Soil liquefaction phenomena observed in recent seismic events in Emilia-Romagna Region, Italy

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SUMMARY – *Significant and widespread liquefaction effects, which caused panic of inhabitants and damage to buildings and infrastructures, were observed in various areas of Emilia-Romagna region, Italy, during the seismic events of May 20 and 29, 2012, with magnitude respectively of* M_l *5.9 and* M_l*. 5.8. In Italian seismic literature these phenomena represent an interesting case study for a number of reasons: for the exceptional impacts, for the size of the area in which liquefaction effects were observed, for the amount of damage produced, for the rarity of soil liquefaction Italian case histories. Immediately after the earthquake of 20 May an extensive field reconnaissance was conducted through the natural and built environment to capture as quickly as possible surface evidences of liquefaction and to document the extent and the severity of damage. The most significant and widespread liquefaction impacts were found in the two settlements of San Carlo and Mirabello. With the aim of a better understanding of the observed scenarios, a detailed investigation program, including geophysical surveys and geotechnical testing (soundings, cone penetration tests, seismic cone penetration tests, cross-hole and down-hole tests as well as many cyclic laboratory tests), was planned. These investigations are now in progress and will be object of forecoming technical notes. This paper summarizes the observation of soil liquefaction effects made during field investigations and presents a first interpretation, based on available information on ground shaking and soil conditions, of the factors that may have contributed to determine the low liquefaction resistance of soils.*

Keywords: Emilia-Romagna earthquake, soil liquefaction, earthquake damage, earthquake geotechnical risk.

1. **Introduction**

Since 19 May 2012 Italian region of Emilia-Romagna and surrounding parts of Veneto and Lombardia are hit by a long seismic sequence characterized in the first three weeks by about two thousand of shakes with magnitudes ranging between 1 and 5.9. Two major events of local magnitude (M_l) 5.9 and 5.8 respectively occurred on the 20th and 29th of May, causing widespread ground shaking that resulted in 27 victims and in many building collapses. The main shocks of May 20 and 29 were followed by relevant aftershocks with magnitude $4.8 \leq M_l \leq 5.3$, located in the Ferrara active thrust belt (Figure 1). According a recent report of the Mirandola Earthquake Working Group the aftershocks distribution covers an area of 800 km^2 extending in the E-W direction for a length of nearly 55 km. The hypocentral depth of the shocks is generally 5 km and 10 km.

The closest acceleration recording station (MRN) is located at Mirandola, at distance of 17 km to the epicenter of the May 20th earthquake and of 2 km to the epicenter of the May 29th earthquake.

Besides the collapse of various unreinforced industrial and civil buildings and old masonry monuments, due to their high vulnerability, the two events caused liquefaction phenomena over large areas in the region. Figure 2 shows that the major widespread effects, that terrified the inhabitants, were those induced in the two settlements of San Carlo and Mirabello by the May 20th main shock. It must be outlined that the main event occurred at 02:03:53 (UTC) and it was followed at 02:06:30 by a M_l 4.8 aftershock, immediately followed by another shock of M_l 5.1 at 02:07:31.

On request of the Regional Administration, immediately after the earthquake of May 20 an extensive field reconnaissance was conducted through the natural and built environment for capturing as quickly as possible surface liquefaction evidences and ascertaining damage to buildings and infrastructures.

It is important to emphasize that such extensive liquefaction represents an exceptional case in Italian seismic literature because also during the most severe Italian earthquakes of the last century liquefaction occurred only in restricted areas and the induced damage was generally very limited. Therefore with the aim of a better understanding of the scenarios observed, a detailed investigation program, including geophysical surveys and geotechnical testing (soundings, cone penetration tests, seismic cone penetration tests, cross-hole and down-hole tests as well as many cyclic laboratory tests), was planned. These investigations are now in progress and will be object of forecoming technical notes.

This paper summarizes the observation of soil liquefaction effects made by the authors during field investigation and presents a first interpretation of the observed liquefaction manifestations at the light of available information on ground shaking and soil conditions as well as on the regional seismicity and geological, geomorphological and geotechnical conditions.

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2. **Soil liquefaction effects observed at San Carlo and Mirabello during 20 May ground shaking**

The two residential settlements of San Carlo and Mirabello, in which major liquefaction impacts were produced during the May 20th ground shaking, are typically small industrial and farm inhabited centers of Po Valley with masonry or concrete buildings of two or three floors with shallow foundations. They are surrounded by many manufacturing plants. Most of residential buildings and factories was built in the second part of last century. In the two centers the most severe damage was suffered by factories and old masonry monuments and farm houses. Many of them collapsed, but also ordinary buildings and infrastructures (roads and pipelines) were damaged and a large part of buildings was evacuated.

