THE PIANURA PADANA EMILIANA EARTHQUAKE

The industrial warehouse area of Mirabello – located 12 km west-southwest of Ferrara, in northern Italy – suffered dissimilar intensities of damage during the earthquake sequence started on May 20th, 2012. The observed site effects were mainly concentrated along the course of the paleo-river bed of the Rhine River, where other villages are situated: Sant'Agostino, San Carlo, Mirabello and Vigarano Mainarda. The extent of the damage has highlighted the need to improve seismic resistance countermeasures of residential and industrial buildings as well as to identify appropriate measures to address the risk of liquefaction and surface rupturing. Our study tries to consider the effect that geomorphology had on the observed damage at Mirabello. The analysis is based on both newly collected geological and geophysical data and the revision of historical data related to the geomorphological evolution of the area. The main outcome of this work regards the importance of detailed mapping of the local structure of the paleo-river bed and its spatial variation. The opportunity to use the non-invasive and indirect methods, such as the Electrical Resistivity Tomography and Induced Polarization (ERT/IP), in mapping subsurface fractures and, possibly, the spatial continuity of the liquefied sand layer(s), has proved its efficiency. Such methods could be promoted to become an integral part to support other subsurface methods routinely employed for the reconstruction of the geological and hydrogeological models. Finally, the possibility to repeat the geoelectric measurements at low costs may also promote it as a tool for short-/long-term consolidation monitoring

Geological and geophysical investigations of “site effects” due to liquefaction in Mirabello following the May 20th, 2012 Emilia earthquake

Nasser Abu Zeid, Elena Marrocchino, Carmela Vaccaro, Daniel Nieto, Marilena Martinucci

On May 20th, 2012 at 04:03:53 an earthquake (ML: 5.9, hypocenter depth: 6,3 km, INGV) hit the area near to Finale Emilia. The co-seismic effects associated with this event were observed in the nearby towns located within 20/25 km from the epicenter and belonging to four provinces (i.e., Ferrara, Modena, Mantova and Rovigo).

Nasser Abu Zeid, Elena Marrocchino, Carmela Vaccaro
University of Ferrara

Daniel Nieto
National Institute of Oceanography and Experimental Geophysics – OGS, Trieste

Marilena Martinucci
Edilgeo

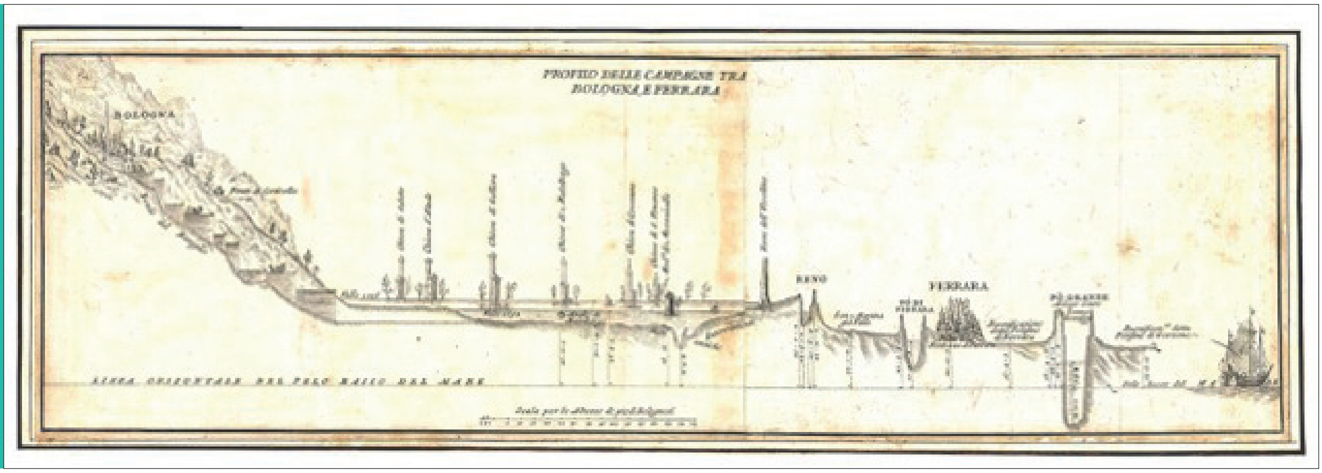

FIGURE 1 Sketch summarizing the details of Reno River deviation, started in 1604, as was proposed by Giovanni Domenico Cassini. The profile extends from Bologna (left) to Ferrara (right)
Source: Museum of Rural Life of Mirabello, Ferrara[3]

