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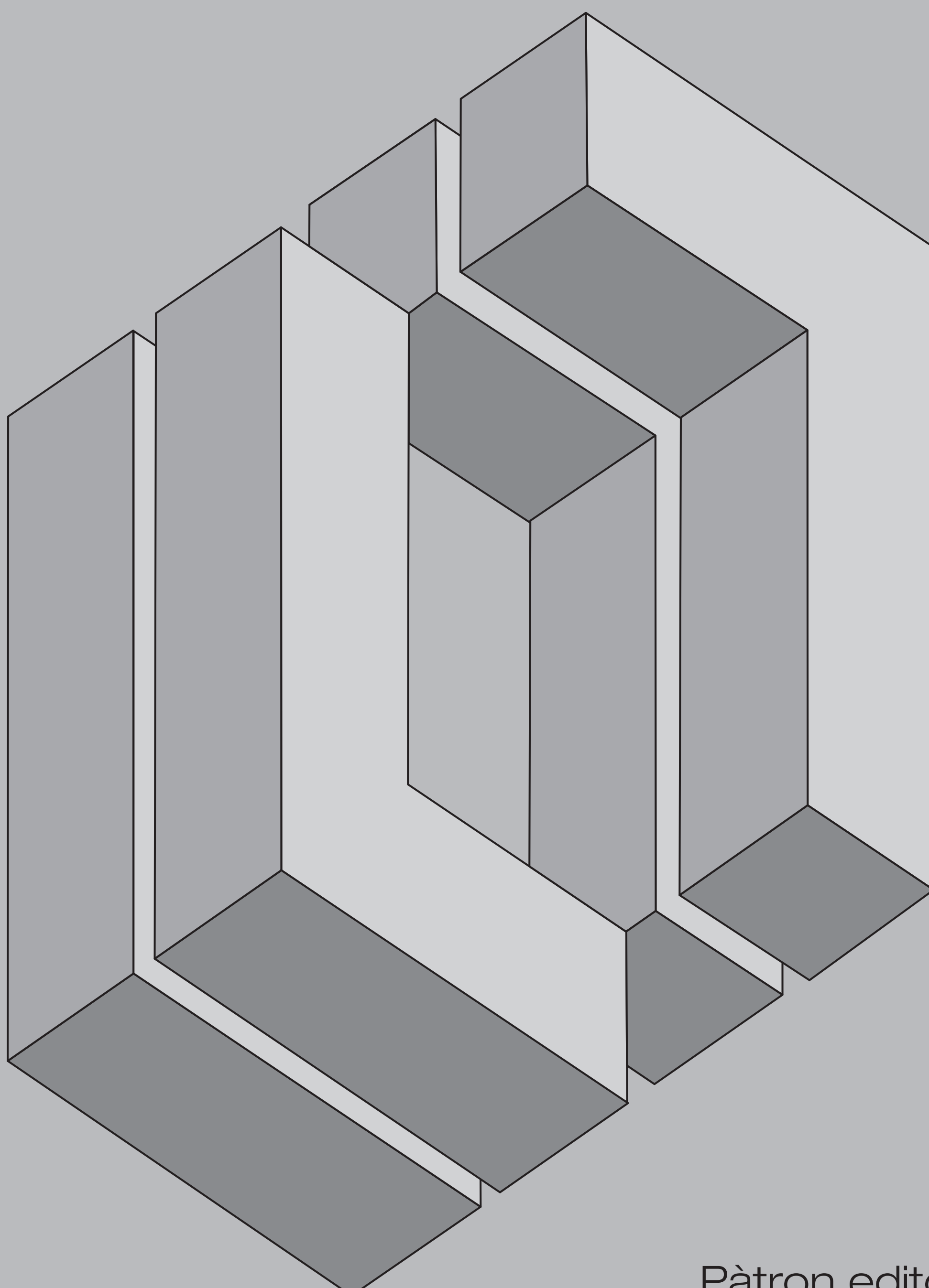

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The Emilia Romagna, May 2012 earthquake sequence. The influence of the vertical earthquake component and related geoscientific and engineering aspects

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SUMMARY – The 20-29 May 2012 earthquake events occurred along Emilia Romagna segment of Po Plain valley (Pianura Padana), a NW – SE oriented basin along the Southern tectonic boundary of Adria plate, with Northern Apennines. Major earthquake sequence events' focal mechanisms, evince the activation of low angle thrust structures, separating the earthquake activity on at least 2 distinct fault planes, with similar slip characteristics. Both planes seem to be on the same seismogenic source, on the Western part of 1570 events' source, interpreting the delimitation of the seismic activity of the May – June 2012 earthquake sequence. Widely observed secondary effects were categorized with respect to spatial distribution, density and trend, to: i) individual liquefaction cases, ii)Strictly oriented liquefactions and lateral spreading due to exposure of unconformities to surfacial liquefaction-prone geological formations and iii) extended liquefactions of confined liquefiable formations (at a depth of≈10m) and lateral spreading along river strike. This depth resulted in less surfacial deformation and differential subsidence, as well as very limited structural damage. Only fences, pavements and other light weight structures have been heavily damaged, deformed and dislodged. The incurred structural damage is extremely heavy for the churches and the cultural heritage, as well as for the industrial infrastucture of the region, besides the death toll and injuries. The available strong motion records are not adequate in order to explain in a rational and reliable way the above mentioned heavy damage. Based on years' experience in post earthquake investigations and on results of numerous full scale tests of structures on shaking tables, the authors concluded that the main reasons of the damage is the extremely high vertical ground shaking (of the order of 1.0 g) in combination with the moderate horizontal motions. Due to this very high value of the vertical ground shaking, impact phenomena are observed as well as total or partial loss of friction (due to the loss of gravitational forces).The incurred damage are grouped in general categories possessing similar characteristics. The majority of the observed damage of churches is mainly due to collapse of their roofing systems. This occurred due to resonance-like vertical vibration of the timber trusses of the roofs. This was proved by analysing representative dimensions of timber trusses with the overburden mass and, it was found that their fundamental periods are between 0.06 and 0.10 sec. On the other hand, a predominant period of the vertical component is, according to the recorded first event of 20th May 2012, 0.06 to 0.07 sec. Thus, intensive up and down motions are induced in the whole trusses and in their horizontal lower beams resulting in dislocations from their supports on the walls. On the other hand, it is well known that the arrival time between P (vertical) and S (horizontal) waves in epicentral regions is quite small. This resulted in a convolution between vertical and horizontal ground motions. The top of the walls, where are the supports of the trusses, were significantly displaced as free standing vertical cantilevers due to the loss of connection with the truss. In this way the trusses totally lost their supports and collapsed. In examining the debris one may guess what structure between the two (truss or wall) collapsed first. A proof of the dominance of the vertical component might be based, among others, on the response of bell towers that in the majority of the cases were not significantly damaged and on the fact that the mode of collapse is inside the ground plan of the building. Quite similar observations are also valid for the damaged industrial facilities. The natural vertical periods of the roofs are also, between 0.06 and 0.10 sec. The constructed supports are from functional point of view quite similar to those used for the support of the timber trusses in the churches (just simply supported cantilevers). Nevertheless, by using the conventional bolts in the supports, it is not certain whether or not the situation would be ameliorated. In order to prevent the effects of the high frequency impact type of the vertical ground motion a kind of absorbing elastomeric devices could be used in the supports of beams and trusses besides the conventional anchoring systems. Also, a kind of base isolation devices, that should not depend on friction at the base of the structures might be used. Finally, the partial collapse of the ceramic factory is attributed to the rhythmic phenomena of destruction. After the present communication was completed, it has just been released the important and technically very interesting vertical strong motion record of the second event, presenting a peak ground acceleration of the order of 0.9 g, a fact that comes in full agreement with the findings and arguments exposed in the present paper.

Keywords: Earthquake reconnaissance; Apennines-Po Plain seismotectonics; strong motion records; vertical seismic component; cultural heritage damage; prefabricated industrial buildings; rack steel structures.

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1. **Intoduction-Seismotectonic regime**

On May 20, 2012, 02:03:53 UTC, a shallow event of $M_w = 6.1 - M_L = 5.9$, /19/, /21/ took place in Northern Italy, along the Dorsale Ferrarese, near Finale Emilia, at Po Plain area. This main seismic event was accompanied by a series of aftershocks and another strong event, of $M_w = 5.8 - M_L = 5.8$, May 29, 2012, 07:00:03 UTC, /19/, /21/ about 20 km W of the first event's epicenter.

The death toll and injuries reached 7 and 50 after the first event and 20 and 350 after the second one, respectively. The homeless people were about 500 and 15,000 respectively. The affected population was roughly 250,000.

The catastrophic results of the earthquake sequence are worse than could be anticipated, in general, from earthquakes of this magnitude. These results could be much worse as far as the human casualties is concerned, if the first event would occur some hours later, when a lot of people could be stuffed in the churches in order to participate to the Holy Mass ceremony that was going to take place. The same could happen if the second event would occur during some critical time of the year. And this is because 62 churches around the region either totally or partially collapsed; 230 suffered serious damage, and the remaining others light ones. On the other hand if the earthquake occurred during working hours when factories and shops are in full function, a lot of people would have been killed and injured. The resulting human casualties can be rather easily estimated and could be registered under the new term "potential human casualties". According to a plau-

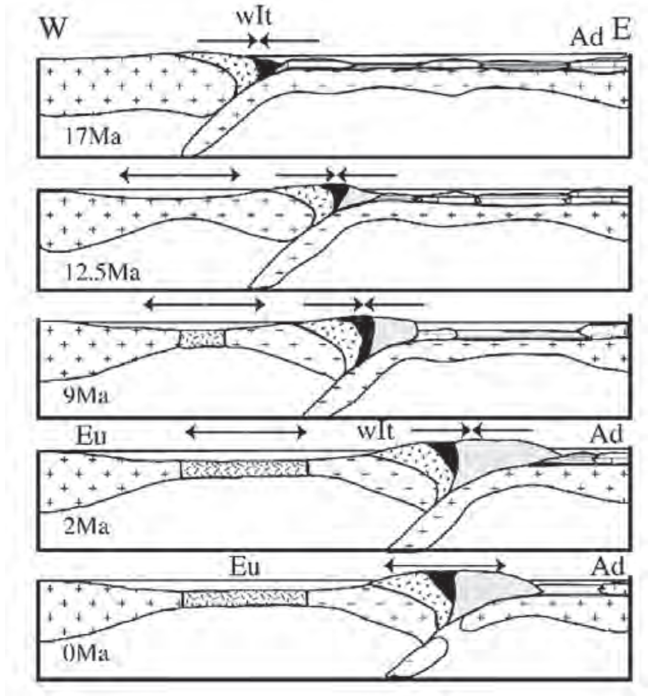

Fig. 1. *Schematic evolution of the Tyrrhenian Sea and Apennine arc. In this modification of scenario /22/, subduction and back arc spreading ceased within the past 2 Ma (Myears), making Italy west of the Apennines part of Eurasia (Eu). Adria (Ad) motion then caused a shift from convergence to extension in the Apennines, /26/.*
Schema evolutivo del Tirreno e arco Appenninico. In questo scenario /22/ l'estensione della zona di subduzione e del bacino di retroarco si è esaurita nei passati 2Ma (Milioni di anni) rendendo la porzione dell'Italia ad ovest degli Appennini parte dell'Eurasia (Eu). Il moto della placca Adriatica (Ad) generò successivamente negli Appennini una variazione da convergenza a distensione /26/.

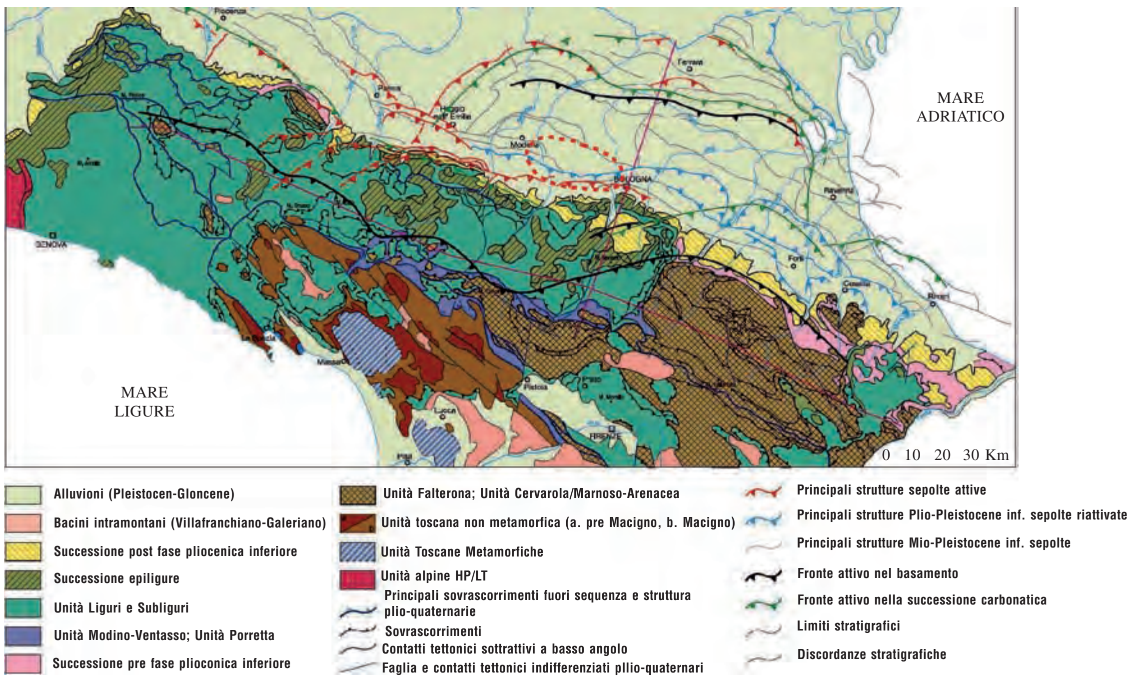

Fig. 2. *Tectonic scheme of the Northern Apennines after /15/, /23/. Inset on right upper corner shows a stratigraphic scheme of the Neogene-Quaternary units of the Po Plain and the Apennines – Po Plain margin. Red dashed line delimits meizoseismal area of 20-29th May 2012 earthquake sequence (modified, original by /8/).*
Schema tettonico del nord degli Appennini da /15/, /23/. L'inserto in alto a destra mostra uno schema stratigrafico delle unità del Neogene-Quaternario della Valle Padana e del margine Appennino – Valle Padana. La linea tratteggiata in rosso delimita l'area mesosismica della sequenza del 20-29 Maggio 2012 (Modificato, originale da /8/).