It must be noted that only in recent times, since 2005, these centers were classified seismic with a low-medium level of seismicity. From 2008 the new Italian code for aseismic building design prescribes to consider a horizontal peak acceleration value of 0.125-0.150g on firm

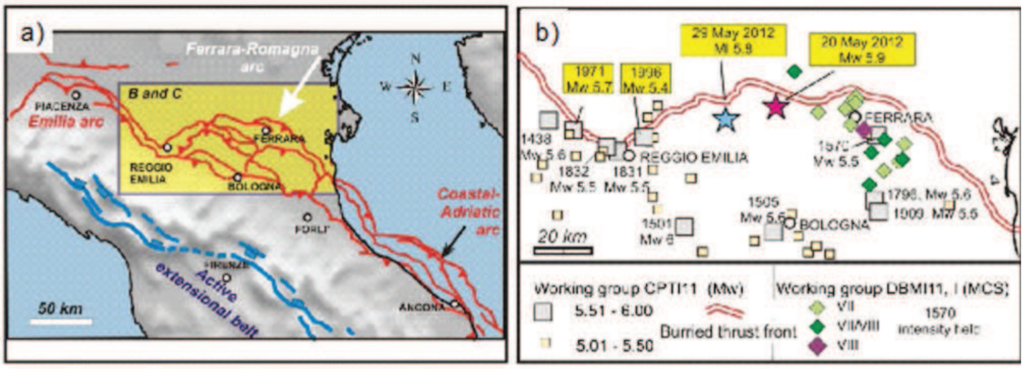

Fig. 1. *Seismotectonic framework of the Emilia 2012 earthquake. (a) Schematic map of the Padan-Adriatic Thrust Belt of Northern Italy with boundary of the study area (rectangle). (b) Major historical earthquakes within the study area and macroseismic field of the 1570 earthquake. (after Mirandola Earthquake Working Group, 2012, modified).*
Struttura sismotettonica del terremoto dell'Emilia 2012. (a) Mappa della Thrust Belt del Nord Italia con i confini dell'area allo studio (rettangolo) (b) Piu importanti terremoti storici della zona interessata e campo macrosismico dell'evento del 1570 (da Mirandola Earthquake Working Group, 2012, modificato).

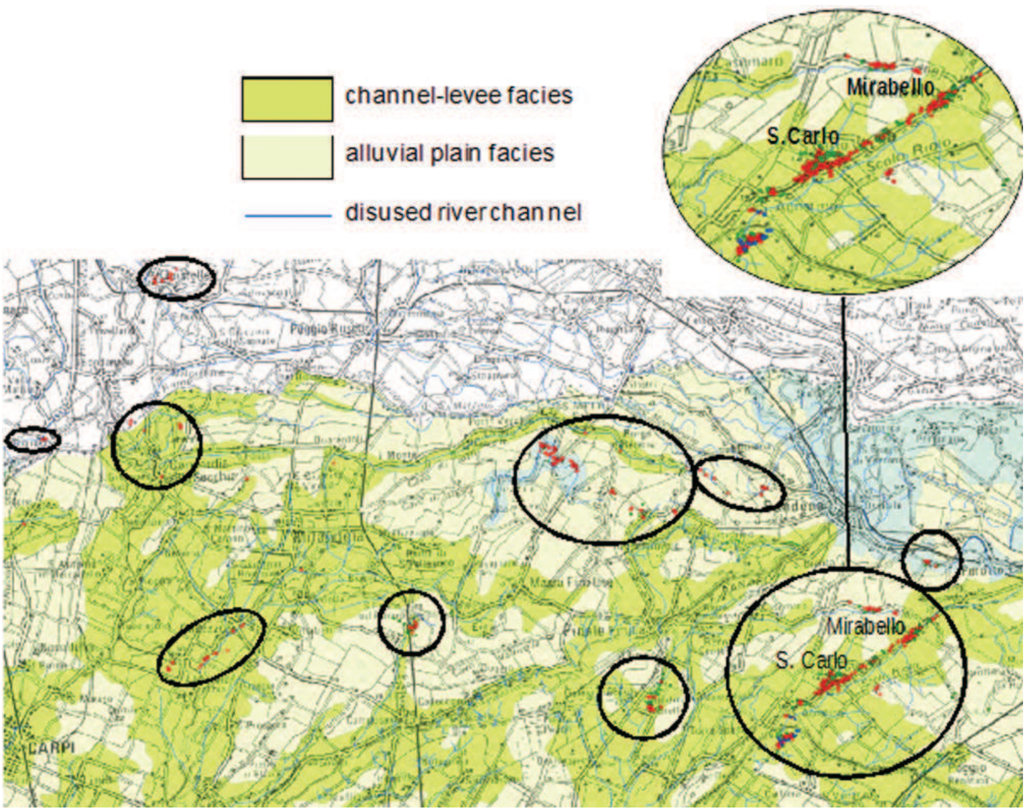

Fig. 2. *Map of soil liquefaction phenomena observed during the earthquakes of May 20 and 29, 2012 and soil liquefaction at San Carlo and Mirabello (after Martelli, 2012, modified).*
Mappa dei fenomeni di liquefazione osservati durante i terremoti del 20 e 29 Maggio 2012. Nell'inserto mappa dei fenomeni di liquefazione a San Carlo e Mirabello (Martelli 2012, modificato).

Fig. 3. *Liquefaction evidences and damages at San Carlo (photos by DICeA Geotechnical team).*
Evidenze di liquefazione e danni a San Carlo (foto DICeA gruppo Geotecnico).

soil. The seismic history reveals that in this zone earthquakes are generally of low intensity and only the magnitude of the earthquake occurred on 1570 can be considered comparable to that of the main shock of May 20.

