Gaibanella (FE)	VII-VIII
Gambulaga (FE)	VII-VIII
Castelmassa (RO)	VII-VIII
S. Maria Codifiume (FE)	VII-VIII
Bondeno (FE)	VII
Casaglia (FE)	VII
Cassana (FE)	VII
Gurzone (RO)	VII
Masi Torello (FE)	VII
Occhiobello (RO)	VII
Runco (FE)	VII
San Nicolò (FE)	VII
Aguscello (FE)	VI-VII
Baura (FE)	VI-VII
Canaro (RO)	VI-VII
Corpo Reno (FE)	VI-VII
Fiesso Umbertiano (RO)	VI-VII
Focomorto (FE)	VI-VII
Formignana (FE)	VI-VII
Fossalta (FE)	VI-VII
Melara (RO)	VI-VII
Quartiere (FE)	VI-VII
Sabbioncello San Vittore (FE)	VI-VII
Tresigallo (FE)	VI-VII
Vigarano Pieve (FE)	VI-VII
Voghenza (FE)	VI-VII
Voghiera (FE)	VI-VII
Calto (RO)	VI
Cento (FE)	VI
Finale Emilia (MO)	VI
Francolino (FE)	VI
Papozze (RO)	VI
Ravalle (FE)	VI
Viconovo (FE)	VI
San Giovanni in Persiceto (BO)	Felt
Sermide (MN)	NC

TABLE 1 Places mainly affected by the earthquake of 1570
Source: INGV

For some of these places (in particular Bondeno, Cento, Finale Emilia, San Giovanni in Persiceto and Sermide) a comparison between the damage suffered in 1570 and the present one is possible, as reported in the Report of the Quest (INGV) after the first shock of May 20^{th}.
Bondeno needs some clarifications. The damage assessment (VII MCS) is based essentially on a letter reporting indirect information. Based on this information Bondeno and Finale Emilia were severely damaged. Finale Emilia, according to an eyewitness, suffered limited damage (see below), then it is likely that damage level in Bondeno may have been overestimated: *"The damage [Ferrara] is such that it cannot be estimated, but we fear the worst, because should another [earthquake] occur like that of last night, it would certainly cause all Ferrara to go to the ground, just as it seemingly happened in Finale [Emilia] and Bondeno*" (Passeri, 1570).
In a letter sent on November 22^{nd}, 1570, from Finale Emilia to the Duke's Secretary, the limited damage suffered by the town is reported. "*Then Friday... while writing in my study, there occurred a great earthquake, which lasted the space of half a miserere* [few seconds], *continuous and impetuous, some chimneys were ruined, but despite the great noise it did not cause much damage, whereas in other occurrences I knew of minor earthquakes which caused much more damage, but in other places...*" (Bartolaio, 1570).
A similar situation was in Cento, with light damage: "*At eight o'clock there was an earthquake, not so great, with not any damage, and the following night at midnight another furious and noisy earthquake; on the same night at three o'clock a weaker earthquake, four chimneys fell down and no more damage ... but* [in the earthquake] *not anyone did get hurt here in Cento*" (Filippi, 1570).
For Sermide and San Giovanni in Persiceto, the quake was felt and is remembered laconically in chronicles. For the same locations the Quest reports the following damage descriptions.

Bondeno (FE) (Arcoraci L. et al 2012a)
General characteristics: it woke and scared everyone, with strong vibration and drop of small orna-

FIGURE 9 Soil liquefaction near Bondeno
Source: ENEA

FIGURE 10 Bondeno: damage of grade 2-3 (EMS98 classification)
Source: ENEA

ments; oscillation of liquids; the clock in the square at the earthquake time has stopped.
Damage to civil structures: the main damage is the breakage or falling of chimneys; sporadic minor damage (cracks spread) to buildings of type B (brick building, with possible presence of curbs, with a sufficient degree of maintenance); some crumbling brick buildings, unreinforced buildings suffered moderate damage. Damage to monuments and special buildings: moderate damage to churches, with fallen friezes and cracks in the facade; collapse of the portico of the cemetery; collapse of industrial buildings.

Cento (FE) (Arcoraci L. et al 2012a)
General characteristics felt by the whole population. Damage to civil structures: few buildings of type A (brick or stone buildings, not reinforced, pushing roof structure, wooden beams, low maintenance, no chains nor presence of curbs) and B have suffered minor damage to the plaster.
Damage to monuments and special buildings: collapse of the spire of the steeple of the church of S. Lorenzo.

Finale Emilia (FE) (Arcoraci L. et al 2012a)
General characteristics: no information. Damage to civil structures: isolated buildings of type A (brick or horizontal elements without constraints, with pushing roofs) partially or entirely collapsed.
Many evidences of type 1 and 2 damage (light lesions, many cracks, falling plaster) in buildings of Type B; large fall of chimneys and tiles. Some serious damage to buildings of type B and C (buildings with curbs and / or reinforcement, reinforced concrete floors, concrete buildings).
Minor and no structural isolated damage to concrete buildings. Damage to monuments and special buildings: serious damage to historic buildings, with collapse and destruction.