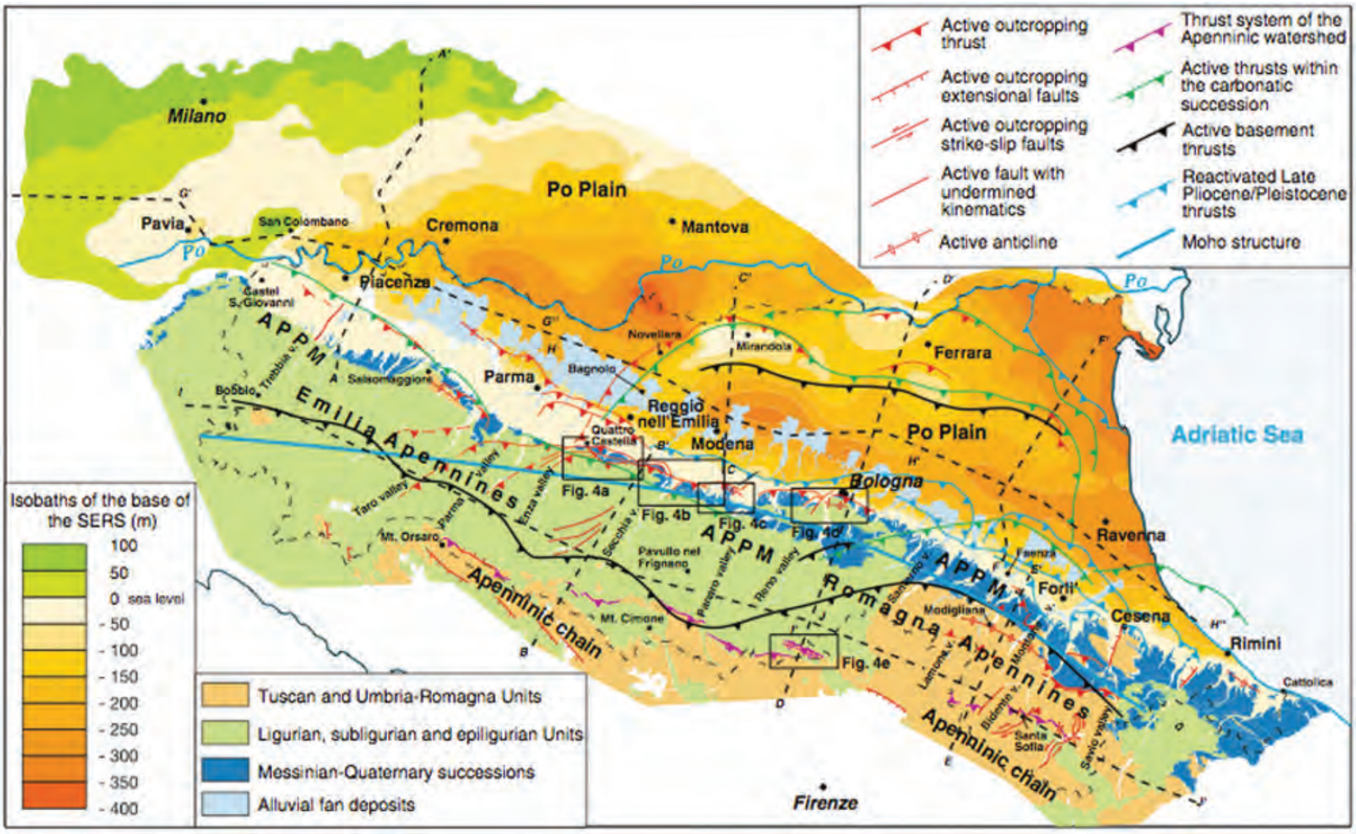

Fig. 3. *Recent and active structures of the Emilia-Romagna. Subsurface geology in the Po Plain is illustrated as isobaths of the base of the Upper Emilia-Romagna Synthem (450,000 years), APPM: Apennines–Po Plain margin.*
Strutture recenti e attive dell'Emilia-Romagna. Geologia sotto-superficiale nella Valle Padana illustrata attraverso isobate della base del sintema Emiliano-Romagnolo superiore (450,000 anni). APPM: margine Appennino-Valle Padana.

sible estimation, the potential death toll could reach the order of 3,000 (62x30+230x5) and the injured, the order of 8,500 (62x65+230x20) people. This is presented in the introduction of the present communication in order to ring a bell on how much deadly, besides their proved destructiveness, could be small to medium size (i.e. M_w 5.0 to 6.0) shallow focus earthquakes if they occur close or under villages, cities and industrial agglomerates, as commonly could happen in Italy, Europe and other countries around the globe, due to the density and quite uniform distribution of population.

This earthquake sequence is located along the Po Plain valley (Pianura Padana), a NW – SE oriented basin along the Southern tectonic boundary of Adria plate, with Northern Apennines. This area is viewed as a tectonic domain between Eurasian and African plate. The Neotectonic status of this former convergent boundary is still under debate, as it seems to have changed very recently. Continuous GPS data confirm Eastern Italy moving Northeast relatively to stable Eurasia, /3/, proving that the previously convergent boundary of subducting Adria plate has shifted to extension, after Pleistocene, /26/.

Focal mechanisms of earthquakes, show that active subduction has stopped on the Po Plain boundary and is still active only in the Calabrian-Sicilian part of the zone, since seismicity below 200 km is present there. The Northern Apennines – Adria plate subducting boundary seems to be active since Miocene, when Adria plate started subducting westwards under Italy, forming Apennines as its orogene system, at a main Northwestern trend. As the process continued, the subducting zone migrated eastward and Adria plate rotated counterclockwise resulting to this segment's independent tectonic status and movement from that point until today. Adria plate's tectonic independency from the Southern Alps on the North and Northern Apennines on the Northwestern boundary, is further supported by the lack of a well organised belt of seismicity that should otherwise be located on the boundary. The lack of homogenous seismicity also advocates the existence of more than one rotation poles, accommodated by differential motion between crustal blocks of the plate itself.

On a more local basis, the Northern Apennines – Po Plain area consists of a thrust and fold belt, composed by NE verging tectonic units, part of the Cenozoic collision orogene between the Corso-Sardinian block of the European plate and the Adria plate. The Ligurian and Subligurian units represent the uppermost tectonic units of the Apennine nappe and correspond to alochthonous terrain structures originaly composed by oceanic realm of the Alpine Tethyan ocean. These tectonic units overlie an autochtonous system of the Tuscan and Umbria – Romagna units. These units were originally deposited at the passive margin of the Adrian plate

Tab. 1. *Main seismic events of Emilia Romagna Plain from 20th May – 3rd June 2012, M_L>4.5 provided by /21/.*
Principali eventi sismici dell'Emilia Romagna dal 20 Maggio al 3 Giugno, 2012, M_L>4.5 /21/.

Date	Time (UTC)	Latitude (N)	Longitude (E)	Depth (Km)	Mag (M_L)
2012-05-20	2:03:53	44.89	11.23	6.3	5.9
2012-05-29	7:00:03	44.85	11.09	10.2	5.8
2012-05-29	10:55:57	44.89	11.01	6.8	5.3
2012-05-29	11:00:25	44.879	10.947	5.4	5.20
2012-06-03	19:20:43	44.899	10.943	9.2	5.10
2012-05-20	13:18:02	44.831	11.49	4.7	5.10
2012-05-20	2:07:31	44.863	11.37	5	5.10
2012-05-29	11:00:02	44.873	10.95	11	4.90
2012-05-20	3:02:50	44.86	11.1	10	4.90
2012-05-20	2:06:30	44.886	11.189	7.7	4.80
2012-05-29	8:27:23	44.854	11.106	10	4.70
2012-05-29	8:25:51	44.901	10.943	3.2	4.50
2012-05-20	17:37:14	44.88	11.38	3.2	4.50

since Middle Trisassic and consist of thick siliciclastic foredeep sediments of Oligocene – Miocene, overlying Mecozoic – Cenozoic carbonate rock formations and thick Triassic evaporites, as the base of the sediments for both units.

Recent and active structures of the external Northern Apennines fold-and-thrust belt can be divided into three sectors: the Apenninic chain, the Apennines–Po Plain margin, and the Po Plain.

The Apenninic chain consists of a major system of thrust faults, developing in correspondence and parallel to the main Apenninic divide. The Apennines–Po Plain margin is characterised by the presence of two distinct sectors, extending North-West and South-East of Bologna (Fig. 3). The Northwestern sector (Emilia Apennines) is well defined by presence of the major Pede-Apenninic thrust front (PTF, /7/). This area in the Southeastern part known as Romagna Apennines, is characterised by a Northeast dipping plane that leads to the development of tilted surfaces connecting the plain with the Apenninic relieves, affecting the Quaternary deposits in the area and is closely related to movement along blind back thrusts, buried under the thick sediment sequences.

Recent tectonic activity is well defined in the area by non continuous buried structures along the Emilia Apennines–Po Plain margin. Northwest of Parma, the buried Emilia Folds as a continuity of the Southeastern Broni-Stradella thrust is a good example of how non-continuous structures prove presence of active deformation. Several seismic profiles from the broader area confirm that Middle Pleistocene sediments are folded and faulted (Fig. 4).

Blind back thrust on the base of Pliocene sequence between Bologna and Forli also prove activity along the Romagna Apennines–Po Plain margin.

Po Plain could not be studied on detail until seismic profiles were available for the area. The sediments of Po Plain appear to be deformated with both thrusts and faulting at the Plioquaternary sediments. Those structures correspond at depth to major basement thrusts and folds, being expressed as Emilia and Ferrara folds to the West and Eastern part respectively. Reconstruction of the Holocene basis of the sediments through the use of seismic profiles, resulted in understanding that PTF was active in the area between Reggio Emilia and Bologna.

The Holocene base that was proved to be active, is located at a very shallow depth, such as 9 m west of Reggio Emilia and in western Romagna, whereas it is located deeper 20 m along the Adriatic coast, be-

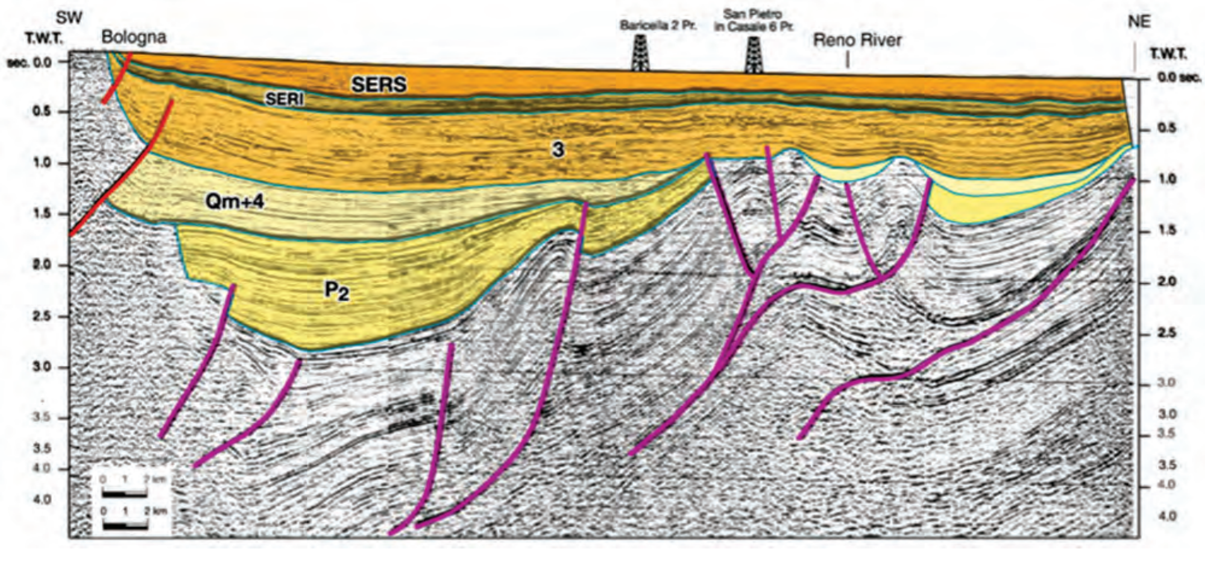

Fig. 4. *Example of interpreted seismic line (modified from /25/). Note that Middle Pleistocene and Late Pleistocene units (3: Imola Sands; SERI: Lower Emilia-Romagna Synthem;SERS: Upper Emilia-Romagna Synthem) are folded and faulted. P2: Late Pliocene; Qm: Lower Pleistocene marine sediments; 4: Yellow Sands (1–0.8 M years).*
Esempio di allineamento sismico (modificato da /25/). Si noti che le unità del Pleistocene medio e inferiore (3: sabbie di Imola; SERI: sintema Emiliano-Romagnolo inferiore; SERS: sintema Emiliano-Romagnolo superiore) sono piegate e fratturate. P2: Pliocene inferiore; Om: Sedimenti marini del Pleistocene inferiore; 4: sabbie gialle (1-0.8 milioni di anni).

tween Ravenna and the Po river delta. Besides the very shallow point at Reggio Emilia, this limit seems to be changing depth dramatically, defining fault scarps. Such structures of extensional character on the surface and compressional character on a greater depth, are connected to explain both seismicity at very shallow levels with extensional mechanisms and observed hydrological anomalies and subsidence in addition to local changes in the hydrographic pattern, such as direction changes of Po river and steams.

2. **Recent earthquake sequence**

In seismological terms the seismic sequence that was set off by the May 20, 2012, 02:03:53 UTC, $M_L = 5.9$, /21/, at 6.3 km depth, was located on the Eastern part of the sequence, as it is shown on the figure below. The aftershock sequence was spread along a WNW-ESE orientation, parallel to the Northern Apennines orogenic belt and Po Plain structures.

The main event focal mechanism shows almost pure thrust slip on a low angle surface, at a strike of 105º, ESE-WNW. Poor data don't provide credible proof concerning any possible slip directivity, due to small Magnitude of the events. Slip model on the Western part, as far as the May 29th 2012 event is concerned, seems to be influenced by aftershock activity, as shown by the epicenters of M = 5.1, M = 5.2 and M = 5.3 in the slip model (Fig. 6). As far as the separation of the two main events, slip model shows that the two main events of 20th and 29th of May have distinct and separate slip sources, converging to the fact that the two slip sources may be separate fault planes and not only separate slip events on the same fault plane.

On the terms of stress redistribution, this almost pure thrust movement as shown by the focal mechanism of the main event of the May 20th 2012 (Figs 5 and 7), indicates almost pure N-S trending compression that must have resulted to Coulomb stress redistribution. Pure thrust faulting results to stress drop at roof and footwall of the fault surface, and stress rise at the edges of the slip surface, at WNW and ESE sides of the fractured area, as far as this event is concerned.

As we mentioned above, Po Plain area is characterised by non continuous, parallel or subparallel to Northern Apennine – Po Plain shallow thrusts and folds. This non continuous type of structure could hardly result to greater events than a $M_L = 6.5$ and this could take place only on the same surface. Aftershock sequence of the first event, until the arrival of the $M_L = 5.8$ event of May 29th, was spread along a 50km zone, as shown on Fig. 5. After the May 29th $M_L = 5.8$ event, its aftershock sequence was bounded within almost half the length of the aftershock area of the first group of earthquakes. The spatial distribution of the second major event's aftershocks suggests that this event is not on the same fault plane as the May 20th event, but seems to have an homologous seismic source, with the same characteristics. The focal mechanisms shown both on Fig. 5 and Table 2, show that both structures are subparallel to Moho structure as shown on Fig. 3, as well as the rest of active thrust and fault systems.