On the 20^{th} of May, the main shock of magnitude 5.9 produced strong ground motions, specially in the vertical direction. Liquefied sand erupted and flooded many large areas of the two settlements. As Figures 3 and 4 show, the surface phenomena observed immediately after the quake were typical soil liquefaction evidences, that is: sand boils, vents, sinkholes, craters, surface ruptures, extensional fissures. Many

Fig. 4. *Liquefaction evidences and damages at Mirabello (photos by DICeA Geotechnical team).*
Evidenze di liquefazione e danni a Mirabello (foto DICeA gruppo Geotecnico).

open spaces, as courtyards, gardens and roads, were completely covered by the ejected sand, mud and water. The thickness of erupted material was in many cases more than 30 cm. In some buildings, from pavement cracks the sand uplifted up to 100 cm. The erupted sands appeared fine graded, relatively clean and of uniform size. Some pipes were broken. Many roads were fissured. Residents described high water spouts issuing from the fissures following the earthquake.

Nevertheless, the severity of liquefaction damage was different in the various zones and varied even within one zone ranging from low to severe.

Even if in some areas the impacts were spectacular and absolutely unusual in the Italian context, neither relevant ground settlements nor considerable lateral spreads nor extended flow liquefaction phenomena were observed. There was also clear evidence that ground settlements were in general relatively uniform and limited, and, moreover, that building foundations supported generally well the overlain structures. No significant tilting nor overturning of foundations and rising of submerged structures were noted. More important and widespread damages resulted for buried lifelines (gas and water pipelines).

By observing the structural characteristics of some collapsed manufacturing plants, it was evident that the collapse could be attributable more to structural vulnerability than to liquefaction, even if the occurrence of liquefaction might have been a contributing factor.

It seemed that, even not so intensely as during the May 20th quake, on May 29, some sites of San Carlo and Mirabello re-liquefied during the second earthquake. But in this last case no certain documentation exists as the two settlements were partially evacuated. It must also be noted that the epicenter of the May 29th earthquake was more distant than that of May 20 and that the hypocenter of May 20 was more superficial.

Instead, on May 29, some sites in the areas closest to the epicenter (for instance San Felice sul Panaro) where minor liquefaction effects were observed on May 20, re-liquefied more intensively, but with negligible effects on ground and structure stability or lifeline serviceability.

4. Seismicity and ground motions induced by 20 and 29 May

The origin of the present seismic crisis is related to the activity of the basal Padan-Adriatic thrust belt, caused by the collision of Euro-Asiatic plate, along the Sardinian and Corsican margin, and African plate, along its most North-West border. Its compressive movements, that since late Pliocene caused folding and faults in the overlain sediments, are still in evolution. The Padan-Adriatic thrust belt is articulated in a number of minor outward convex arcs, which from West to East are known as: Emilia, Ferrara-Romagna and Coastal-Adriatic arcs. The Emilia seismic sequence of May-June 2012 reactivated the basal thrust in the central portion of the Ferrara-Romagna arc (Figure 1a).

Historical seismicity shows that this area of the Po Plain was affected by many earthquakes generally of low intensity that have caused effects $I_{MCS} \geq$ VII only in 1346, 1570 and 1796. The national catalogue of liquefaction earthquake-induced phenomena in the last millennium in Italy (Galli e Meloni, 1993) indicates that the Po Valley is a susceptible liquefaction area. Previous liquefaction phenomena were observed in the city of Ferrara during the earthquakes of November 16 and 17, 1570 (Baratta, 1901). According to many authors such event can be considered comparable for intensity to the recent earthquake. It is important to outline that the aftershocks the events of 1570 continued for about two years.

The present seismic sequence is characterized by two main distinguished series of events, referred to two different systems of local parallel superficial faults, most probably interrelated, at least in terms of cause and effect.

The first series initiated on 19 May and generated a seismic long succession of shocks. On 20 May an earthquake with magnitude 5.9 occurred at 02:03:53 (UTC), and was immediately followed at 02:06:30 by a M_l 4.8 shock, and immediately after by another of M_l 5.1 at 02:07:31, that is after three and half minutes after the first and more intense quake. A further shock with magnitude 5.1 occurred at 13:18:02.

Seven stations of the Italian strong motion network (RAN), managed by the National Civil Protection Department (DPC), operating within 50 km from the mainshock epicenter recorded the strong motions of the mainshock, as well as foreshocks and aftershocks of magnitude $M_l \geq 4.0$. The closest station was Mirandola located at epicentral distance of 17 km (Figure 5).

Immediately after the mainshock, the DPC began to install further stations to increase the network coverage in the epicentral area involved by the aftershocks in sites of particular interest for civil protection purposes (Figure 6).

As Figures 5 and 7 show, the three shocks of magnitude >5 occurred on 20 May are comparable in terms of depth and epicentral location and characterized by a progressive shift of the hypocenter towards the surface

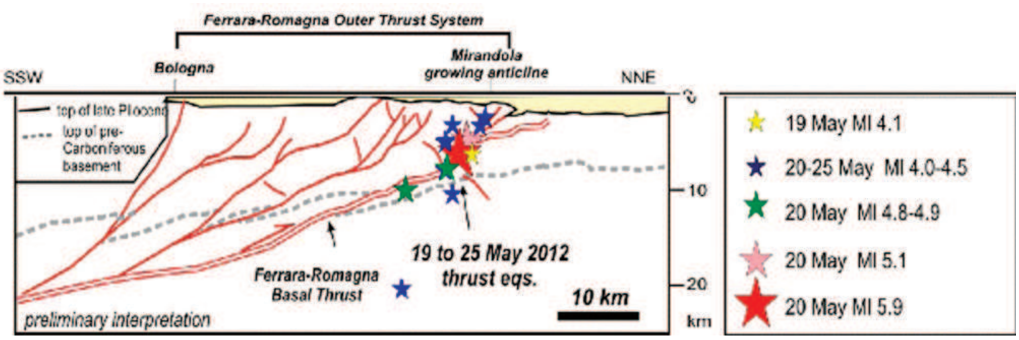

Fig. 5. *Schematic structural sections across the Emilia 2012 hypocentral area with the location of 20 May shakes (after Mirandola Earthquake Working Group).*

Sezioni strutturali schematiche nella zona ipocentrale dell'Emilia con la localizzazione delle scosse del 20 Maggio (Mirandola Earthquake Working Group).