San Giovanni in Persiceto (BO) (Arcoraci L. et al 2012a)
General characteristics: felt by the whole population, who fled outdoors, sporadic falling of light objects. Damage to civil structures: most buildings are of type B masonry, very little damage of grade 1 (capillary cracks). In the surrounding area, largely composed of reinforced concrete buildings, no damage was detected. Damage to monuments and special buildings: church, fall of a statue.

Sermide (MN) (Arcoraci L. et al 2012a)
General characteristics: felt by the whole population. Damage to civil structures: rare fall of chimneys. Damage to monuments and special buildings: no evidence of damage to churches.

The 1796 earthquake

*"Alle ore poi quattro, e tre quarti dopo la mezzanotte secondo l'orologio francese si è sentita una terribile scossa di terremoto, anzi due una più forte dell'altra, che a mio giudizio dev'essere durata due o più minuti secondi, no avendo in vita mia che è di 44 anni sentito l'eguale" (*At 4.45 A.M., French time, a terrible earthquake was felt, or rather two shocks, one stronger than the other, which I believe to have lasted two or more minutes, since in my whole 44-year life I never felt any suchlike*. Lami, XVIII Century*).

The event, which took place on October 22nd, a few months after the French occupation, was preceded by a low intensity shock, but without any damage that might have put people on alert.

The quake was felt North to Brescia, South and West to Senigallia and Lucca, respectively. The area most affected by the damage was quite extensive. Ferrara, Portonovo Medicina suffered damage, but also Bologna and Vicenza did (Table 2). Minor damage in other places.

The descriptions of the damage in San Felice sul Panaro and Mirandola were very interesting.

Francesco Lami, the author mentioned above, witnessed the earthquake effects in San Felice sul Panaro. He only reported the downfall of many chimneys: "*I was shocked and panicked, in the dark noise and swaying of the house, the motion was from west to east. Many house chimneys fell*" (*Lami, XVIII Century*).

At Mirandola, we know from a contemporary chronicle that the quake was very strong but the damage was limited: "*The morning of 22nd (October, 1796) at quarter to five a strong earthquake caused the falling of 24 chimneys and damaged a little part of a face [of a statue] of the church of S. Francesco. For this misfortune after lunch a Triduum was organized."* (*Anonymous, XIX Century*)

For San Felice sul Panaro and Mirandola, in the recent earthquake, Quest team observed the following damage.

Locality	MCS
Portonovo	VII
Ferrara	VII
Medicina	VII
Bologna	VI-VII
Vicenza	VI-VII
San Felice sul Panaro	VI
Ravenna	VI
Mirandola	VI
Mantova	VI
Imola	VI
Forlì	VI
Correggio	VI

TABLE 2 Locations with levels of damage up to VI (MCS), 1796 earthquake
Source: INGV

FIGURE 11 The damaged fortress of San Felice sul Panaro
Source: ENEA

San Felice sul Panaro (MO) (Arcoraci et al. 2012a)

General characteristics: felt by the whole scared population, fled outside. Damage to civil structures: the earthquake has heavily damaged the historic downtown, very small if compared to the extension of the country; entire and partial collapse of some old houses already in poor status; widespread damage of grade 3 (moderate structural damage or major damage in the structural parts of the building) in buildings of Type A and B, with the fall of ledges, slip tiles, large and deep

cracks; observed fall of chimneys; a dozen buildings have minor damage (grade 2, diffuse cracks); concrete buildings do not show significant findings.
Damage to monuments and special buildings: entire or partial collapses in most of the monumental buildings such as churches, the castle, the theatre, the towers; the overpass of the highway was displaced by 20 cm, approximately; several concrete industrial buildings, located on the outskirts, have suffered collapses; almost all the abandoned houses in the surrounding countryside have partially or entirely collapsed.

Mirandola (MO) (Arcoraci L. et al 2012a)
Resentment: the quake was felt by the whole population with fear; diffuse loss of objects (paintings, bottles, computers, printers, and so on); also on the lower floors and in shops. Damage to civil structures: the historic downtown is the most corrupt, many buildings are affected by light to moderate damage, ranging from cracks in large and deep capillary lesions mainly on buildings of type B; widespread loss of chimneys and cornices; occasionally there has been more severe damage such as partial collapses; these little damage outside the historic downtown, especially the fall of chimneys in buildings of Type C (both brick and concrete buildings); isolated cases of damage of grade 3 (deep lesions in the outbreak of the cladding and covering iron) in recent constructed buildings. Damage to monuments and special buildings: widespread damage and severe partial collapses to monumental buildings (cathedral, churches, towers, historical buildings); in some cases, the collapse of industrial buildings in the periphery of the city was observed; in suburbs and surrounding countryside, frequent partial collapses of buildings and entirely collapsed rural buildings (farmhouses and barns) have been observed.