Such active tectonic structures are very common along Po Plain area. The seismic sequence of the 17th of November 1570 – end of February 1571, with a

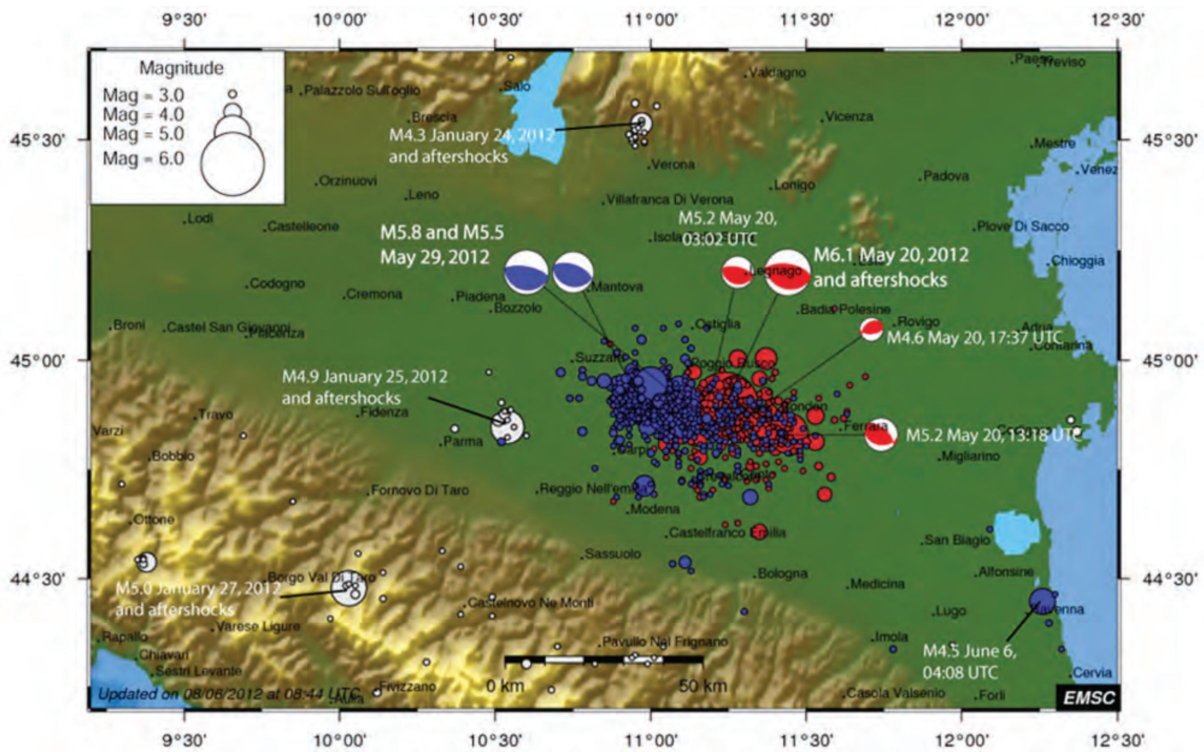

Fig. 5. *Main events and Aftershock locations of Northern Italy – Emilia Romagna earthquake sequence, /19/.*
Localizzazione degli eventi principali e delle repliche della sequenza sismica Nord Italia- Emilia Romagna /19/.

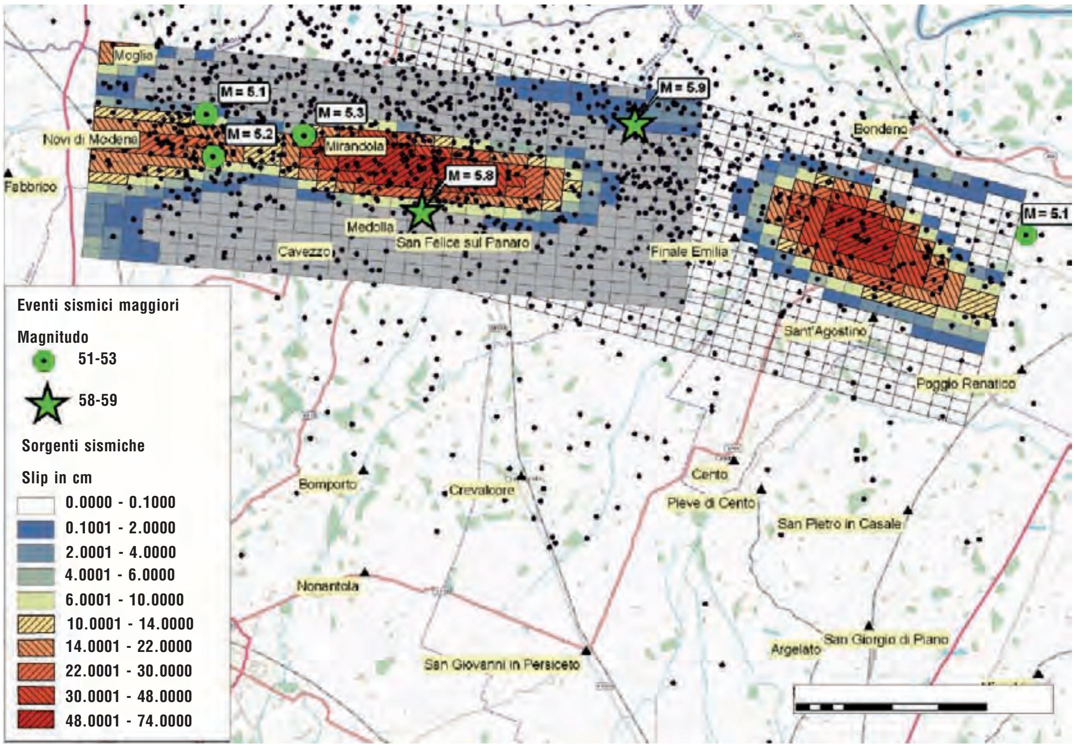

Fig. 6. *Preliminary source model of the main events of the sequence of Emilia. The main shock of 20 May 2012 is missing data for distribution of slip shown as white – transparent areas on the SAR COSMO-SkyMed, /1 / slip model above.*
Modello preliminare delle sorgenti dei principali eventi della sequenza emiliana. Per l'evento principale del 20 maggio 2012 manca il dato SAR COSMO-SkyMed sulla distribuzione degli scorrimenti (aree trasparenti) qui riportato /1/.

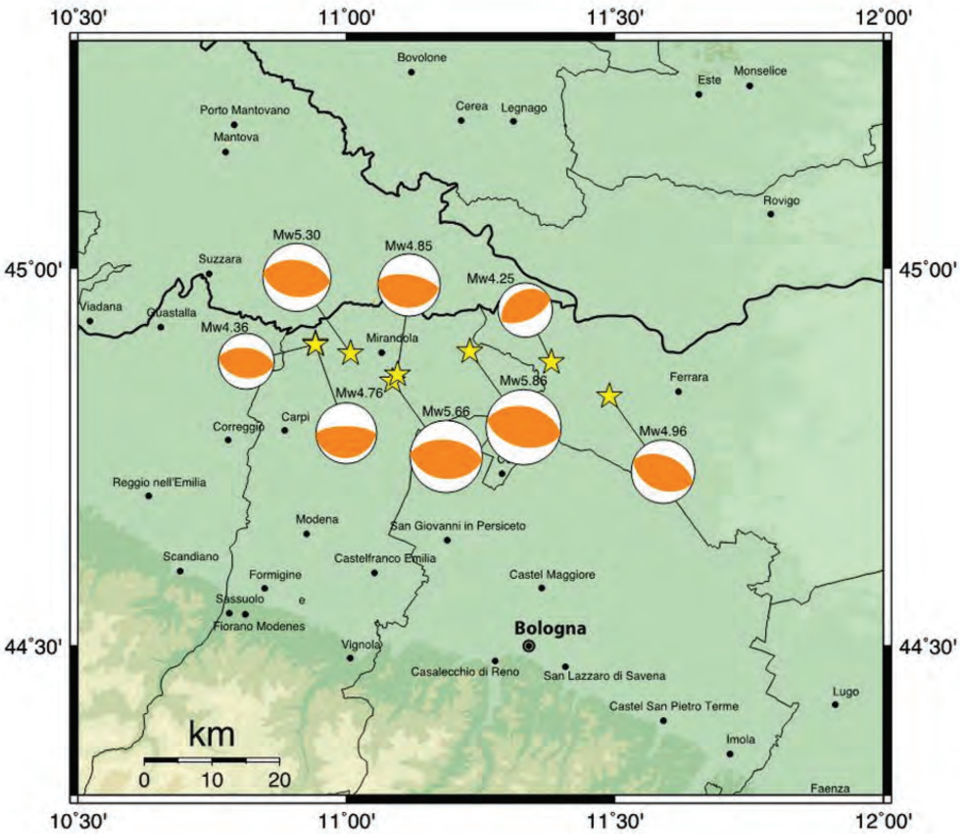

Fig. 7. *Focal mechanisms and moment magnitude (Mw) of the main events of Emilia Romagna earthquake sequence (Ml≥4.5). Mechanisms show main horizontal compression of N-S, /21/.*
Meccanismi focali e magnitudo momento (Mw) degli eventi principali della sequenza dell'Emilia Romagna (Ml≥4.5). I meccanismi focali indicano una prevalente compressione orizzontale N-S, /21/.

Tab. 2. *Focal mechanisms and maximum slip distribution of the two main events of the Northern Italy – Emilia Romagna earthquake sequence.*
Meccanismi focali e distribuzione dello scorrimento massimo dei due eventi principali della sequenza sismica del Nord Italia-Emilia Romagna.

Source	Length	Width	Top depth	Strike	Dip	Rake	Slip max
20/5	35 km	20 km	500 m	105°	50°	85°	>68 cm
29/5	32 km	20 km	1000. m	95°	55°	90°	72 cm

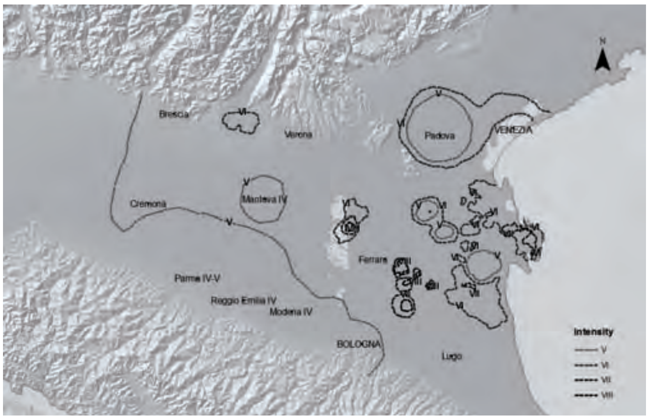

Fig. 8. *Spatial distribution of macroseismic intensity of the November 17th, 1570 seismic sequence.*
Distribuzione spaziale delle intensità macrosismiche della sequenza sismica del 17 Novembre 1570.

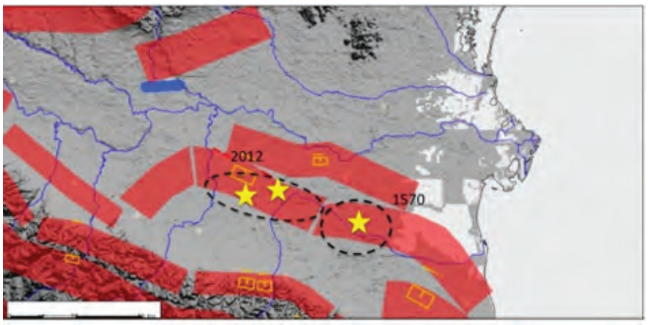

Fig. 9. *Estimation of seismogenic source activation of the 1570 and 2012 events. (Modified map of INGV Database of Seismogenic Sources, /21/).*
Stima delle sorgenti sismogenetiche attive per gli eventi del 1570 e del 2012 (mappa modificata del database delle sorgenti sismogenetiche dell'INGV /21/).

magnitude of 5.5 as calculated by maximum macroseismic intensity values, is a similar earthquake sequence with similar spatial distribution with the May – June 2012 earthquake sequence. The 1570-1571 sequence is located on the Eastern part of the 2012 aftershock location area, forming a certain limit of NNW-SSE trend, where macroseismic intensities drop on the Eastern part (Figs 8 and 9).

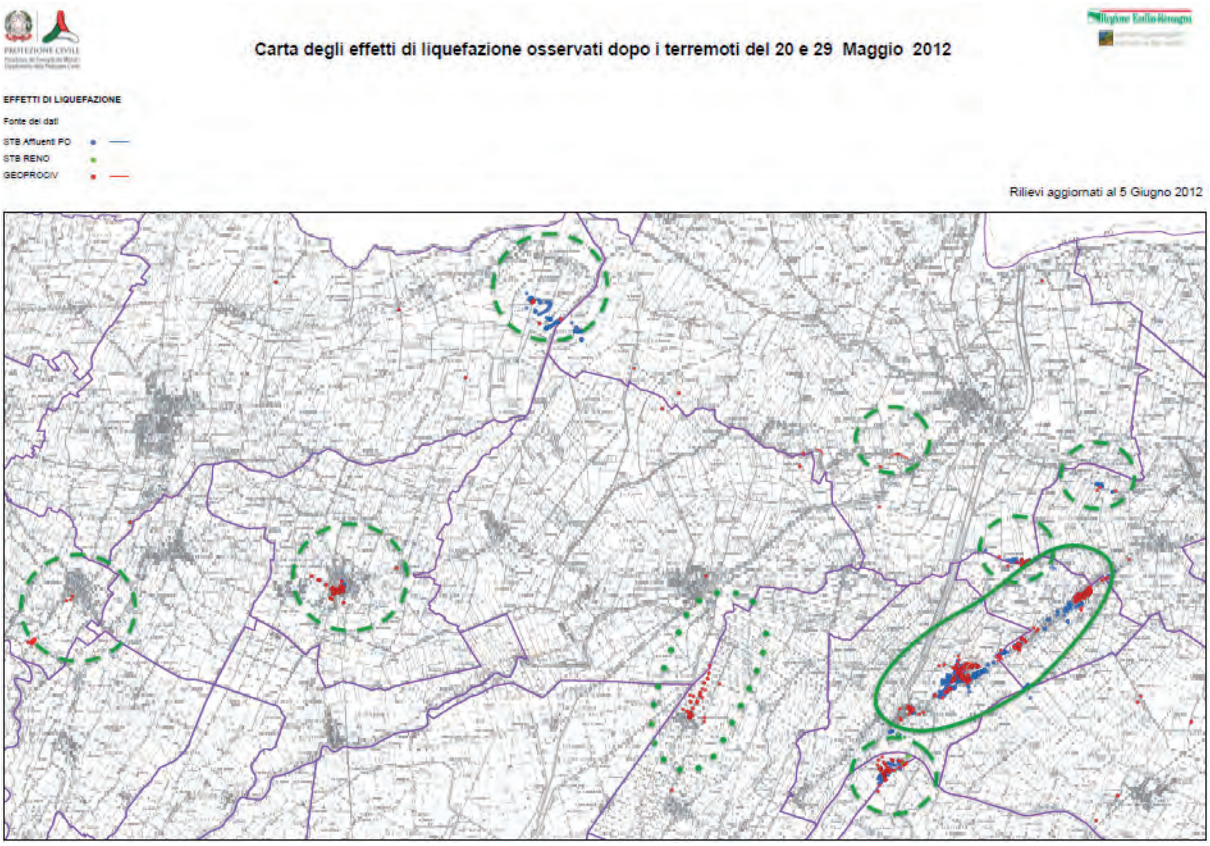

Fig. 10. *Main location of secondary environmental effects from May – June 2012 seismic sequence, as surveyed by /21/. Dashed lines locate isolated individual liquefaction locations of category (i), dotted line locates strictly oriented liquefactions of category (ii) and continuous line locates liquefactions of category (iii) corresponding to the WSW-ENE zone that was surveyed (combined observations map) by /24/.*
Distribuzione di effetti ambientali secondari causati dagli eventi del Maggio-Giugno 2012, come da rilevamenti riportati in /21/. Le linee tratteggiate indicano zone isolate di liquefazione del suolo di classe (i), quelle punteggiate individuano liquefazioni di classe (ii) con un preciso orientamento, mentre la linea continua (iii) indica la zona OSO-ENE sottoposta a indagine (mappa cumulativa di rilevamenti) da /24/.