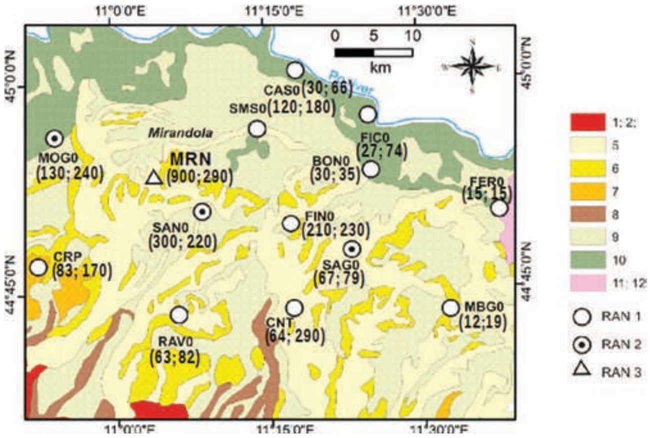

Fig. 6. *Geological map and the temporary network distribution (from Carta Geologica di Pianura dell'Emilia Romagna, 1: 250.000). Keys: 1-2) Alluvial fan and terraced deposits; 5-10) Alluvial plain deposits; 11-12) Deltaic and littoral deposits. RAN 1, RAN 2: temporary stations, RAN 3: Mirandola permanent RAN station. Vertical and maximum horizontal PGA (in gals) recorded during the main shock of 29 May are in brackets. (after Mirandola Earthquake Working Group).*
Mappa geologica e distribuzione della rete temporanea (da Carta Geologica di Pianura dell'Emilia Romagna, 1:250.000). Legenda: 1-2) Conoide di deiezione e terrazzi alluvionali; 4-10) depositi piani alluvionali; 11-12) depositi deltizi e litorali. RAN 1, RAN 2: stazioni temporanee. In parentesi le massime PGA orizzontali e verticali (in gals) registrate durante l'evento principale del 29 Maggio (Mirandola Earthquake Working Group).

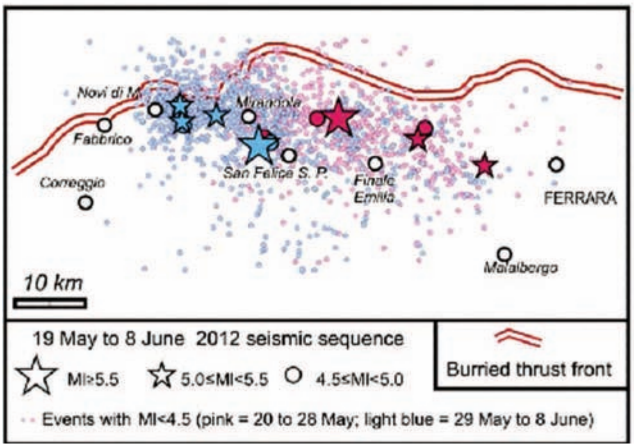

Fig. 7. *Location of the epicenters of the seismic sequence (updated to 8 June 2012) (after Mirandola Earthquake Working Group).*
Posizione degli epicentri della sequenza sismica (aggiornata all'8 Giugno 2012) (Mirandola Earthquake Working Group).

and versus the areas where liquefaction impacts were more severe.

The second series of events of 29 May initiated at 07:00:03 (UTC) with a main shock of M_l 5.8. It was followed by another two shocks at 10:55:57 and at 11:00:25 with M_l respectively of 5.3 and 5.2. The events are located farther west of the epicenters of the first series close to the Apennine margin, nearly 12 km WSW-ward of the 20 May event.

The focal mechanisms are in the two series of events of compressive type with a North-South direction of maximum compression and fault planes oriented in East-West direction. The main characteristics of the main shocks of 20 and 29 May are reported in Table 1.

Tab. 1. *Main characteristics of the major shocks (M_l > 5) of the two sequences occurred on 20/05/2012 and 29/05/2012.*
Caratteristiche principali dei principali eventi (M_l > 5) delle due sequenze avvenute il 20 e 29 Maggio 2012.

ID	Date	Hour (UTC)	Lat.	Long.	Depth (km)	M_l
IA	20/05/12	02:03:53	44.89°	11.23°	6.3	5.9
IIA	20/05/12	02:07:31	44.86°	11.37°	5	5.1
IIIA	20/05/12	13:18:02	44.83°	11.49°	4.7	5.1
IB	29/05/12	07:00:03	44.85°	11.09°	10.2	5.8
IIB	29/05/12	10:55:57	44.89°	11.01°	6.8	5.3
IIIB	29/05/12	11:00:25	44.88°	10.95°	5.4	5.2

Figure 8 reports the accelerograms as well the response spectra of the two series of earthquakes, recorded at (MNR) station.