Considerations

It is now possible to draw some general considerations for the above mentioned localities. As regards the towns of Cento (FE), Finale Emilia (FE), Mirandola (MO) and San Felice sul Panaro (MO), the effects of 2012 earthquakes matched or exceeded the maximum levels of damage caused by historical seismic events (Table 3).
This statement is clearer when comparing the descriptions of the recent damage on historical centers and monuments, which have (and in some cases had) structural characteristics close to those in use in 1796 or 1570, although restored and consolidated over the centuries. Regarding Bondeno, for which some remarks about the VII MCS assigned to this location due to the 1570 earthquake were previously made, the level of damage after the May 20 event is likely to

a)
b)


FIGURE 12 Mirandola. Damage in the historical downtown
Source: ENEA

Fc

be similar with its all-time maximum. In San Giovanni in Persiceto and Sermide, at least in the shock of May 20 did not exceed their maximum level of damage.
Other general considerations can be done for the industrial structures and isolated rural buildings. Both these typologies were in large numbers destroyed, entirely or in part, on the occasion of the recent earthquakes.
Although they were included in the analysis of the damage caused by the 2012 earthquakes, as stated by the authors of macroseismic surveys (Arcoraci et al, 2012a-b; Galli et al, 2012), it must be highlighted that the probable structural deficiencies in the case of industrial structures, and the poor state of maintenance for rural buildings increased their level of damage.
Moreover, it must be emphasized that a great number of residential masonry buildings, also in the case of recent constructions, suffered damage of grade 3 and 4 (in some cases up to grade 5). The class of vulnerability of such buildings should be assessed considering the degree of connection of the various structural elements (Section 2.2.2.6 EMS98 and DM 1987/11/20), so as to assign a reliable macroseismic intensity. This important aspect of seismological analysis should be enhanced by further specific studies.
Finally, the role played by the local geological features in the distribution of the level of damage must be stressed. For example, in localities like San Carlo, Sant'Agostino and Mirabello, significant effects on territory and buildings, related to liquefaction phenomena and surface fracture, have been observed (see another paper on this issue). In addition, the level of ground motion measured locally has highlighted the appearance of local seismic amplification phenomena (see below).
Some relevant aspects of the accelerograms' records
The two main events, May 20th (A, M_L=5.9) and May 29th (B, M_L=5.8), have been recorded by 139 and 145 accelerometric stations, respectively (Mirandola Earthquake Working Group (2012). In this analysis we consider two records, Mirandola and Modena; in Table 4, the epicentral distance and the soil clas-

Locality	Maximum damage level reached (1)	Earthquakes (1)	Iloc May 20, 2012	Emilia (cumulative)
Mirandola	VI MCS	Oct. 22, 1796 June 7, 1891 Oct. 27, 1914 July 15, 1971 May 2, 1987	VI-VII EMS (2) VII MCS (3)	VII-VIII EMS (2) VII MCS (3)
Finale Emilia	VII MCS	March 17, 1574	VII EMS (2) VI-VII MCS (3)	VII EMS (2) VI-VII MCS (3)
San Felice sul Panaro	VI MCS	Oct. 22, 1796 May 2, 1987 May 8, 1987	VII EMS (2) VII MCS (3)	VII EMS (2) VII MCS (3)
Bondeno	VII MCS	Nov. 17, 1570	VI EMS (2) V-VI MCS (3)	VI EMS (2) VI MCS (3)
Cento	VI MCS	Nov. 17, 1570 Jan. 13, 1909 Oct. 27, 1914	V EMS (2)	VI EMS (2) VI MCS (3)
San Giovanni in Persiceto	VI-VII MCS	Jan. 3, 1505	V EMS (2)	V EMS (2) V MCS (3)
Sermide	V-VI MCS	Jan. 13, 1909	V EMS (2)	V EMS (2) V MCS (3)

TABLE 3 *Sources: (1) = DBMI 11 (2) = Arcoraci et al, 2012b (3) = Galli et al, 2012*

Station	Epicentral Distance (km)	Soil Type (NTC2008)
Mirandola (A)	13	C
Modena(A)	38	C
Mirandola (B)	4	C
Modena (B)	27	C

TABLE 4 Selected records

sification are presented according to the Technical Code. Both sites are classified as C (deep deposits of dense or medium-dense sand, gravel or stiff clay, with thickness from several tens to many hundreds of m, Vs30=180–360 m/s), according to geological data, as regards Mirandola, and in situ measurements, as to Modena. In Fig. 13, the geological cross section for Mirandola station is shown. The geological cross section for Modena station and the experimental station VS profile are shown in Figg. 14 and 15, respectively. Time histories and FFT (Figg. 16 and 17) exhibit the following feature:

1) Higher duration for Modena, higher epicentral distance. Duration is not taken into account in the code for standard design.
2) Low frequency content, < 1 Hz, is apparent for both sites, as expected for the local soil condition. This fact, associated to high acceleration, will be discussed with the exam of the response spectra for Mirandola.
3) High frequency content, > 10 Hz, is mainly present for UP component in Mirandola, as result of the epicentral distance and of the deep soil characteristics; this fact could have played a relevant role in the damaging effects on old masonry.