Fig. 11. *ENE-WSW trending lateral spreading and liquefaction in San Carlo. Estimated ground crack length 300m. Maximum opening of 1m and vertical offset of 0.5m.*
Andamento ENE-OSO delle spaccature nel terreno e della liquefazione a San Carlo. La lunghezza della lesione è stimata in 300 m, la sua massima apertura 1 m e lo spostamento verticale 0.5 m.

Fig. 12. *Well with liquefied sand deposition due to violent ejection in San Carlo.*
Un pozzo con depositi di sabbia liquefatta, in seguito alla sua violenta espulsione, a San Carlo.

At a level of seismic source activation, the 1570 earthquake sequence seems to be located at a different seismogenic source, suggesting that the NNW-SSE limit of the higher intensities could be a result of the discontinuity of the seismogenic source, as shown on Fig.7. The spatial distribution of May – June 2012 aftershock locations also confirms the existence of such a discontinuity and explains the distribution of the eastern limit of the aftershock locations as well. According to this rationale, the seismic activity could not migrate further on the East, since the seismic source of the 2012 events, seems to be terminating at this point.

3. **Environmental effects – liquefaction**

Secondary environmental earthquake effects were widely observed within the meizoseismal area, mainly liquefactions and ground cracks, in respect to local geological and geomorphological characteristics. The main concentration of these events was observed within a ESE-WNW trending zone, near Sant' Agostino, Emilia Romagna. The concentration and magnitude of secondary effects, reached a maximum at San Carlo, near Sant Agostino, Emilia Romagna.

Ground cracks with great amounts of ejected liquified sand on the field and water fountains as high as 1.5m were observed by local residents at the time of the 20th May 2012 earthquake event, and suggests that the material was ejected with high pressure, higher than usually observed at events of this magnitude and depth. This concludes that the liquified zone is located at a lower depth than usual, around 10m as suggested by local geology (Figs. 11-15).

Spatial distribution of the secondary phenomena of liquefaction and lateral spreading, can be categorized by means of density and trend, as it is evident in the liquefaction location map (Fig. 10).

i) Individual liquefaction cases, with limited expansion and without preferred orientation. Such liquefactions were observed on areas with drilled wells or under special local circumstances, such as small excavations on surfacial geological formations.

ii) Strictly oriented in agreement with agricultural roads and ditches. On those cases it is clear that liquefactions appear on the surface due to existence and exposure of unconformities to surfacial liquefaction prone geological formations. Such cases are the liquefactions of Dodici Moreli, on the Eastern part of Sant' Agostino, trending NNE – SSW.

iii) Extended liquefactions and lateral spreading on older river terraces, along Sant' Agostino – San Carlo and Mirabello, trending WSW – ENE. Blue to grey fine liquefaction-prone sand deposits are covered by more cohesive and coarse formations about 10 m thick that cannot get liquified. Those formations were ruptured along the strike of the river, possibly due to lateral spreading mechanism, resulting to liquified sands outpour. Those liquefaction-prone formations are deposited at a depth of about 10m and due to the overlying unliquifiable formations weight, the developed pressure was even greater, resulting to violent ejection of liquified material.

Due to the same liquefaction and pressure augmentation mechanism, liquified material ejected violently from wells, as seen in Fig. 12. Due to the greater depth of liquifiable formations, no great damage was observed on the area, in contradiction with Adapazari liquefactions (Izmit 1999-Turkey) and Christchurch liquefactions (New Zealand – 2011). This great differentiation in damage pattern and degree is observed due to a) the amount

Fig. 13. *Lateral spreading in San Carlo, with ejected liquefied grey fine sand material in residential area. Ground cracks with opening of about 20cm, vertical offset of 10-20cm and local extensional strains is evident.*
Spaccatura nel terreno nella zona residenziale di San Carlo, con espulsione di sabbia fine grigia liquefatta. La larghezza della lesione è di circa 20cm. Sono evidenti la traslazione verticale di circa 10-20 cm e le deformazioni locali, di tipo estensionale.

Fig. 14. *Lateral spreading cutting through roads and residential area, in San Carlo.*
Spaccatura nel terreno che interessa le strade e la zona residenziale a San Carlo.

Fig. 15. *San Carlo residential area. Big amounts of liquefied material have covered roads throughout the city.*
Zona residenziale di San Carlo. Grandi quantità di terreno liquefatto hanno coperto le strade in tutto il paese.

of seismic energy absorbed by liquified material and the violent ejection, resulting to impairment of seismic energy on the surface and less destructive action and b) the coarser thick formation's behavior, as its fracture to big blocks resulted to less surfacial deformation and less differential subsidence, causing less damage.

As it is shown in Fig. 14, fences, pavements and other light weight structures, that apparently were founded superficially, have been heavily damaged, deformed and dislodged. On the other hand, builiding structures suffered either no damage or extremely limited. According to the evidence the underground water table level is quite high, and in agreement with the above mentioned, most probably, the foundation level of the buildings is set a little deeper on a stronger ground formation.

The only reported damage is a geometric deformation of two neighbouring buildings that were found to have tilted one against the other, as rigid bodies and without other apparent damage as shown in Fig. 16. So it is proved that the liquified material in deeper formations actually functioned as a kind of base isolation absorbing seismic energy, as already mentioned.

4. A contribution in order to explain the incurred damage

In order to study the response of structures and to try to explain the reason of the observed damage, it is absolutely necessary to know the ground motion to which the respective structures have been exposed. Actually, if we rely on the existing strong motion data, unfortunately, this is not possible to be achieved. And this is because the incurred damage that we observed, during our site investigation, is much more intense than it could be justified by implementing the above mentioned available data. For the first event of 20th May 2012, /17/, the record closest to the epicenter is at Mirandola station at an epicentral distance of about 14 km and, for the second event, only horizontal records are available.

As a result, the maximum horizontal acceleration values that can be reasonably accepted for the whole region are, for both directions and both events, a little bit less than 0.3 g. The vertical component recorded at the same station for the first event is a little bit higher than 0.3 g. This value must be much higher for areas closer to the epicenter of the second event of 29th May 2012, /18/. The Mirandola station lays at an epicentral distance of about 2.0 km from the second event. It would be extremely helpful if such records could be available, not only for the results of the second event, but also for the first one, by accepting similar maximum epicentral values for the vertical component. And this is because on one hand the maximum vertical accelerations are almost independent from the earthquake magnitude, /10/, /11, /12/ and /13/, and on the other hand the focal mechanisms of both events are quite the same. Our interest is focused on the investigation of the vertical earthquake component because we strongly believe that this component is catalytic together with the horizontal one for the explanation of the incurred damage to structures for the whole earthquake sequence, within the epicentral region. This is based on:

– similar observations carried out by the authors after the Christchurch 2011 and L'Aquila 2009, catastrophic earthquakes where strong motion records were available with eminent vertical acceleration values,

– on a years' experience on numerous post earthquake investigations around the globe at epicentral regions carried out by the authors, and

Fig. 16. *Rigid body motion of two neighbouring buildings that tilted one against the other. The buildings did not show other apparent damage.*
Moto rigido di due edifici confinanti, che si sono inclinati uno verso l'altro. Gli edifici non mostrano segni apparenti di danni.

– on the evaluated results and observation of the response of several hundreds of full scale tests, of any kind of structures, using the 6 DOF shaking table of NTUA.

– According to this experience, in epicentral regions of shallow focus reverse – thrust fault earthquakes, the vertical ground acceleration is of the order of 1.0 g. This is also justified in the present case after our site investigation. It is also well known that the attenuation of the vertical component with distance is much more intense compared to that of the horizontal one.

– Besides the above mentioned, one may define the following characteristics of the strong vertical earthquake component and its effects on structures in epicentral regions of shallow focus earthquakes.

4.1. *Resultant of horizontal and vertical components*

The closer to the epicenter we are, the higher is the vertical component compared to the horizontal ones, and strong phase of the three components of motion come closer in time of occurrence. This means that in the case under investigation the three components are creating a much stronger vector than each one separately. And even more, since we are in the strong phase of the excitation and mostly within the non linear domain of the materials, unforeseeable phenomena may appear as far as the whole stability of the structure as well as its overall kinematic state are concerned.

4.2. *Peculiarities of the compound ground motion in epicentral regions*

There are regions within the epicentral area that might be quite close one to the other, among which a considerable difference of the seismic intensity might be observed. As it is shown in Fig. 17, the final motion along the vertical direction is a superposition of the P waves and of the vertical projection of the particle motion of the surface or Rayleigh (R) waves. Therefore according to the wave length of the surface waves we might have regions of low and regions of high seismic intensity.

As it is shown in Fig. 17 the distance among those two regions is half wave length of surface waves which, according to the quality of the ground, might be from 50 to 150 m. This alternative variation of ground intensity is rhythmic and may cause a great variation in the earthquake response of structures, /9/ and /27/. According to that evidence, we might have regions in which we observe either not any motion and not any earthquake effect, or extreme damage and even collapse of structures. This peculiarity is repeated in a rhythmic way.

A representative example of this is given in Fig. 18a, where a part of the ceramic warehouse, in Sant Agostino, totally collapsed while an other part remained intact, see Fig. 18b.

On the other hand, in order to get an idea about the differential horizontal movement and the intensity of

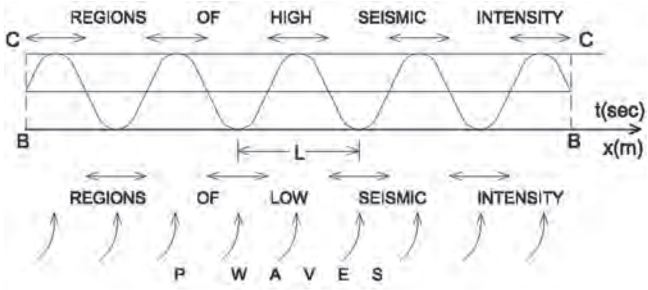

Fig. 17. *Ground motion in the epicentral regions (where the vertical earthquake motion dominates): in B-B is the surface of the ground at its initial position; in C-C is the extreme position of the ground due to P waves and the vertical projection of R wave particle motion; B- C compressional field is the vertical projection of the final motion of the ground particles; L is the wave length of surface waves.*
Moto del terreno nelle zone epicentrali (dove la componente verticale è dominante): in B-B la superficie del terreno è nella situazione iniziale; in C-C il terreno è nella sua posizione estrema a causa delle onde P e della componente verticale del moto del terreno dovuto alle onde R; lo stato di compressione B-C è la componente verticale del moto risultante delle particelle di terreno; L è la lunghezza d'onda delle onde di superficie.

the horizontal ground motion, a characteristic checking point is the intensity of the impact, if there is any, between adjacent structures bridged by simply supported cantilevers, as it is shown in Figs 19a and b.

4.3. *Effect of the vertical component on the structure as a rigid body*

The effect of the vertical component along the height of a structure considered as a rigid body, is of an impact character. In some cases the appearance of damage is as if explosions occurred under its foundation. This phenomenon can be interpreted as an impact wave that strikes vertically the lowest part of the structure and the wave is propagating upwards. Due to peculiarities and discontinuities of a structure, various reflections, interferences and other similar phenomena may be created. A very simple basic model simulating this process, that may be easily understood, is provided in Fig. 20.

4.4. *"Jumping" structures*

There are cases in which the whole structure jumps up and down on its supports. This mode might be like cases a) or b) of Fig. 20. In the most of the cases the impact phenomenon takes place after the downwards motion – fall of the structure (totally or partially) as it is shown in Fig. 21.

During this complex kinematic situation the following major phenomena take place

i) Downwards – fall motion phase. The structure is falling down (a few centimeters) in which all gravitational forces are vanished. And as it is logic, any friction that depends on gravitational loads, is vanished too. If the downwards motion is not absolutely symmetrical around the Z axis, then uncontrollable and unpredictable torsional phenomena may be developed. For this reason

Fig. 18. *a) A part of the ceramic warehouse in Sant' Agostino totally collapsed; b) This part of the same warehouse did not move. This can be very well justified by the relative position of the stored material to the steel members of the racks, which is in all positions the same. It must be taken under consideration that the positioning of the stored materials is computerized.*
a) Una parte dello stabilimento delle Ceramiche Sant'Agostino completamente collassato; b) questa porzione dello stesso edificio non si è mossa. Ciò può essere giustificato dal posizionamento delle merci sugli scaffali metallici, che è la stessa in tutte le posizioni, in quanto lo stoccaggio è computerizzato.

one may observe rotation of rigid bodies around the Z axis, as for example it is shown in Fig. 22.

But this phenomenon may affect also the response of seismically isolated buildings supported by devices, the basic function of which depends on friction.

It is quite interesting to mention here that, during this phase of motion, structures are without the vertical loads for which they have been designed. In order to illustrate this case, the respective deformations of a simple structural frame are schematically drown in Figs 23a and b. The state of Fig. 23b is valid only in the outer space where there is no gravity. During the downwards motion the column's axial compresional forces are vanished unless tensile forces are created. The cross section eccentricities are augmented at the maximum, a fact that in columns greately reduces their strength. The smaller the cross section is, the

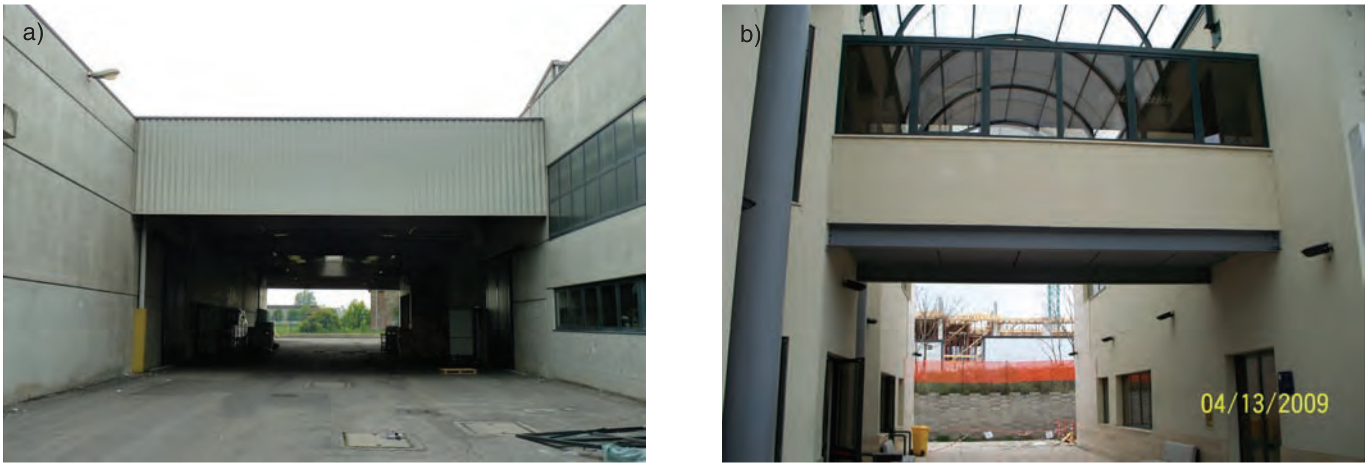

Fig. 19. *The differential horizontal motion between neighboring structures is usually expressed by some damage in the bridging structure and the connecting parts; a) in the ceramic factory in Sant' Agostino and b) in the University of L'Aquila after the 2009 earthquake. At both cases not any sign of differential horizontal motion was noticed.*
Il movimento orizzontale differenziale tra edifici contigui è di solito evidenziato da lesioni nelle strutture di collegamento e/o nei giunti; a) Stabilimento Ceramiche Sant'Agostino e b) l'Università di L'Aquila dopo il terremoto del 2009. In entrambi i casi non si notano segni di movimenti relativi in direzione orizzontale.