From the perspective of liquefaction, the event responsible of the main impacts of liquefaction is the main shock of 20 May while the event of 29 May caused liquefaction in various sites but not so widespread and exceptional as that of 20 May at San Carlo and Mirabello.

Probably, also the immediately successive shocks of magnitude 4.8 and 5.1 that followed the main shock of 20 May might have had a role, in so that the following shocks occurred within the successive three and half minutes might have formed practically a unique sequence of long duration. Being liquefaction very sensible to the number of significant load cycles of the earthquake, the second and the third shocks might have increase the extension of liquefaction induced by the main shock. This hypothesis, that obviously must be verified through further research and numerical simulations, appears plausible.

It must also noted that the hypocenters of three shocks are shallow (6.3, 7.7 and 5.0 km respectively) and their epicenters are at a distance from liquefied sites of 17, 6.8 and 7 km respectively.

Figure 8 shows that the maximum peak of acceleration recorded on 20 May is 0.309g and is related to the vertical component (UP-DOWN), while the peaks of horizontal components are 0.264g and 0.261g respectively S-N and W-E ones. A first application of one of the most reliable Italian attenuation laws [Sabetta and Pugliese, 1996] would suggest that, at the sites where liquefaction effects were more severe, the peak ground horizontal acceleration values might have been noticeably lower (about 0.12 g).

The bracketed duration of the N-S component is 8.1 s. This value of duration is generally too short for triggering liquefaction. So the previous hypothesis regarding the possibility that the rapid succession of the two shocks may have constituted practically a unique sequence might be find a first confirm. The response spectrum of the same component shows that the maximum value of the pseudoacceleration corresponds to a period of 0.26 sec.

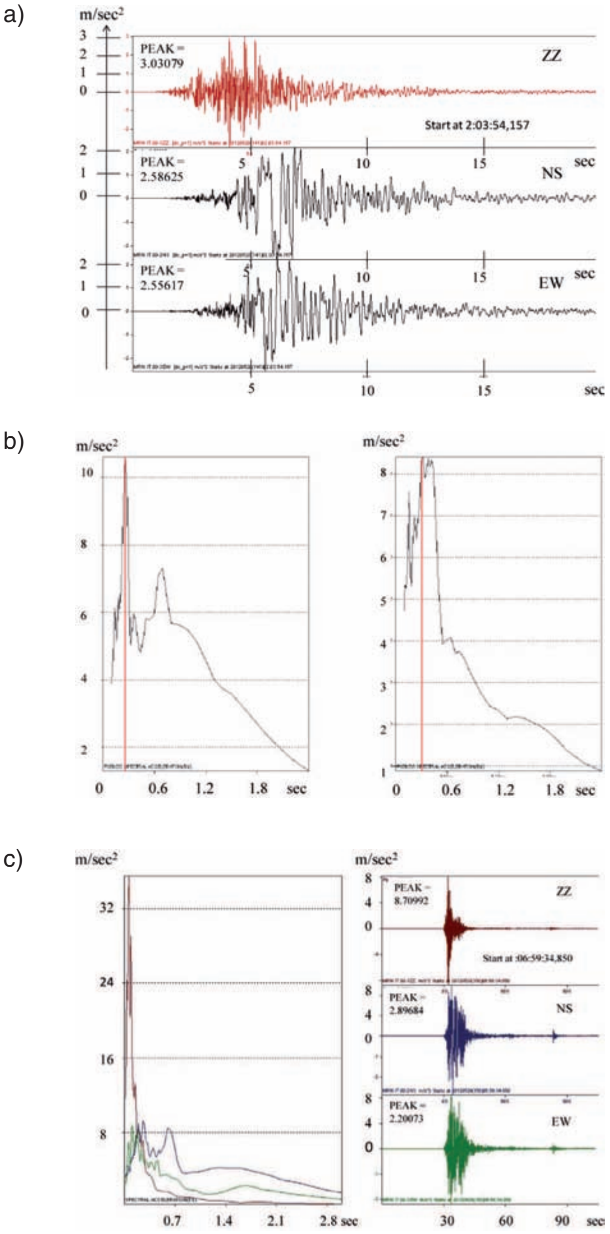

Fig. 8. *Accelerograms of the main shock of 20 May 2012 recorded at Mirandola station (A) and pseudo – spectral accelerations (5%) of the NS and EW horizontal components(B). C) Pseudo-spectral accelerations and accelerograms of the main shock of 29 May 2012 recorded at Mirandola station.*
Accelerogrammi dell'evento principale del 20 Maggio 2012 registrato a Mirandola (A) e accelerazioni pseudo spettrali (5%) delle componenti orizzontali NS e EW (B). C) Accelerazioni pseudo spettrali e accelerogrammi dell'evento principale del 29 Maggio 2012 registrati a Mirandola.