A comparison of the response spectra of the Mirandola station (A) with the provisions of the technical code (NTC 2008), Fig. 18, shows that even for the SLC (Collapse prevention Limit State) the Spectral Accelerations (SA) and the Spectral Displacements (SD) of the record are higher than the code provision.
All the other records do not show the same feature; PGAs other than Mirandola are lower than .05 g for event (A) and the same happens for event (B) except for two stations at 16 km, PGA=240 cm/s^2. and at 26 km, PGA=130 cm/s^2; however, it is worth underlining that event (B) gave 900 cm/s/s at Mirandola, UP component, and 79 cm/s^2 at Sant'Agostino station, 4 km epicentral distance, where soil liquefaction phenomena occurred.

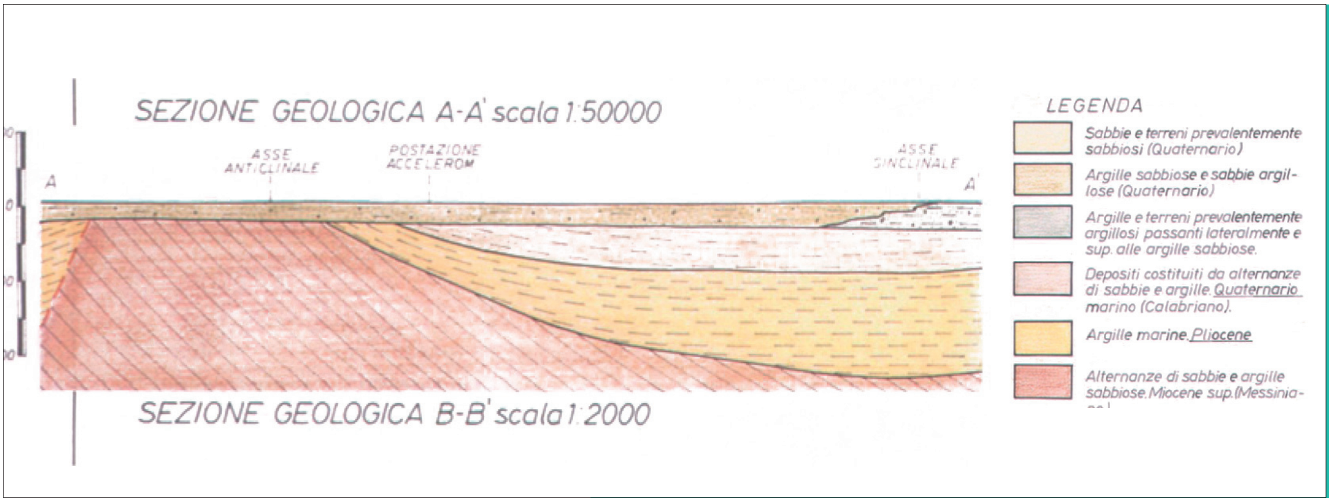

FIGURE 13 Mirandola station geological cross section
Source: INGV

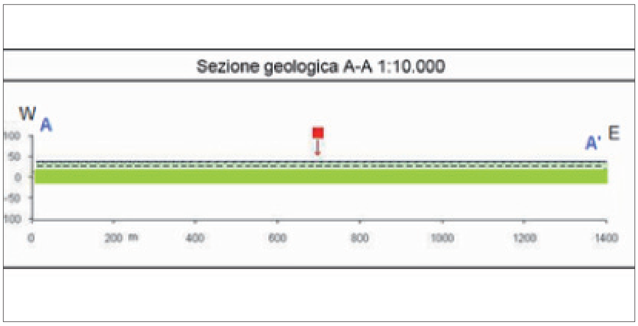

FIGURE 14 Mirandola station geological cross section
Source: INGV

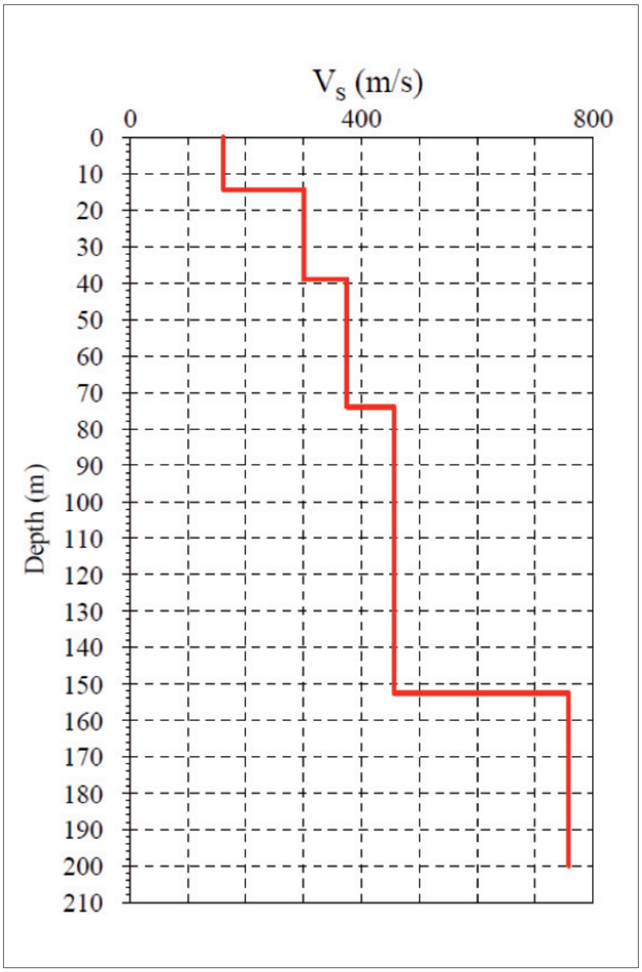

FIGURE 15 Mirandola Station VS Profile
Source: INGV

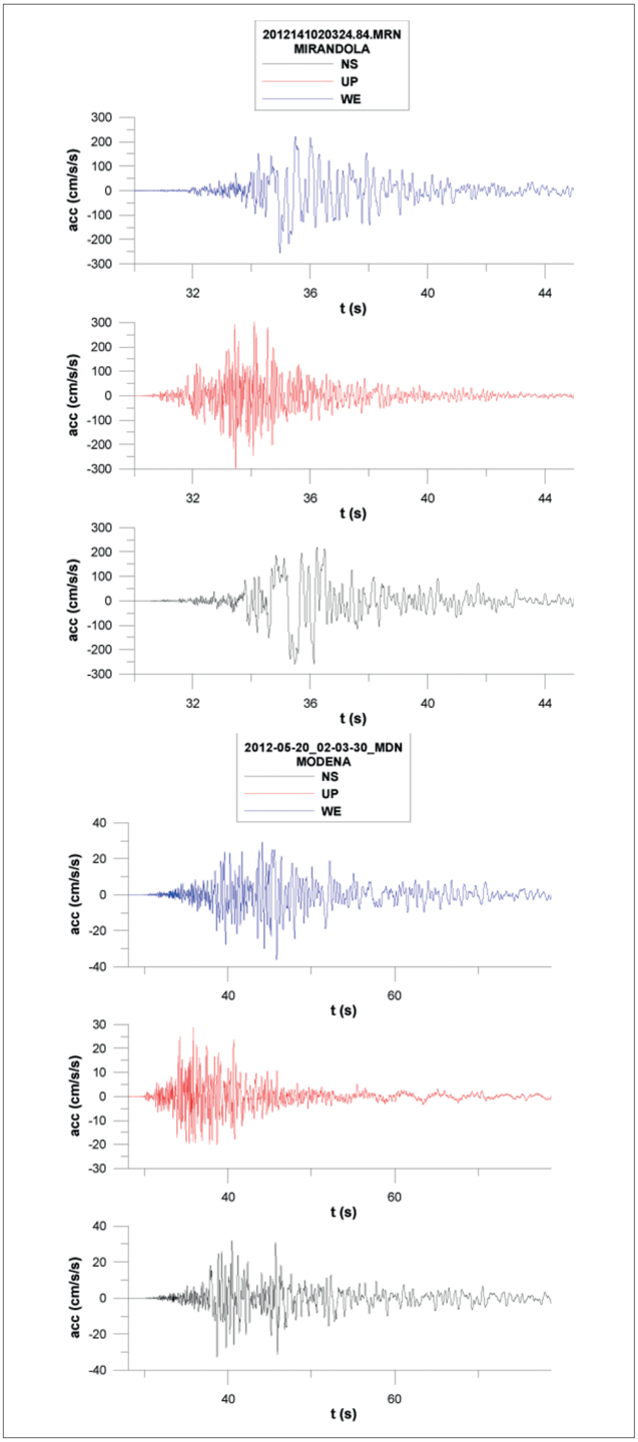

FIGURE 16 Mirandola (A) and Modena (A) uncorrected records