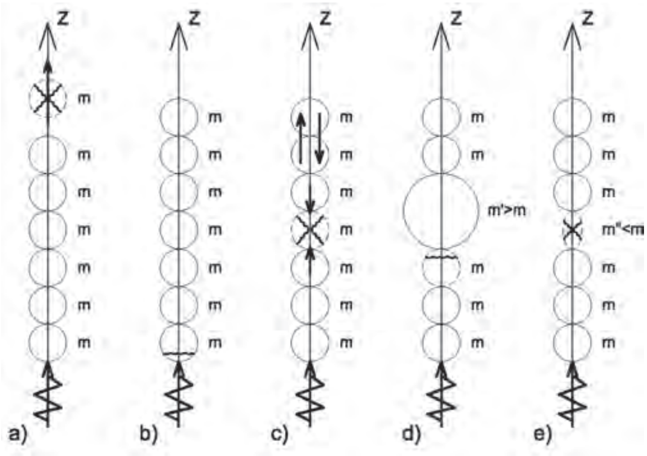

Fig. 20. *Impact phenomenon along the height of a structure; a) a fully elastic impact with regularity and continuity along the height. The top particles are ejected. The lesser is the top mass, the stronger is its ejecting; b) in a plastic impact at the base, the seismic energy is absorbed at that point and the rest of the structure remains intact; c) due to interference of incident and reflected waves, damage may occur at any point along the height of the structure. Nevertheless, there are frequent cases in which this point coincides with the middle point of it; d) and e) if a discontinuity of mass or stiffness intervenes along the direction of the wave propagation, high concentration of stresses may be created resulting in damage.*
Schematizzazioni del fenomeno di impatto lungo lo sviluppo verticale di un edificio; a) impatto completamente di tipo elastico, con regolarità e continuità lungo lo sviluppo verticale. Minore è la massa alla sommità, più violenta è la sua espulsione; b) nel caso di un impatto a carattere anelastico alla base, l'energia sismica è assorbita in quella zona, ed il resto dell'edificio rimane intatto; c) a causa dell'interferenza tra onde dirette e riflesse, il danneggiamento si può verificare in qualunque punto, lungo lo sviluppo verticale dell'edificio. Frequentemente ciò accade nella zona a metà altezza dell'edificio stesso; d) ed e) Se lungo lo sviluppo verticale dell'edificio (cioè nella direzione di propagazione delle onde) si ha una discontinuità di massa o di rigidezza, si possono generare forti concentrazioni di tensioni, con conseguente danneggiamento.

worse are the effects from the increase of the eccentricity.

The whole mechanism is very difficult to be understood, since we do not possess a living experience of

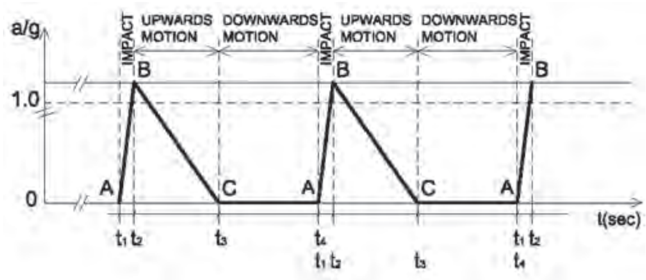

Fig. 21. *Accelerations created on the center of mass of a structure elastically jumping on the ground due to the vertical earthquake component: A-B, Δt1 = t2-t1 impact phase; B, t2 detachment from the ground; B-C, Δt2 = t3-t2 upwards motion, up to the highest position at C; C-A, Δt3 = Δt2 = t4-t3, zero acceleration during its downwards motion (the structure is in a space without gravity!).*
Accelerazioni indotte nel baricentro di una struttura che "salta" in campo elastico sul terreno, a causa della componente verticale del terremoto: A-B, Δt1 = t2-t1 fase di impatto; B, t2 distacco dal suolo; B-C, Δt2 = t3-t2 moto verticale, fino a raggiungere la posizione più elevata in C; C-A, Δt3 = Δt2 = t4-t3, azzeramento delle sollecitazioni gravitazionali durante la fase di moto verso il basso (la struttura si trova in assenza di gravità!).

such a space. Eventually, we can refer to the sensation we can experience on a rollercoaster, when climbing up or rolling down at high speed, feeling ourselves terribly heavy (going up) and very light (going down). On other words the whole phenomenon takes place into the relative space from which the gravity has been subtracted.

Nevertheless, there are numerous evidence by which this argument may be proved. A characteristic example, among many similar others, is shown in Fig. 24, after the L'Aquila, 2009 earthquake.

ii) Impact phase, A-B of Fig. 21. The results of the impact phenomenon are worsened if the impact phase is preceded by the downwards motion phase.

During this motion phase very high accelerations in the body of the structure and its members, are created. Those acceleration values mainly depend on the type of the impact phenomena that take place, namely on how

Fig. 22. *The sculpture has not any horizontal translation; only torsion due to unsymmetrical friction at its base. Its dimensions are quite small to attribute this motion to any peculiarity of the horizontal ground motion.*
La scultura non mostra segni di traslazione orizzontale, ma esclusivamente torsione a causa di un attrito non simmetrico alla base. Le sue dimensioni sono troppo piccole per poter attribuire questo tipo di spostamento a qualche peculiarità del moto orizzontale del terreno.

much elastic or plastic (energy absorbing) they are. Therefore, the magnitude of those peak values, have a little relation to the peak ground accelerations. The structure as a whole or its members at the instant of impact, and for some time after that, continue to keep their kinematic status, either being at rest position, or at the downwards motion.

The impact at the base of the structure is due to the difference of the characteristics, as far as vertical waves are concerned, between structure and ground. It is logic to assume that this difference is minimized in earthen structures, of large horizontal cross sections. Based on this logic, structures with masonry walls must be less vulnerable than structures with columns (masonry or concrete).

Representative examples of the impact, case b) of Fig. 20, are given in Figs 25a and b and Figs 26a, b and c.

An other example is given in Fig. 27 in which the dome collapsed vertically within its plan. This type of damage is a trademark of the presence of a strong vertical earthquake component.

4.5. *Behavior of "Short Columns" under the action of the vertical component*

As a practical example of the structural behaviour described in Fig. 20, case e), hereafter the behaviour of a "short column" (shown in Fig. 28) under vertical acceleration component is presented and discussed.

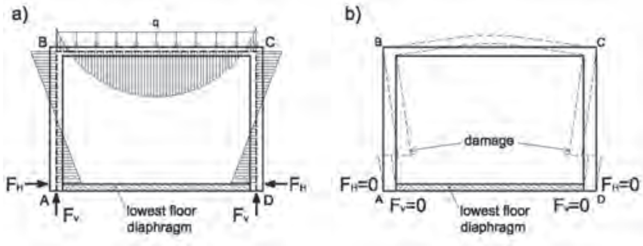

Fig. 23. *During the downwards motion phase, the structure, designed to carry mainly gravitational loads, is suddenly in a space condition without gravity; a) the case with gravity; b) the existing frame is without gravity.*
Durante la fase di moto verso il basso, la struttura, progettata per sostenere principalmente carichi verticali di tipo gravitazionale, si trova improvvisamente in una condizione in assenza di gravità; a) situazione con gravità b) struttura in assenza di gravità.

In the most cases (always under the assumption of epicentral regions of shallow focus earthquakes) in spite of the fact that there are neither notable horizontal motions nor window glass panels broken, considerable damage of load bearing members ("short columns") is observed. In this case one has to notice that in the most of the related cases, the braking plane is perpendicular to the main plane of the wall while there is not any noticeable vertical residual displacement.

The force F might be calculated according to the formula:

$$F = \int_0^{\ell} p \times b \times dx \qquad (1)$$

where:

p is the pressure (kN/m^2) due to vertically propagated body waves,

b is the width of the wall and

ℓ is the influence length of the wall

In order to investigate the reason why the window glass panels are not broken, let us assume the following scenario: A vertical shortening of the opening $\Delta h = 3$cm, height of opening h = 0.4 up to 1.0m. The resulting unit compressional strain $\varepsilon_z = 3/(40 \div 100) = 75\%$ up to 30%. This is bringing the steel, concrete and masonry materials in the state of fracture. On the other hand a window is composed from the glass panel and the surrounding frame and there is a gap between them. Into this gap it is certainly possible to be absorbed a shortening of 1.5cm at each side.

An illustrated example of this case is presented in Figs 29a, b and c, after the Parnitha, Athens, 1999 earthquake in which the vertical earthquake component of the order of 1.0 g was dominating in the epicentral region.

Relation (1) could also be applied in order to estimate the additional forces that are acting due to the combined vertical ground waves on columns founded on a raft foundation, in the form of:

$$\int_0^{\ell_x} \int_0^{\ell_y} p \times dx \times dy \qquad (2)$$

where:

ℓ_x and ℓ_y are the distances among the columns along X and Y directions respectively.

Fig. 24. *During the L'Aquila, 2009 earthquake all perimetric columns at the base of the structure were displaced outwards, the building sat down almost vertically, while most of the glass panels remained unbroken, and almost no other damage was optically observed from the outside.*
Durante il terremoto de L'Aquila nel 2009, tutte le colonne perimetrali alla base della struttura sono state spinte verso l'esterno e l'edificio ha ceduto praticamente in verticale, la maggior parte dei vetri delle finestre sono rimasti intatti, e dall'esterno, non era osservabile quasi nessun altro danno.

Fig. 25. *a) A reinforced concrete structure, in Sant' Agostino ceramic factory, the only recorded damage was around the base of almost all its internal columns; b) There is no shortening of the column at the point of impact. Apparently the damage was caused by tension. Due to this tension the intensity of the impact is augmented, because of the stored energy in the reinforcement.*
a) Struttura in c.a. nello stabilimento delle Ceramiche Sant'Agostino, l'unico danno osservato è alla base di quasi tutte le colonne interne; b) Non si osserva accorciamento delle colonne nella zona di impatto. Apparentemente il danno è stato causato da sollecitazioni di trazione, che hanno aumentato l'intensità dell'impatto per via dell'energia assorbita dalle armature.

Fig. 26. *The Mirandola Town hall; a) no major damage is noted by a rapid optical survey from the exterior, except the damage shown in b) and c) at the bottom of the masonry columns due to impact.*
Il Municipio di Mirandola; a) da un rapido esame visivo dall'esterno non si notano gravi danni, ad esclusione di quelli mostrati in b) e c) alla base delle colonne in muratura, in seguito a impatto.

4.6. *Behaviour of floors and roofs*

Besides the impact effect of the vertical earthquake component, a very important and additional dynamic vibrational excitation of floors and roofs is also involved.

By applying the formula:

$$\omega = \left(\frac{\pi}{\ell}\right)^2 \times \sqrt{\frac{\mathrm{E} \times J}{m}} \qquad (3)$$

where:

ℓ is the opening of a beam or truss

E is the modulus of elasticity of the material

J is the moment of inertia of a beam or truss and

m is the participating to the vibration mass normalized to unit beam or truss length

and for the dimensions of either the prefabricated r/c roof beams of representative industrial buildings, or

Fig. 27. *Vertical collapse within the plan of the ground floor of the dome of Duomo church in L'Aquila, after the 2009 earthquake. There is not any other noticeable damage. Glass window panels are intact.*
Collasso verticale all'interno del perimetro della cupola del Duomo de L'Aquila, in seguito al terremoto del 2009. Non si notano altri danni. Le vetrate sono intatte.

the wooden trusses of churches, we found that their natural periods are of the order of 0.06 up to 0.10 sec (10 up to 17 Hz). We know that the dominating periods of vertical component strong pulses coincide with this range of periods. This coincidence, in combination with the very high exciting accelerations and the inherent low structural damping, may help us to understand the reason of the majority of damaged roofs either to industrial facilities or to churches and houses.

Actually, the vertical dynamic response of roofing systems in the epicentral regions of the earthquake sequence under consideration, might be extremely intense. With an estimated excitation of their supports of the order of 1.0 g the response accelerations might reach 3.0 to 4.0 g. This means that the whole roofing structure "flies" in space. But even with only the 0.3 g vertical acceleration recorded at Mirandola the effective accelerations of the roofs are of the order of 1.0 g, which is still very high. Trusses and various roofing systems, floors and beams the periods of which, along the vertical axis, correspond to acceleration response spectral values higher than 1.0 g may become extremely critical and may cause various damages in the whole structure. Additionally, the horizontal motion, a strong part of which is acting simultaneously with the vertical component, has already displaced the supports. The results of this combination proved dramatic, causing the collapse of many structures.

Due to the vertical vibration of the floors or roofs, the ends of the beams at their supports function as levers, as it is schematically shown in Fig. 30a. The excitation is introduced from their supports, and is in full phase with the vibration of the beam or truss. The flexibility of timber floors or trusses produces a considerable rotational angle (ϕ), see Fig. 30a.

This fact explains the causes of horizontal cracks observed in many buildings (e.g. in L'Aquila after the 2009 earthquake as shown in Figs 30b and c), at the lower floor levels, eventually at the interface between r/c beams and masonry infills. A probable explanation is based on: a) the dynamic difference between a r/c beam (and as we can see of a considerable length) and a brick wall and b) the impact phenomenon on this type of structures, seems to be stronger at their lower floors. At the building of Fig. 30c, the damaged façade

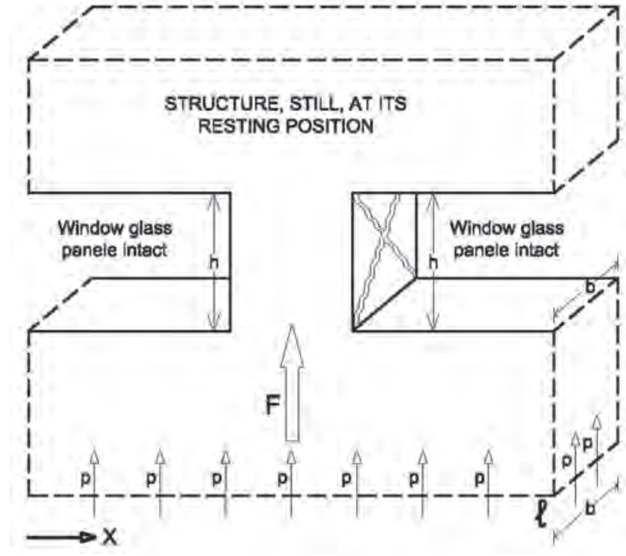

Fig. 28. *A part of a wall with a "short column". The pressure p (kPa) due to vertically propagated body waves, integrated along the length (l) produces a force F of an impact character. The residual shortening of height (h) is relatively extremely small.*
Una porzione di muro con una "colonna tozza". La pressione p (kPa) dovuta alla propagazione verticale delle onde di volume, per tutta la lunghezza (l), produce una forza F a carattere impulsivo. L'accorciamento residuo sull'altezza (h) è relativamente molto piccolo.