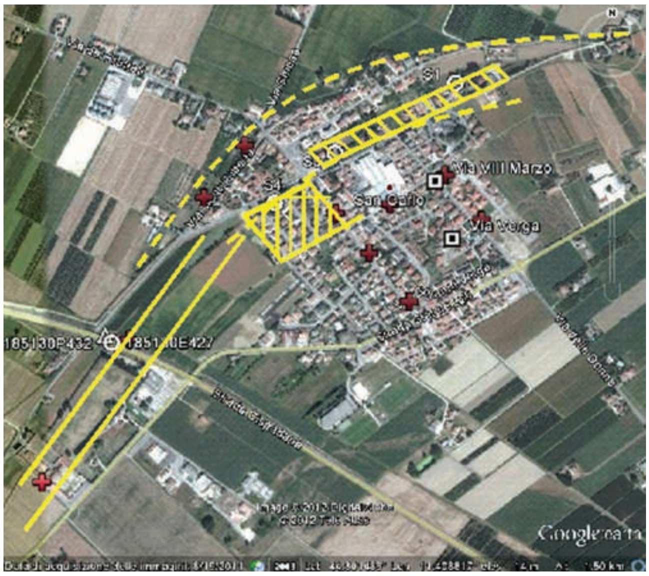

Fig. 9. *San Carlo: map of observed liquefaction effects (soil ruptures = continuous lines; sand boils and volcanoes, vents, flooding from swells,... = cross; foundation settlements and rotation = hatched rectangles). Dashed lines delimit paleoalvos area.*
San Carlo: mappa degli effetti di liquefazione (fratture del suolo = linee continue; bolle di sabbia e vulcani, sfiati, inondazioni da swells,... = croci; cedimenti di fondazioni e rotazioni = area tratteggiata). Le linee tratteggiate delimitano i paleoalvei.

Fig. 10. *Mirabello: map of observed liquefaction effects (continuous lines = soil ruptures; crosses = sand boils and volcanoes, vents, flooding from swells etc.; hatched rectangles = foundation settlements and rotation). Dashed lines delimit paleoalveos area.*
Mirabello: mappa degli effetti di liquefazione (fratture del suolo = linee continue; bolle di sabbia e vulcani, sfiati, inondazioni da swells,... = croci; cedimenti di fondazioni e rotazioni = area tratteggiata). Le linee tratteggiate delimitano i paleoalvei.

5. **Subsoil conditions**

The areas of San Carlo and Mirabello, affected by liquefaction, lie on deep alluvial deposits of the Po Valley, a large basin of Quaternary sedimentation. The inferior Pleistocene sediments are characterized by sandy clays of marine origin while superior Pleistocene alternates marine clay facies with continental sands. Holocene deposits are of continental origin and are represented by alternations of sandy clays, sands, silty sands and peats. The upper strata are constituted by fine graded cohesionless soils (sands and silts) of alluvial recent origin and are spatially heterogeneous (Figure 6). In the area the water table depth is generally very superficial. According to a recent research conducted by Emilia-Romagna Region [Severi and

Staffilani, 2012] during spring the water table in the area is about 80 and 130 cm below the ground surface. Before the seismic events the water table was at a season maximum.

The morphology and the physical features of the region were in a visible manner shaped in the past by human action, with a lot of works conducted for many centuries for flood defense and marsh reclamation. Since the sixteen century, the interventions were very frequent and extensive. Therefore the area is crossed by many ancient underground drainages, paleoalveos, reclamation works, and many streams that run along the plain in some zones get lost into the subsoil.

In the course of time, farming activity settled in the area by occupying natural humps formed by rivers and their abandoned branches, also extending to surrounding areas by means of soil filling. Some historical studies [Cazzola, 1997] indicate that for filling were generally used some special silts because they were considered very fertile. From the Unity of Italy (1861) on, in order to incentivize a more rapid agriculture development, in the whole region many spectacular reclamation works were undertaken, with three types of interventions: filling, drainages, and mechanical water uplifts. In many sites, the stream muddy waters were deviated in zones delimited by natural or artificial embankments, that occupy a large part of the territory. Since the 1960, industrial development became more accelerated and many reclaimed areas were occupied by factories and dwellings.

Historical information shows that the two zones under observation are situated in paleoalvos and embankments of the Reno river. The experimental evidence showed that the main effects of liquefaction were observed in correspondence of abandoned river channels and embankments, as clearly evidenced in Figures 9 and 10, where main liquefaction effect observations at San Carlo and Mirabello are summarized.

Subsoil stratigraphy of San Carlo (Figure 11), deduced from the borehole 185130P132 (Figure 9) of Regional database, consists of a shallow silty layer (2 m thick) overlying a fine to medium sand stratum (5 m thick) underlied by a cohesive thick layer of clay. A 2 m thick stratum of coarser sand can be encountered at about 19 m. By applying the simplified procedure of Robertson and Wride (1998) to a CPT profile available in the same site (Figure 12), it is possible to observe that the layer susceptible of liquefaction extends from about 2 to 6 m. The associate index of liquefaction, I_L, determined by assuming the magnitude and peak acceleration values prescribed by the Italian seismic code (D.M. 24.01.2008) indicates that the risk is low (Table 2).

After the 20^{th} of May shocks a deep trench (Figure 13) has been excavated at San Carlo. It reveals the presence of a shallower non liquefiable layer followed by the liquefiable sand stratum. It shows as the rising sand in some places reached the surface, causing, in free field conditions, sand boils, volcanoes, large and long cracks. Grain size distribution curves of some samples of liquefied ejected sands (Figure 14) compared with critical curves suggested by the Italian seismic code (D.M. 24.01.2008) indicates material susceptible of liquefaction.