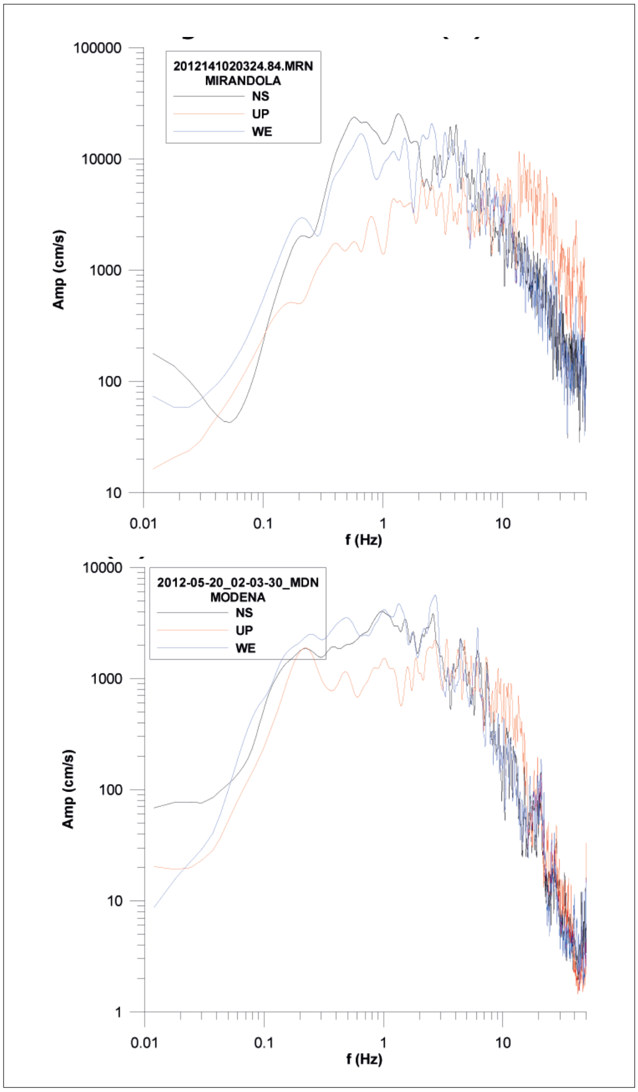

FIGURE 17 Mirandola (A) and Modena (A) Fourier spectra of uncorrected records

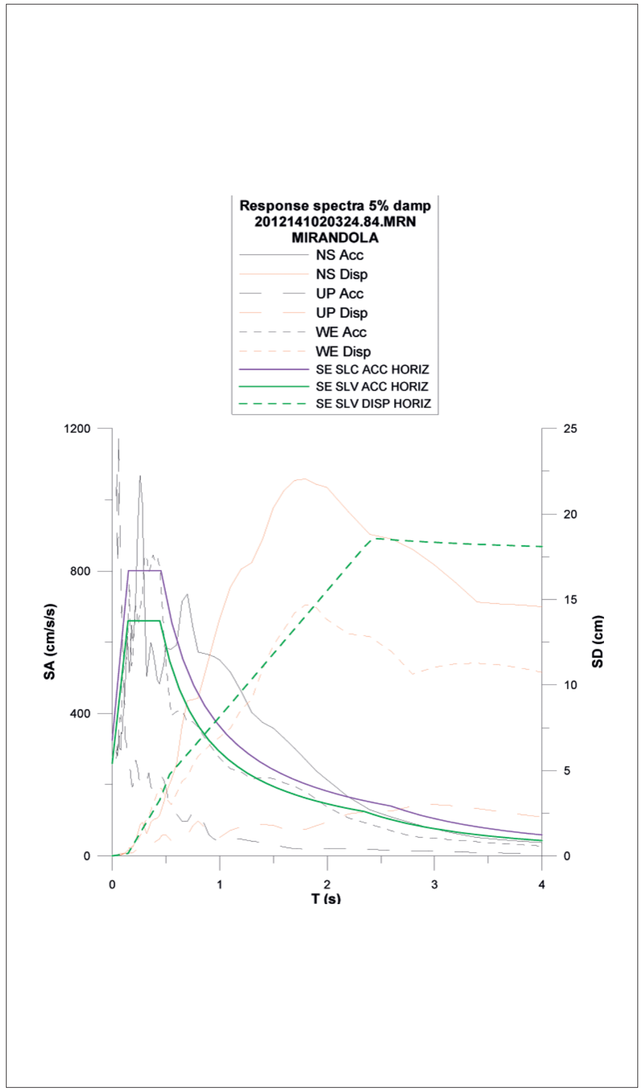

FIGURE 18 Comparison of the response spectra of the Mirandola station (A) with NTC2008

How can we explain then the considerable damage occurred both to civil and industrial buildings? One possible answer comes from the displacement time histories, shown in Figg. 19 and 20, and the soil characteristics. In the near field, the displacement has a pulse-like shape and the duration is very low.