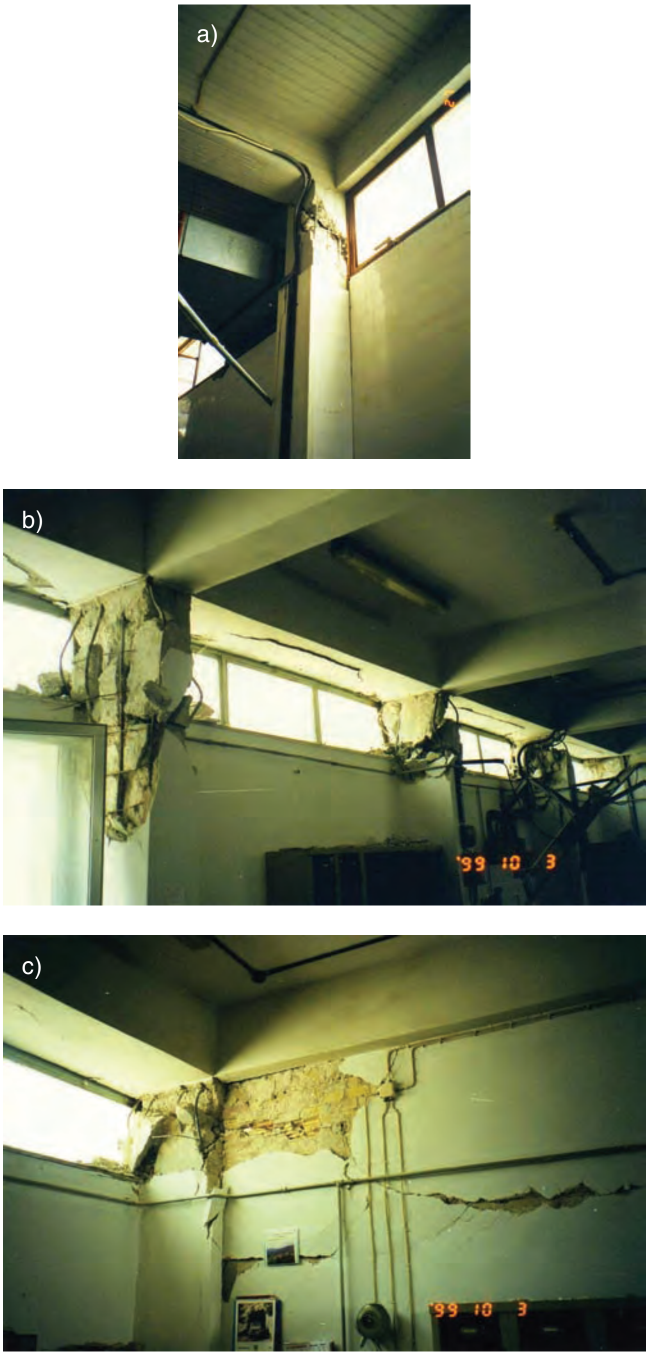

Fig. 29. *"Short column", under a vertically propagated body wave action. The braking plane is perpendicular to the plane of the concrete wall and the respective beam. The adjacent window glass panel is unbroken. Not any significant residual vertical shortening is noticed. In c) the presence of a masonry wall perpendicular to the plane of the concrete wall did not prevent the break of the "short column".*
Una "colonna tozza" sotto l'azione di onde di volume in direzione verticale. Il piano di rottura è perpendicolare al piano del muro in c.a. ed alla relativa trave. Il vetro della finestra adiacente è intatto. Non si osserva alcun significativo accorciamento residuo in direzione verticale. In c) la presenza di un muro in mattoni ortogonale al piano della parete in c.a. non ha evitato la rottura della "colonna tozza".

is supported on a short cantilever that, in general, is augmenting the damaging effects.

The simple support of beams as it is shown in Figs 31a, b and c, is not allowed by modern earthquake codes. Nevertheless, in most cases the existing anchoring devices are not adequate and/or strong enough in order to undertake the vertical and horizontal actions.

The devices at the supports must be constructed so that no up-down jumping movement of the beam or truss is allowed and to limit the differential horizontal displacements.

The lack of those provisions in the supports might be the basic reason for the numerous damages and collapses of industrial buildings' roofs made with prefabricated beams as it is shown in Figs. 32a to f. On the other hand, if any kind of beam to column joint was provided the response of the vertical element would be ameliorated. After that, we may conclude that structures, as the prefabricated ones, that are going to be applied in great numbers, must be designed for a higher degree of importance, than the one presently considered in Seismic Design Codes.

4.7. *Behaviour of churches and other masonry structures*

The incurred damage on churches in its main lines follows an almost identical pattern of failure mode: in most cases the western part of the church is damaged, and especially the respective roofing system collapsed. A representative selection of damaged churches is shown in Fig. 33a to h. In most cases, the western façade consists in a rather tall wall, that could be considered as a free standing vertical cantilever. This wall lost, in general, its upper part always above a window or skylight opening. We know very well that the damage and debris show the epicenter. Since the said damaged churches are all over the region, the damage can not be attributed only and basically to any or both of the

Fig. 30. *a) Additional vibrational effects on floors and roofs from the vertical earthquake component. Usually in most cases, the walls above the floor or roof level are toppling inside the building. This means that the fall is due to upwards motion of the supports (perimetric walls); b) and c) Damages observed in Pettino (L'Aquila) after the 2009 Earthquake*
a) Effetti delle vibrazioni sui solai e le coperture, a causa della componente verticale del sisma. Nella maggior parte dei casi, i muri al di sopra del livello del solaio o del tetto ricadono all'interno del perimetro dell'edificio. Ciò significa che la caduta è dovuta al moto verso l'alto degli appoggi (muri perimetrali); b) e c) danni osservati a Pettino (L'Aquila) dopo il terremoto del 2009.

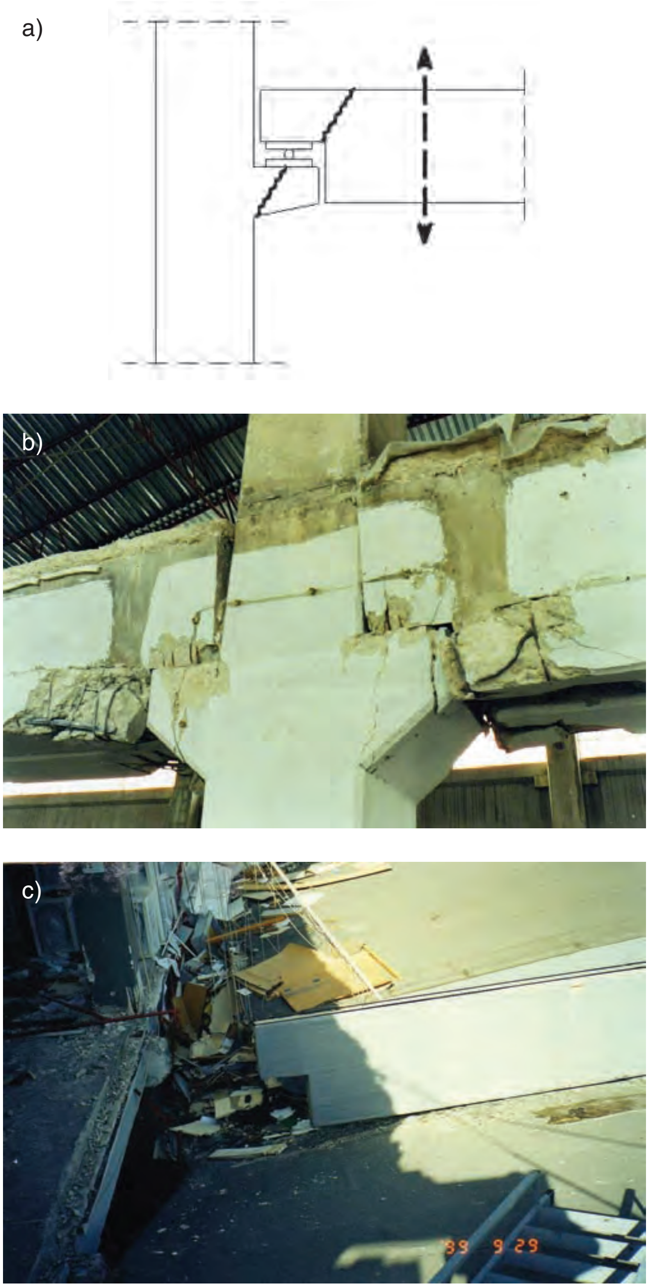

Fig. 31. *a) Due to the vertical seismic component, the beam is jumping up an down on its supports if it is not sufficiently anchored; b) the corber or the beam, or both are broken. In this case a vertical bolt is provided but it was too short and the beam jumped over; c) if there is a horizontal motion too, the results are worsened.*
a) A causa della componente verticale del sisma, la trave "salta" su e giù sugli appoggi se non è adeguatamente ancorata; b) la mensola d'appoggio o la trave, o entrambi, risultano danneggiate. In questo caso, era stato previsto uno spinotto verticale metallico di collegamento troppo corto, e la trave si è sfilata; c) i risultati sono ancor più gravi [catastrofici] nel caso si sovrapponga una componente di moto orizzontale

horizontal seismic components. On the other hand the damage is limited mainly at the top of the wall. Therefore we could argue that the damage is mainly due to the vertical vibration of the roofing system as it has been already exposed. Equal damage could occur also at the eastern part of the church if it was of the same construction type of the western one. The eastern part,

Fig. 32 a to f *Simply supported prefabricated beams for the roofing systems and without any reliable anchoring were subjected to a combination of a very strong-impact-type-vertical component with a strong horizontal one. Those images of destruction are typical around the epicentral region.*
Travi di copertura prefabbricate in semplice appoggio, prive di collegamenti affidabili, soggette alla combinazione di una forte componente sismica verticale e di una forte componente sismica orizzontale. Immagini di danni di questo tipo sono caratteristiche delle zone epicentrali del terremoto.

above the crypte is usually a masonry half-dome, which is stiffer and stronger that the western façade.

A typical response of the bell towers is shown in Figs. 33b, e and h, in which the top of the spire was damaged. Some minor damage is observed on the rest of the body of the bell tower along the height and mainly around openings, mass or stiffness discontinuities. The reason of the damage to the bell towers is presented in Fig. 20.

In masonry structures at epicentral regions of shallow focus earthquakes, we seldom observe the usual diagonal cracks that are developed under horizontal seismic

Fig. 33. *The incurred damage of churches follows almost an identical pattern. The bell towers survived with only minor damage along the height. In most cases the top of the spire was damaged; a), b) church of San Marino at Buonacompra; c,) d) church of San Francesco at Mirandola, very heavy damage. The bell tower collapsed after the second event; e) Santa Maria Maggiore, Cathedral of Mirandola; f) a view from the north towards S-E; g), h), two damaged churches in Mirandola.*

La tipologia del danno subito dalle chiese è ricorrente. I campanili hanno resistito con danni limitati lungo il loro sviluppo verticale. Nella maggior parte dei casi ha subito danni la parte superiore della guglia. a), b) la chiesa di San Marino a Buonacompra; c), d) la chiesa di San Francesco a Mirandola con danni molto gravi. Il campanile è crollato dopo la seconda scossa; e) Santa Maria Maggiore, Cattedrale di Mirandola; f) una vista da nord, verso S-E; g), h) altre due chiese danneggiate a Mirandola.

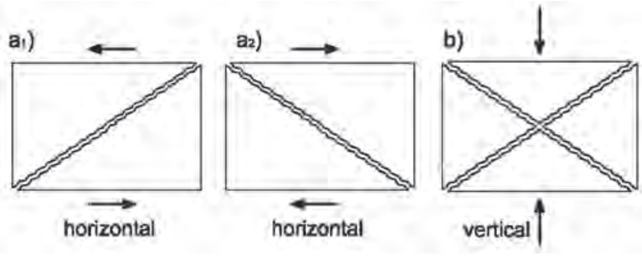

Fig. 34. *It is difficult to distinguish the damage pattern between the effects of: a1) + a2) horizontal and b) strong vertical earthquake components, after /4/.*
È difficile distinguere il meccanismo di danno causato: a1) + a2) dalla componente orizzontale del terremoto, b) dalla forte componente verticale; tratto da /4/.

motions /4/. On the other hand, it is quite difficult to distinguish the effects of alternative sign horizontal and strong vertical earthquake actions, as it is schematically shown in Figs. 34 a_1, a_2 and b.

In macroscopic field observations – in order to decide about the dominance and intensity of the vertical earthquake component – one has to examine some other parameters too, since identical damage patterns are also resulting from the overturning response of structures. The latter one is due to horizontal motion components.

An ideal damage is symmetrical around the vertical axis as it is shown in Figs. 35a and b after the Dinar, Turkey, 1995 earthquake /14/.

The symmetrical detachment of the top four corners edges is the trademark of the dominance of the vertical component and, as a consequence, of the macroseismic epicentral region.

In Figs. 36a to f a representative set of damaged and undamaged masonry structures, each one deserving a special and in depth study, is presented. For example, case b) shows a set of adjacent buildings that were almost not moved, since the joint between them and the window glass panels are intact. Also, absolutely intact are the cases d) and e). In case e) a lot of modifications have been carried out as it is externally observed.

4.8. *Behaviour of racking systems*

Massive economic losses as well as human casualties occurred due to collapse of racking systems in factories. In most cases, racks designed for seismic loading resisted well to the earthquake. Only in few cases, presently under investigation, seismically designed racking structures collapsed. Most non-seismically designed structures, as well as structures not fixed to the ground (as often occurred in warehouse racks supporting Parmesan Cheese for aging), overturned and totally collapsed, generally with a domino effect, with consequent loss of goods.

In several cases rack structures were hosted in r/c prefabricated buildings. In some of them, the building collapsed and the rack survived, while in some other cases the building survived and the rack system collapsed. Frequently, both the rack and the building collapsed, which one of them was collapsing first inducing collapse of the other has still to be investigated.

With the advance of the computerized storage of industrial products, the use of racking systems becomes more popular. Therefore, there is a great and urgent need for compiling Seismic Design Standard Recommendations for racking systems that are presently missing at a European level in general.

4.9. *Effects of ground conditions and ground motion records*

The vertical earthquake component is quite sensitive to various ground and bed rock conditions due to its high frequency content and many other parameters. And even more, this has an outstanding importance due to its high qualitative non linearity. Actually, this motion may affect the structure and/or its parts by two differ-

Figs. 35 a, b *The damage to symmetrical masonry structures are symmetrical around the vertical vector. The well known diagonal cracks are not developed. The horizontal cracks at roof and first storey levels are due to vertical vibration of the roof and floor respectively. Typical is the detachment of all four top corners around the building. Dinar, Turkey, 1995 earthquake, /14/.*
Il danno subito dalle strutture in muratura simmetriche, è simmetrico rispetto all'asse verticale. Non si sviluppano le tipiche lesioni diagonali. Le lesioni orizzontali a livello della copertura e del primo piano sono causate dalle vibrazioni in direzione verticale rispettivamente della copertura e del solaio. È tipico il crollo dei quattro angoli superiori dell'edificio. Immagini scattate a Dinar, Turchia, dopo il terremoto del 1995 /4/.