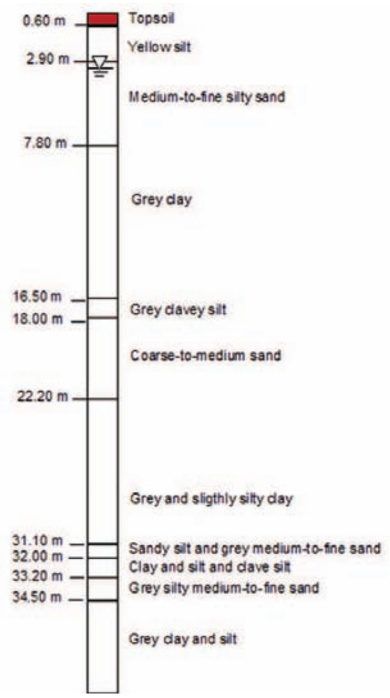

Fig. 11. *Soil stratigraphy from borehole BH 185130P432 of Regional database.*
Profilo stratigrafico del suolo da foro di sonda BH 185130P432 dell'archivio regionale.

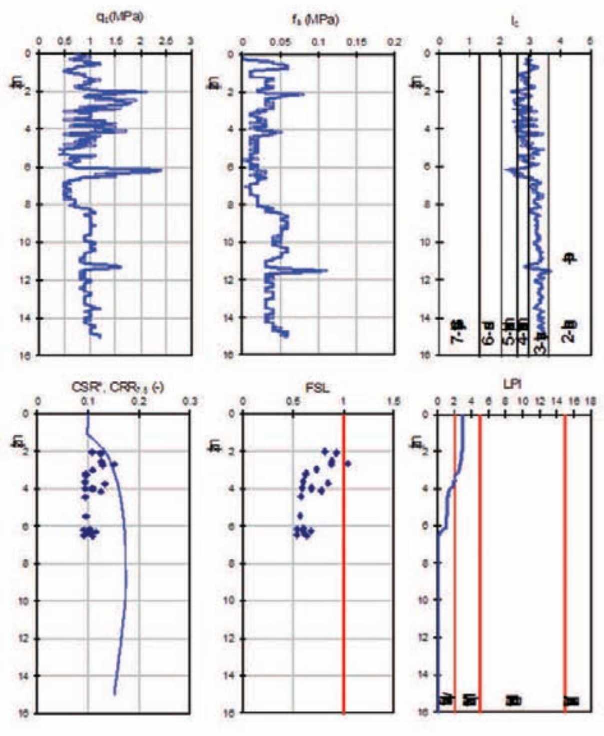

Fig. 12. *Tip (q_c) and sleeve friction (f_s) resistances from cone penetration test results (185130E427); soil classification index (Ic), Cyclic Shear Ratio (CSR), Cyclic Resistance Ratio (CRR) determined by following Robertson and Wride procedure (Youd et al., 2001); Safety factor against liquefaction (FSL) and Liquefaction Potential Index (LPI).*
Resistenza alla punta (q_c) e attrito laterale (f_s) da prove penetrometriche statiche (185130E427); Indice di classificazione (Ic), Rapporto di sforzo ciclico (CSR), Rapporto di resistenza ciclica (CRR) determinati secondo Robertson and Wride (Youd et al., 2001); Fattore di sicurezza alla (FSL) e Indice del potenziale di liquefazione (LPI).

Tab. 2. *Liquefaction potential index and associated risk level.*
Indice del potenziale di liquefazione e livello di rischio associato.

Value of I_L	Liquefaction risk
$I_L = 0$	very low
$0 < I_L \leq 5$	low
$5 < I_L \leq 15$	high
$15 < I_L$	very high

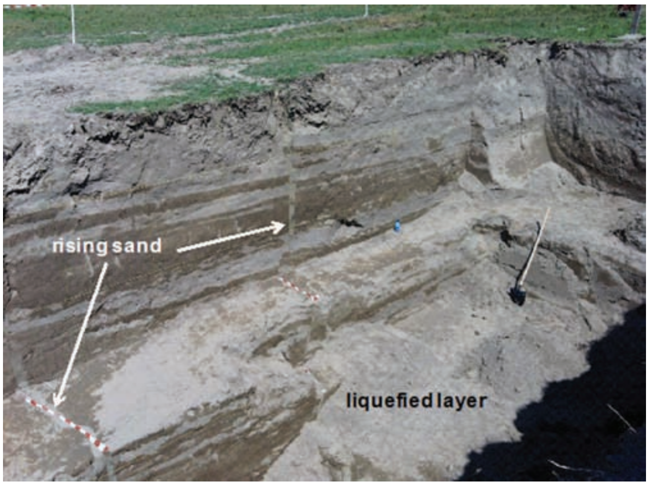

Fig. 13. *Deep trench (6m depth) at San Carlo (photos by DICeA Geotechnical team).*
Trincea profonda (profondita' 6m) a San Carlo (foto DICeA gruppo Geotecnico).

6. **Conclusions**

A realistic explanation of soil liquefaction impacts induced by Emilia-Romagna earthquakes will be possible only when high-quality data from geophysical surveys and geotechnical testing become available.

Nevertheless, at the light of available data, a first interpretation is possible.