Going far from the epicenter, surface waves are generated; these waves have low frequency and last several tens of seconds; since the propagation velocity of surface waves is a little lower than V_s (Fig. 15), when extended in plan structures it could have been subjected to differential motion. This effect could have been the reason of the collapse of several industrial buildings, with or without concurrent effects as soil liquefaction or poor structural characteristics.

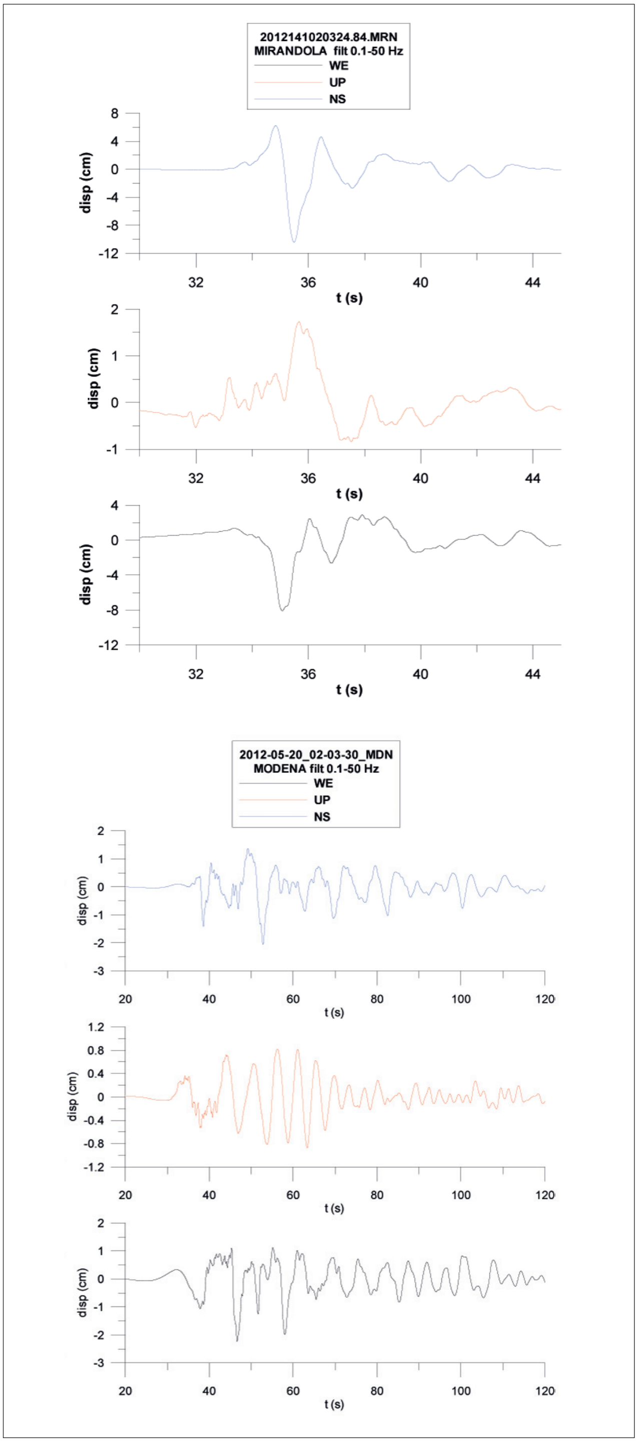

FIGURE 19 Displacement time histories: Mirandola (A) and Modena (A)