Fig. 36. *A selection of representative damage incurred in masonry buildings as well as undamaged buildings. Each one of those deserves a special in depth investigation.*
Danni rappresentativi ad edifici in muratura, ed edifici non danneggiati. Ciascun singolo caso meriterebbe uno studio approfondito.

ent ways: one is the impact type and the other is pure dynamic type. In the first we examine wave propagation in a rigid body, while in the second we examine the dynamic vertical response. In both cases the barrier of 1.0 g is crucial for the input motion and the response respectively. If we are under this barrier, things are, more or less, in a rather manageable way, the results can be rather easily calculated, and the various structural members dimensioned. In general, the effects are of minor importance. On the contrary, if the vertical ground acceleration or the dynamic response exceed the barrier of 1.0 g the effects are extremely difficult to be analysed, due to the facts that have been already mentioned. On the other hand the horizontal ground

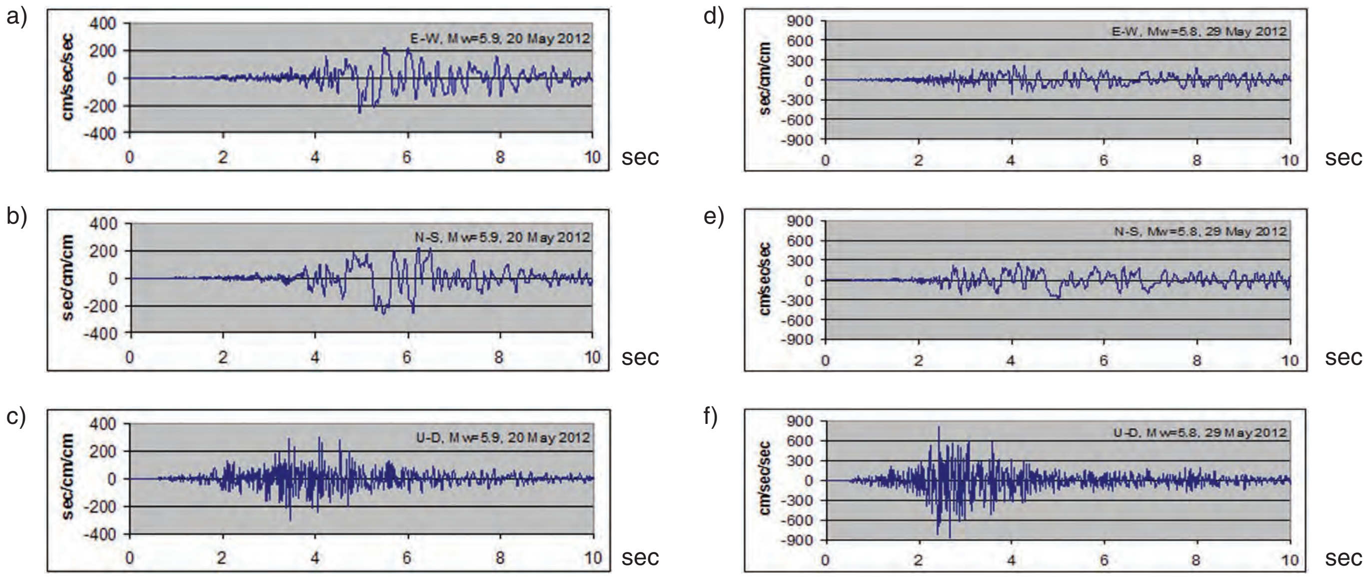

Fig. 37. *Strong phase of the acceleration time histories recorded at Mirandola station; a), b) and c) for the first event, epicentral distance 14 km; d), e) and f) for the second event, epicentral distance 2.0 km, /17/, /18/, /19/, /24/ and links. The starting of time is arbitrary.*
Fase significativa dell'accelerogramma registrato alla stazione di Mirandola; a), b) e c) per il primo evento, con distanza dall'epicentro di 14 km; d) e) ed f) per il secondo evento, con distanza dall'epicentro di 2.0 km, da /17/, /18/, /19/, /24/ e links vari. L'origine, sull'asse temporale, è arbitraria.

motion is less sensitive and there is not the aforementioned barrier of 1.0 g.

Another characteristic of the affected region is its high underground water table level. Due to the high incompressibility of the water and its very low damping in the propagation of P waves, their damaging (i.e. potential of the vertical earthquake component) on structures is augmented, /12/, /13/.

The shock spectra (displacement of impact motions) are rather flat, while their acceleration time histories possess a quite short predominant period of less than 0.1 sec (more than 10 Hz). This is depicted in the acceleration response spectrum of the first event, /17/, /24/ which shows peak values at periods around 0.06 to 0.07 sec. Also, it is logical to mention that, in water saturated regions, the dynamic characteristics of the vertical time histories are almost the same, independently from the intensity.

The best device in order to confront the vertical earthquake component with the characteristics already presented, is the provision of a kind of seismic isolators at the base of the building, or of the roofing system for monumental buildings. In any case, the response of those devices, for reasons already mentioned, must not depend and/or rely on friction.

After having integrated the present communication, the acceleration time history of the vertical component of the second main event of 29^{th} May 2012 was released /17/, /18/ and /24/. The available set of records for the two main events are show in Fig. 37, while the respective response spectra for $\zeta = 5\%$ are shown in Fig. 38. The peak value is around 0.9 g, while its acceleration response spectrum has a peak value of 3.2 g at around 0.065 sec period. Those extremely interesting new data comes in full agreement with our findings and arguments exposed in the present communication. This record is really extremely important since it will be a reference for researchers designers and code makers. Based on this record together with the horizontal ones, incurred damages in structures in the past and the future will be more easily documented. And this is mainly because it is quite improbable to dispose such a record very close to the epicenter.

Comparing the time lag of the starting of the strong phase between horizontal and vertical ground motions, we can estimate that for the first event is about 2.0 sec while for the second one is about 0.5 to 0.7 sec. Therefore the coincidence in time of the three component is much more pronounced for the second event than for the first one. Also, comparing Figs. 37c and f) and Figs 38c and f) we could conclude that the characteristics of the vertical wave forms are almost independent of the epicentral distance and intensity of the motion (based on the filters and damping used).

5. Conclusions

– The incurred damage from the recent Emilia-Romagna earthquake sequence is higher than could be anticipated for such earthquakes of small to medium size (M_w 5.0 to 6.0). This might be attributed, primarily, to the vicinity of shallow focus earthquakes to the built environment and the adversely overlapped areas affected by the main event and its aftershocks, in combination with the increased vulnerability of the exposed structures to such type of seismic ground motions.

– Small to medium size shallow focus earthquakes may occur everywhere, also in non seismic regions in Europe, close or under villages, cities and industrial agglomerates due to the density and quite uniform distribution of population.

– The seismic risk assessment based only on the historical series, sometimes can be inadequate to provide the necessary safety factors for buildings having a high importance factor, such as historical heritage

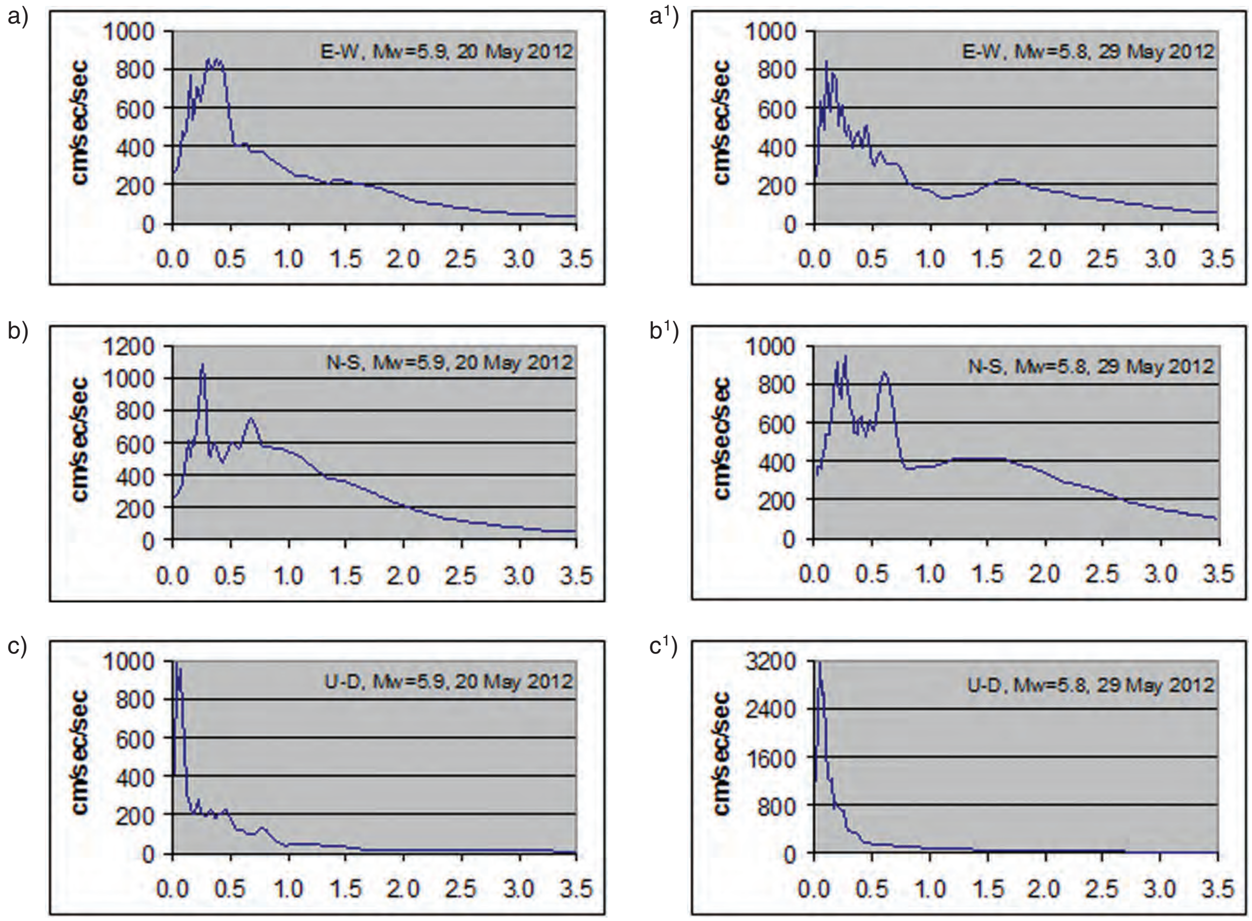

Fig. 38. *Acceleration response spectra for the records presented in Fig. 37 and for ζ = 5%, a), b) and c) for the first event and a'), b') and c') for the second event, after /17/, /18/, /19, /24/ and links.*
Spettri di risposta in termini di accelerazione per gli eventi presentati in Fig. 37 per ζ = 5%, a), b) e c) per il primo evento e a'), b') e c') per il secondo evento, da /17/, /18/, /19, /24/ e links vari.

and/or buildings hosting high-tech production activities, when they are widely diffused all over the territory as in case of the Po Plain Region, which is one of the most important industrial district in Europe.

– The historical series shows that events with high intensity can occur in the Po Plain, involving large portions of the Region, as for example, Brescia 1222; Ferrara 1570-1571; Emilia Romagna 2012.

– In the Po Plain area, there are seismogenic sources that can generate strong seismic events, the aftershocks series of which display long seismic periods with relatively large magnitude aftershock events compared to the main shock.

– Spatial distribution and categories of secondary phenomena observed within the meizoseismal area, suggest that the local geological conditions have played a very important role on the grade of damage observed, as a greater depth of liquefiable material results to greater absorption of seismic energy, functioning as a kind of seismic isolation system for structures. Nevertheless, fences, pavements and other light weight structures have been severely damaged and dislodged, following the ground deformations, while building structures were almost not damaged. A probable explanation of this difference may lay on the overburden additional vertical pressures provided by the weight of the building in combination with its strength and stiffness, besides the fact that the level of building foundation is places in deeper and stronger soil layers.

– The vertical earthquake component is quite sensitive to various ground conditions and is more quickly attenuated with distance, compared to the horizontal one.

– Increased importance factors for the design of prefabricated structures should be used, since those structures may be applied in large numbers.

– Special provisions should be carried out for more adequate beam to column connections in prefabricated buildings.

– The extended damage of racking systems stresses the urgent need of Seismic Design Standard Recommendations that are presently missing at a National Italian, Greek and European Level.

– Each one case of collapsed or heavily damaged churches, industrial buildings, structures hosting rack systems and other cases presenting a technical interest must be in detail investigated in order to document the mode and mechanism of the various parts composing the whole. Also, it should be extremely useful if certain analytical investigations would be carried out in structures or part of structures that did no suffer any damage although they should, according to a common earthquake engineering practice.

– It was given the impression and especially for industrial facilities that the most frequent mode of the response to the earthquake was either collapse and/or very heavy damage or almost no damage. If this is reflecting the reality it could be concluded that all those structures presented a brittle earthquake response.

– The maximum intensity of shallow focus earthquakes is almost independent of their magnitude. The only difference lays on the size of the affected area.

– The said vertical component may affect the structures and their structural members by two different and almost simultaneous mechanisms. One is the impact type mechanism and the other is the vibrational type. The first one affects rigid bodies extended vertically like walls, columns, towers including their discontinuities. The second one affects horizontally laying structures like roofs, floors, beams, cantilevers and trusses, by exciting them vertically.

– As far as the impact effect of the earthquake vertical component is concerned, it is extremely non linear above the barrier of 1.0 g ground acceleration. As far as its vibrational effect is concerned those structures (slabs, roof, trusses, beams), whose period along the vertical axis corresponds to acceleration spectral values higher than 1.0 g, become critical, for the stability of the whole structure.

– One of the major effects of the vertical component is the annulment of friction mechanisms that depend on gravitational forces. Those forces are vanished during some phases of the ground motion along the vertical direction. Due to this fact among others, the response of seismically isolated buildings may be adversely affected if the function of the isolating devices depends on friction.

– The incurred destruction of the most of the churches of XVI-XVII century might be attributed, mainly, to resonance of the trusses along the vertical direction due to the vertical earthquake component in combination with the horizontal displacement of their supports due to the horizontal seismic motion. The connection between roof and walls is usually made by a simple support without any special anchoring.

– The incurred destruction of most of the rather modern industrial facilities started from the dislocation and collapse of their prefabricated roofing system with a mechanism similar to that of churches' roofs. Even more, by using the conventional bolts in their supports on the top of the columns it is not certain that the results would be ameliorated.

– If the main event would occur few hours later, when the Holy Communion was taking place, the human casualties could be much higher. This potential loss is a new term as "potential human casualties" that must be always taken under consideration when estimating the effects of an earthquake. For the case under consideration, based on a plausible estimation we carried out, the death toll would reach 3,000 and the injuries 8,500.

– The housing had generally a good behavior, with minor damage, even if not expressly designed for seismic resistance. A great influence on their resistance can be attributed to their regular geometry, box type houses with good brick masonry walls, two or three storey high, vertically stiff floors and roofing system.