As well known, the term liquefaction is a general term that indicates three main different phenomena (cyclic liquefaction, cyclic mobility, flow liquefaction), that produce very different levels of damage. Even if spectacular cyclic liquefaction cannot produce damage to buildings, because it occurs only in horizontal *free field*. But it may produces damage to road pavements or to buried pipes. Cyclic mobility produces limited damage on buildings (moderate ground deformations) because the soil remains on the whole "stable" because the seismic load (*demand*) is smaller than the available liquefaction resistance (*capacity*). Instead, flow liquefaction is triggered when the capacity is smaller than the demand. The effects are devastating: total loss of bearing capacity of soils, very large ground settlements, excessive lateral spreading, vertical offsets, movement of large fluid masses, collapses of natural and artificial slopes, floating of buried structures, failures of wall and harbor quays, etc.

It is also well known that liquefaction is a complex phenomenon that is the result of various factors: triggering factors (earthquake characteristics: magnitude, amplitude of acceleration, duration, etc.) and susceptibility factors (soil properties, water table depth, morphology, presence of buildings, shear stress conditions before ground shaking, etc.).

The observed scenario of impacts produced by the 20th of May shaking shows that several factors contributed to generate a high demand of soil resistance and to reduce the resistance capacity.

As concerns the demand, a key factor was the proximity of the hypocenter to the surface and the closeness of sites to the epicenter. Another key factor, related to the shallow hypocenter, might have been the

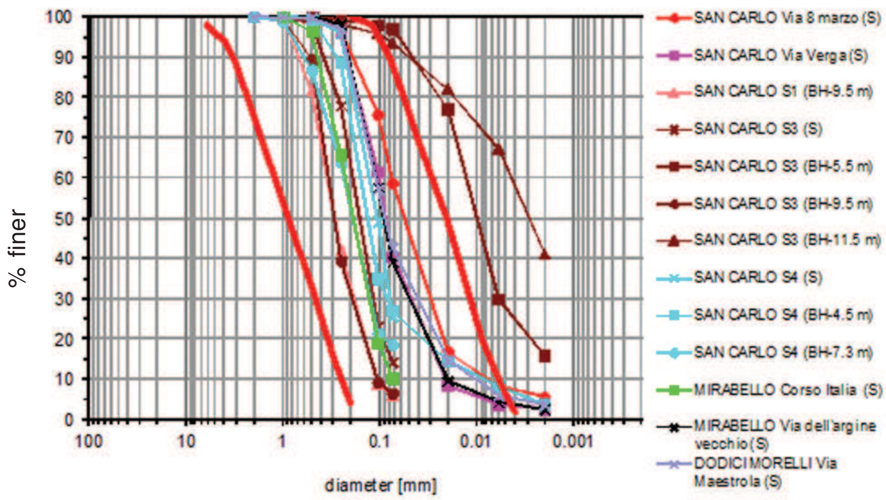

Fig. 14. *Size-grain distributions of undisturbed samples from BH S1, S3 and S4 (San Carlo) and liquefied sands which came out from the surface during the earthquake. Continuous lines represents lower and higher limits (UC > 3.5) for size-grain distributions of liquefiable sands suggested by the Italian seismic code (D.M. 24.01.2008). It must be noted that the two curves outside the boundaries correspond to sandy samples that did not liquefy.*
Distribuzione granulometrica di campioni indisturbati da BH S1, S3 e S4 (San Carlo) e sabbie liquefatte apparse alla superficie durante il terremoto. Le linee continue indicano limiti superiori (UC>3.5) e inferiori per le distribuzioni di granulometria di sabbie a potenziale di liquefazione suggerite dalla norma sismica italiana (D.M. 24.01.2008). Va osservato che le due curve al di fuori dei limiti corrispondono a campioni di sabbia che non hanno subito liquefazione.

high peak of acceleration (0.309g) of the vertical component of ground shaking recorded at Mirandola that was larger than those of the horizontal components (0.264g and 0.261g). Moreover, since triggering liquefaction is also related to the number of significant load cycles, another important factor might have been the rapid succession in three and half minutes of the two shocks of magnitude 5.9 and 5.1. It is plausible that the two shocks might have constituted practically a unique earthquake. The influence of this factor will be analyzed through simulations when high-quality geotechnical data will be available.

As concerns the capacity of soil resistance to liquefaction, the following elements contributed to its rapid reduction during the earthquake: the recent age of some superficial deposits situated in zones of reclamation (paleoalveos and embankements), soil composition (sands and silty with a clay fraction < 10%), in situ state (very loose in the upper strata), the high water table depth. The evidence that in correspondence of residential buildings liquefaction phenomena were generally smaller than in free field might indicate that confining pressure have had a role in reducing the loss of soil resistance.

The wealth of data already available permits that the following conclusion be drawn. As concerns the liquefaction manifestations induced by the 20th of May earthquake at San Carlo and Mirabello in free field, they can be considered from moderate to severe. Instead, the impacts on buildings were in the whole limited, because extreme manifestations such very large ground settlements, tilting, losses of bearing capacity, etc. were not observed. Even if volume of ejected sand was in many case impressive, soil deformations under the buildings were always less than the values suggested by Youd (1998) as indicative of high liquefaction risk, that is 30 cm for lateral displacements and 10 cm for vertical settlements. The general satisfactory behaviour of ordinary buildings could be attributed also to the good performance of the shallow foundations with perimeter footings and connected grade beams. Damage from moderate to severe was observed in gas and water lifelines and roads.

Acknowledgements

The Authors are grateful to the Emilia Region in the person of Dr. Luca Martelli and all the members of the Geotechnical Team of the University of Florence for their contribution to the present paper. Special thanks are due to the Eng. Roberto Bardotti who carried out the laboratory tests.

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