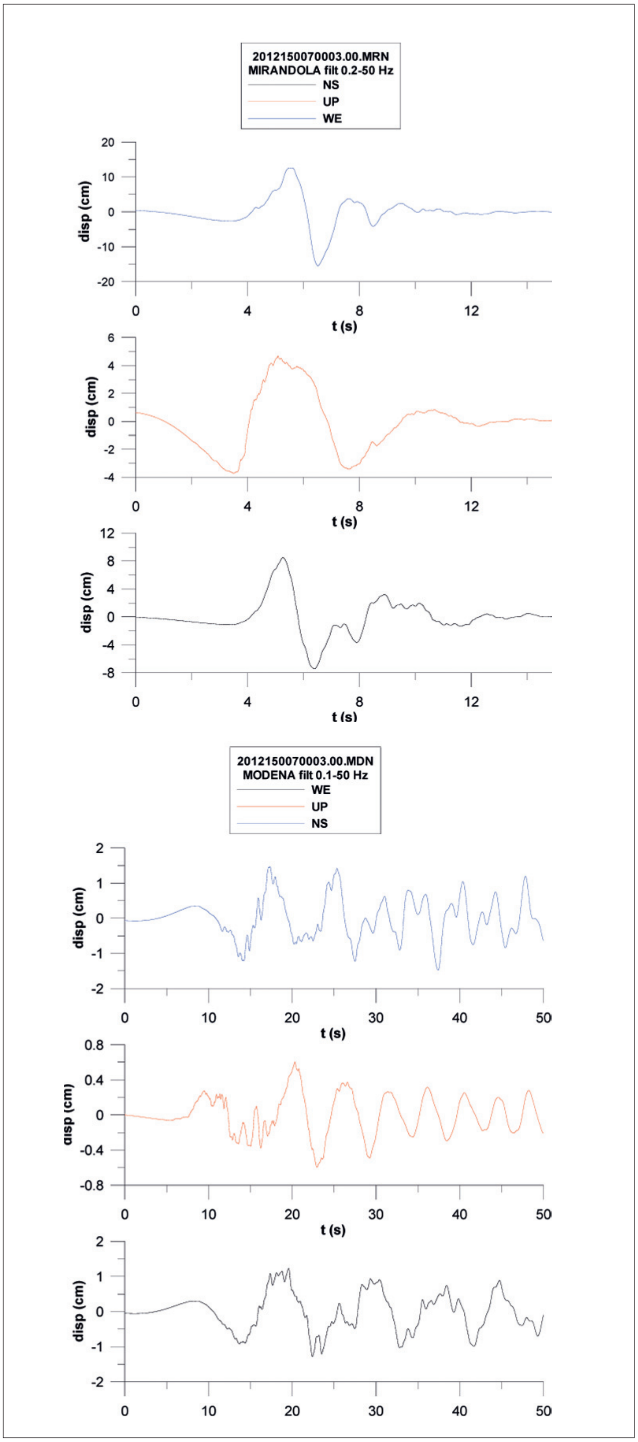

FIGURE 20 Displacement time histories: Mirandola (B) and Modena (B)

Conclusions

The seismic crisis of May-June 2012, for the localities here examined, was definitely the most violent in the last 500 years and should serve as inspiration for a critical review of seismic hazard maps, that only a few years ago assigned a rather low level of seismicity to those areas.

The first problem involves the level of magnitude which can be generated by local seismogenic sources. According to the INGV report "*Redazione della Mappa di pericolosità Sismica prevista dall'Ordinanza 3274 – Rapporto conclusivo – Aprile 2004*" (Drafting of Seismic Hazard Map provided by the Ordinance 3274 - Final Report - April 2004) the final M_w values for the areas under consideration is equal to 6.14.

On the other hand, in the "*Database of Individual Seismogenic Sources, version DISS 03 - INGV" (DISS Working Group, 2010), the existence of the seismogenic source of Mirandola is proposed* "... based on the evidence of the recent tectonic activity of the buried Ferrara Arc, highlighted by the control exerted on the evolution of the drainage network and by the geometry of syntectonic growth strata". Furthermore "*The Mirandola Source is not associated to any historical and/or instrumental earthquake, and as such it may represents a seismic gap. Given its dimension this source is able to generate earthquakes of M_w=5.9. The low slip rate suggests long recurrence interval for the potential earthquake*".

In the commentary enclosed to the DISS Database, particularly interesting are the "Open Questions" that the compilers left unanswered:

1) "Considering that the Mirandola Source is not associated with any earthquake, is it possible that the current Italian seismic catalogue missed an earthquake generated by this source?"
2) "What is the recurrence interval for the earthquakes generated by the Mirandola Source?"

These unanswered questions acquire now a dramatic importance and stress the necessity of further efforts by the scientific community in order to increase our knowledge on the earthquakes occurred in Italy in the past. Generally speaking, the historical seismology, which is based on documentary sources, is the main tool that should be deeply used and could be helpfully integrated with other methodologies, such as archaeoseismology and historical seismography, where ancient constructions are regarded as a potential source of information on past earthquakes, according to the principle that "every building is the manifest history of itself" (Pierotti and Ulivieri, 2001).

Another critical issue involved the level of seismic hazard assigned to the area by the national seismic code. On this issue, for the Municipality of Mirandola, the 0.141g value of PGA calculated for a return period of 475 years, and with local condition of hard rock outcrop and flat morphology (OPCM 3274/03), greatly underestimate the PGA value of 0.264g recorded in the "Mirandola" accelerometric station that, by the way, is located on a thick layer of soft soil which can probably produce local seismic amplification phenomena.

On the other hand, the PGA values diffused by INGV for a return period of 2475 years is 0.306g, corresponding to the 84° percentile more in line with the recorded value. An open question arising from these consideration is: which is the more reliable value of ground-motion parameters to be used for a safe design in seismic areas?

Finally, although the historical memory of the local seismicity seemed lost, the Pianura Padana-Emiliana area is prone to a not negligible seismic hazard which should be calculated with more detail. A great effort should be made for its mitigation, both with an adequate campaign for the reduction of structural vulnerability, and by in-depth studies of Seismic Microzonation and Local Seismic Response.

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