– Most part of the collapsed agricultural buildings, were old poor masonry buildings, with poor mortar, weak connections between the walls at the corners, and quite small or null global connection from the wooden beam floors, with no maintenance, sometimes uninhabited. Generally, with quite simple and superficial foundations, in any case on adverse soil conditions.

– In order to anticipate the impact and high frequency effects of the vertical earthquake component a kind of base isolation devices, that should not depend on friction at the base of structures or long beams and trusses might be used.

– Based on engineering judgment of the incurred damage it was concluded that the vertical earthquake component was of the order of 1.0 g, producing impact type phenomena on structures and structural members. Due to this excitation the structures, or structural members, either immediately collapsed or were jumping up and down. Before finishing this response (the time lag depends on the epicentral distance and for the present case no more that 2.0 sec) the strong phase of the horizontal motions emerged, thus integrating the destruction. The findings and arguments exposed, are in full agreement with those released from the respective authorities: the strong motion record of the $M_w = 5.8$ of 29th May 2012 aftershock, with a peak ground acceleration of the order of 0.9 g and maximum acceleration spectral value of the order of 3.2 g (with 5% critical damping ratio). We hope that this record, together with the relevant structural effects, will be the base for the revolution in European Earthquake Engineering by introducing the characteristics of the vertical earthquake component into the design for a further and rational earthquake protection of structures. Now, the European Earthquake Engineering Society besides the abundant evidence of the catalytic effect of the vertical earthquake component for the incurred destruction (for example Parnitha, Athens 1999; L'Aquila 2009, Emilia Romagna 2012), possesses the respective record that is an undisputable proof.

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References

/1/ Atzori S., Boncori M., Pezzo G., Tolomei C. and Salvi S., 2012. Secondo report analisi dati SAR e modellazione della sorgente del terremoto dell'Emilia. SiGRiS – ASI INGV Report, 8 June, www.sigris.it (Accessed online June 2012).

/2/ Basili R., Valensise G., Vannoli P., Burrato P., Fracassi U., Mariano S., Tiberti M.M. and Boschi E.,

2008. The Database of Individual Seismogenic Sources (DISS), version 3: summarizing 20 years of research on Italy's earthquake geology, Tectonophysics, doi:10.1016/j.tecto.2007.04.014.

/3/ Battaglia M., Murray H., Serpelloni E. and Burgmann R., 2004. The Adriatic region: an independent microplate within the Africa-Eurasia collision zone. Geophys. Res. Lett. 31, l09605, doi:10.1029/2004GL019723.

/4/ Benedetti D., and Carydis P., 1999. Influence of the Vertical Component on damage during shallow-near field earthquakes. *European Earthquake Engineering*, **3**, 3-12.

/5/ Berlusconi A., Livio F., Ferrario F., Gambillara R. and Michetti A., 2012. Earthquake environmental effects accompanying the May 20, 2012, Finale Emilia earthquake; preliminary report., First report, 29-05. The University of Umbria, May 2012.http://www.nug.rwth-aachen.de/media/Uni_Insubria_preliminary_notes_on_ the _20_05_2012_M5.pdf (Accessed online May 2012).

/6/ Boccaletti M., Bonini M., Corti G., Gasperini P., Martelli L., Piccardi L., Severi P. and Vannucci G., 2004. Carta Sismotettonica Della Regione Emilia-Romagna, Scala 1:250 000, Note Illustrative. Servizio Geologico Sismico e Dei Suoli, Firenze.

/7/ Boccaletti M., Coli M., Eva C., Ferrari G., Giglia G., Lazzaretto A., Merlanti F., Nicolich R., Papani G. and Postpischl D., 1985. Considerations on the seismotectonics of the Northern Apennines. *Tectonophysics*, **117**: 7-38.

/8/ Boccaletti M., Corti G. and Martelli L., 2011. Recent and active tectonics of the external zone of the Northern Apennines (Italy), *International Journal of Earth Sciences*, **100**, 1331-1348, doi: 10.1007/s00531-010-0545-y.

/9/ Carydis P., 2011. A sustainable seismic input reduction system for monuments, for existing and new structures by creating large, stiff and strong foundations-practical applications. XXVIII, **2**, 7-24.

/10/ Carydis P., 2004. The effect of the vertical earthquake motion in near field. 8th International Conference on Structures Under Shock and Impact, SUSI VIII, N. Jones & C.A.Brebbia (Editors), WIT Press, 267-282.

/11/ Carydis P., 2002. The vertical seismic component "The Colombus' egg in earthquake enginnering", 12th European Conference on Earthquake Engineering, 9-13 September, London, Elsevier Science Ltd, paper No. 868.

/12/ Carydis P. and Lekkas E., 2011. The Haiti Earthquake Mw = 7.0 of January 12th 2010: structural and geotechnical engineering field observations, near-field ground motion estimation and interpretation of the damage to buildings and infrastructure in the Port-au-Prince area. XXVIII, **3**, 24-42.

/13/ Carydis P., Lekkas E., Papaioannou C., Tsokos A. and Delakouridis J., 2012. The October 23 (M_w = 7.2) and November 9 (M_w = 5.7), 2011 Van, Turkey earthquakes. A geoscientific and engineering report. XXIX, **1**, 13-36.

/14/ Carydis P., Lekkas E., Ersoy U., Uzumeri S.M., Ozcebe G., Polat U., Tankut T. and Erdik M., 1995. The Dinar, Turkey, Earthquake of October 1, 1995, Learning from Earthquakes, EERI Newsletter, Special Earthquake Report, November, 29, **11**, 1-8, California.

/15/ Cerrina Feroni A., Martelli L., Martinelli P. and Ottria G., 2002. Carta geologico-strutturale dell'Apennino emiliano-romagnolo in scala 1:250.000. Regione Emilia-Romagna-C.N.R., Pisa. S.EL.CA, Firenze.

/16/ DISS Working Group, 2010. Database of Individual Seismogenic Sources (DISS), Version 3.1.1: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas. http://diss.rm.ingv.it/diss/, INGV 2010 – Istituto Nazionale di Geofisica e Vulcanologia – All rights reserved.

/17/ Dolce M., Nicoletti M., Ammirati A., Bienconi R., Filippi L., Govini A., Marcucci S., Palma F., Zambonelli E., Lavecchia G., de Nardis R., Brozzetti F., Boncio P., Dirillo D., Romano A., Cocta G., Gallo A., Tiberi L., Zoppá G., Suhadolc P., Ponziani F. and Formica A., 2012. The Emilia thrust earthquake of 20 May (Northern Italy): strong motion and geological observations-Report 1. National Civil Protection Department (DPC): RAN Staff, Geosis-Lab UniChieti, University of Trieste, Regione Umbria-Regional Civil Protection, pp. 12. http://nsmp.wr.usgs.gov/publications/Report_DPC_1_Emilia_EQSc.pdf.

/18/ Dolce M., Nicoletti M., Ammirati A., Bienconi R., Filippi L., Govini A., Marcucci S., Palma F., Zambonelli E., Lavecchia G., de Nardis R., Brozzetti F., Boncio P., Dirillo D., Romano A., Cocta G., Gallo A., Tiberi L., Zoppá G., Suhadolc P., Ponziani F. and Formica A., 2012. The Ferrara arc thrust earthquakes of May-June 2012 (Northern Italy): strong motion and geological observations-Report II. National Civil Protection Department (DPC): RAN Staff, Geosis-Lab UniChieti, University of Trieste, Regione Umbria-Regional Civil Protection, pp. 12. http://nsmp.wr.usgs.gov/publications/Report_DPC_2_Ferrara_EQSBis.pdf.

/19/ EMSC European Mediterranean Seismological Centre M 6.1 and M 5.8 NORTHERN ITALY on May 20th and 29th 2012 earthquake sequence summary, 2012. http://www.emsc-csem.org/Earthquake/209/M-6-1-and-M-5-8-NORTHERN-ITALY-on-May-20th-and-29th-2012 (Accessed online May-une 2012).

/20/ Guidoboni E., Ferrari G., Mariotti D., Comastri A., Tarabusi G. and Valensise G. 2007. Catalogue of Strong Earthquakes in Italy from 461 BC. to 1997 and in the Mediterranean area, from 760 BC. to 1500, An Advanced Laboratory of Historical Seismology, http://storing.ingv.it/cfti4med/.

/21/ INGV Insituto Nazionale di Geofisica e Vulcanologia, Centro Nazionale Terremoti, Lista Terremoti e Aggiornamento di Terremoti in Pianura Padana Emiliana, 2012. http://www.ingv.it/primo-piano/comunicazione/2012/05200508/ (Accessed online May-June 2012).

/22/ Malinverno A. and Ryan W.B.F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as a result of arc migration driven by sinking of the lithosphere. Tectonics, **5**: 227-245.
/23/ Pieri M. and Groppi G., 1981. Subsurface geological structure of the Po Plain Italy, Progetto Finalizzato Geodinamica, C.N.R., Pubbl. **414**, pp. 13.
/24/ Protezione Civile Italiana, 2012. http://www.protezionecivile.gov.it/ (Accessed online May-June 2012).
/25/ RER and ENI-Agip (1998) Riserve idriche sotterranee della Regione Emilia-Rom.
/26/ Stein S. and Sella G.F., 2005. Pleistocene change from convergence to extension in the Apennines as a consequence of Adria microplate motion – The Adria Microplate. GPS Geodesy, Tectonics, and Hazards, NATO ARW Series, vol. 61, Kluwer Academic Publishers, 21-33.
/27/ Wang J.G.Z.O. and Law K.T., 1991. Sitting in Earthquake zones, A.A. Balkena publishers, pp. 120.

RIASSUNTO ESTESO

La sequenza sismica del maggio 2012 in Emilia-Romagna. Influenza della componente verticale del moto sismico: aspetti sismologici e ingegneristici correlati

P. Carydis, C. Castiglioni, E. Lekkas, I. Kostaki, N. Lebesis, A. Drei

Gli eventi sismici del 20-9 maggio 2012 in Emilia Romagna, si sono verificati nella pianura Padana, in un bacino tettonico orientato NW-SE al confine meridionale della piastra tettonica Adriatica, rispetto a quella degli Appennini settentrionali.

I meccanismi focali degli eventi principali della sequenza sismica indicano l'attivazione di strutture a basso angolo di spinta, con l'attività sismica separata in almeno 2 distinti piani di faglia, ma con caratteristiche simili di scorrimento. Interpretando la delimitazione dell'attività sismica del maggio-giugno 2012, entrambe le superfici di faglia sembrano appartenere alla stessa sorgente sismogenetica, collocandosi sulla parte occidentale della sorgente degli eventi sismici del 1570.

Gli effetti secondari della sequenza sismica più diffusamente osservati sono stati classificati in relazione alla loro distribuzione spaziale, andamento e densità in i) i singoli casi di liquefazione, ii) liquefazioni chiaramente orientate con diffusione laterale a causa di variazioni locali nel sottosuolo soggetto a liquefazione, iii) estese liquefazioni di terreni saturi in zone prolungate, ben delimitate, con diffusione laterale (ad una profondità di ≈ 10m) lungo un antico alveo di fiume.

Questa profondità ha dato luogo a limitate deformazioni superficiali, e ridotti cedimenti differenziali, con conseguenti lievi danni strutturali.

Solo recinzioni, marciapiedi e altre strutture leggere sono risultate pesantemente danneggiate, deformate o dislocate. D'altra parte, oltre al numero dei morti e feriti e delle numerose persone evacuate, il danno strutturale subito è estremamente grave per le chiese e per il patrimonio culturale, nonché per la struttura industriale della regione,

Le registrazioni strong-motion disponibili non sono sufficienti per spiegare in modo affidabile i danni pesanti verificatisi.

Sulla base di anni di esperienza nelle indagini post-terremoto e sui risultati di numerosi test in scala reale di strutture su tavola vibrante, gli autori hanno concluso che le ragioni principali dei danni osservati è soprattutto la elevata componente verticale del moto al suolo, in prossimità dell'epicentro (con accelerazioni dell'ordine di 1,0 g) in combinazione con movimenti orizzontali moderati.

A causa del valore molto alto dello scuotimento verticale del suolo, si osservano sia fenomeni di impatto che perdita totale o parziale di attrito (dovuta alla diminuzione delle forze gravitazionali).

I danni subiti sono raggruppati in diverse categorie generali in base a caratteristiche analoghe. La maggior parte dei danni osservati delle chiese è dovuta principalmente al crollo dei loro sistemi di copertura.

Ciò è avvenuto grazie alla risonanza fra eccitazione sismica e vibrazione verticale delle capriate in legno dei tetti.

Analizzando casi rappresentativi del comportamento dinamico di capriate in legno unitamente alla massa dello strato di copertura, si ottengono periodi propri fondamentali tra 0,06 e 0,10 sec.

D'altra parte, un periodo predominante della componente verticale del moto al suolo è, secondo il primo evento registrato il 20 maggio 2012, di 0.06-0.07 sec.

Ne segue che intensi movimenti verticali sono indotti nel complesso delle capriate e nelle travi orizzontali minori, dando luogo a danneggiamenti e dislocazioni dai loro supporti sulle pareti. D'altra parte, è noto che il tempo di arrivo, nelle regioni epicentrali, tra le onde P, e le onde S, che in tali zone hanno rispettivamente andamento verticale, e andamento orizzontale, è piuttosto piccola.

Ciò determina una convoluzione tra movimenti verticali e orizzontali del suolo.

La parte superiore delle pareti, dove sono i supporti delle capriate, sono state significativamente dislocate, comportandosi come mensole verticali in seguito alla perdita di connessione con il traliccio. Come ulteriore conseguenza le capriate, avendo perso i loro sostegni, sono crollate. Dall'esame delle macerie si può facilmente verificare quale fra le due strutture (capriate o pareti) sia crollata prima.

Una prova dell'importanza predominante della componente verticale può essere indicata, tra l'altro, dalla risposta dei campanili, che nella maggior parte dei casi non sono significativamente danneggiati, e dal fatto che le parti collassate sono ricadute all'interno del perimetro del piano terra dell'edificio.

Osservazioni molto simili valgono anche per gli edifici industriali danneggiati. I periodi propri verticali delle coperture sono anch'essi tra 0,06 e 0,10 sec. Gli appoggi delle travi di copertura sono costruiti, dal punto di vista funzionale, in modo molto simile a quelli utilizzati per il sostegno delle capriate in legno nelle chiese (travi con appoggi semplici).

Nondimeno, utilizzando bulloni o spinotti convenzionali nei collegamenti agli appoggi, non è chiaro fino a che punto la situazione potrebbe essere migliorata.

Per prevenire effetti di impatto con alta frequenza dovuti al moto verticale del suolo, potrebbe essere utilizzato all'appoggio delle travi qualche tipo di dispositivo elastomerico per l'assorbimento dell'energia, in aggiunta ai sistemi convenzionali di ancoraggio. Inoltre potrebbero essere utilizzati dispositivi di isolamento alla base il cui funzionamento non dipenda principalmente dall'attrito per scorrimento orizzontale.

Infine, il crollo parziale della fabbrica di ceramica è attribuito principalmente ai numerosi cicli di sollecitazione verticale. Poco dopo il completamento della presente comunicazione, è stata resa pubblica una importante, e tecnicamente molto interessante, registrazione del moto verticale del secondo evento, che presenta un picco di accelerazione al suolo dell'ordine di 0.9 g, un fatto che si accorda pienamente con i risultati e gli argomenti esposti nel presente documento.