The observed heterogeneous near-field damage distribution indicated that the geologic and geomorphologic characteristics of these territories had an important role in causing, and sometimes augmenting, the observed site effects1. The most important effects are related to the occurrence of liquefaction and subsequent formation of tension cracks. These effects were observed, mainly, along the levees of the paleo-river bed of the Reno River, where the towns of San Carlo, Sant'Agostino and Mirabello are situated. The site effects, at Mirabello, had heavily encroached the factories where fractures have crossed them, leading in many cases to their demolition and consequent reconstruction for safety reasons2.
This work concerns the presentation and discussion of the peculiar geological and geomorphological characteristics of this area which, according to the observed damage distribution, could aid in clarifying the reason(s) of these co-seismic site effects. Moreover, modern geophysical techniques (ERT/IP) were employed in this work to retrieve rapid subsurface information about the depth extent of these fractures. To start with, we show an historic map depicting the hydrometric profile in the year 1760, where it reports a summary of the hydrologic regime of the Paleo-Reno River with respect to ground elevation of the surrounding territories of Bologna and Ferrara. The profile evidences that during large flood events, water had submerged churches and towers whilst, in low level periods, the water level was much higher than in Sanmartina Valley, located further to the northeast of Mirabello. This confirms the artificial and hanging river typology of the Reno palaeo-river channels (Fig. 1).

Geology and geomorphology

The subsurface geology of the Reno River, in the study area, can be better understood through a brief reconstruction of the historical evolution of the Padana Alluvial Plain. Briefly, we can say that the general structure of the paleo-river bed is the result of many anthropogenic interventions following, most probably, major climatic changes and seismic events that likely led to deviating and rectifying the Reno's natural course.
Documented information related to the earliest works can be traced back to the Roman Age (i.e., second century A.D.)[4,5,6,7,]. In that period, the Sant'Agostino territories were subjected to intense rain periods. This indirectly supports the acceleration of works concluded in that period in order to mitigate the flood risk 8,9. A summary of the main climatic periods is reported in Table 1.

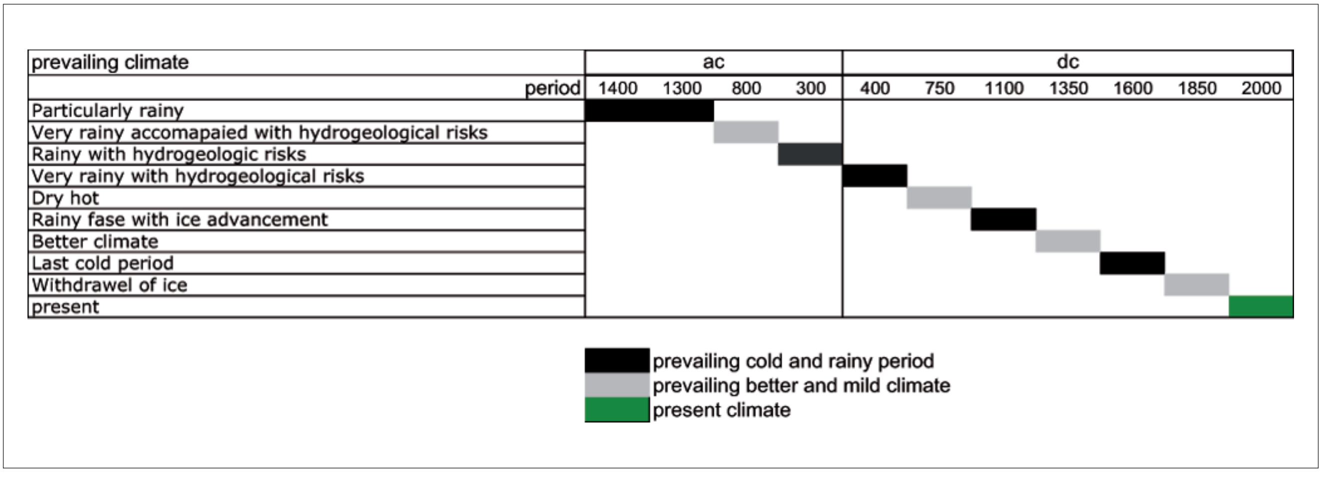

TABLE 1 Climate evolution of the Sant'Agostino village and the nearby territories [8,9]

The Reno River has been affected by numerous movements of its bed and floods probably caused by climatic changes in addition to a series of past earthquakes that may have produced damage to its banks. The most important earthquakes that occurred in the Emilia Plain, during the eleventh century after Christ, include the two large events that destroyed Verona City on 29th March, 1001 and 1st March, 1117. These events also resulted in the destruction of many cities in Emilia[10]. In Ferrara we remember the earthquakes occurred on 24th June, 1119. The low urbanization and lack of historical documentation makes it difficult to reconstruct the paleo-rivers routes[11,12]. This period of arid climatic conditions has been very important in the structuring of the territory of the municipality of Mirabello, due to the reduced flow of the Reno River, which in the year 1152 was no longer navigable. During this draught period, the city of Bologna financed several projects for the construction of dams along the following rivers: Santerno, Lamone, Senio, Sillaro, Quaderna, Gaiana and Savena in order to increase the flow and ensure navigability. The water drainage and the fortification of the levees did prevent the sediment transport from the Apennine, which augmented the subsidence phenomenon in the Emilia territories. This resulted in the formation of vast marshes. Although the Reno River was not concerned at this stage of the reorganization of its bed, its basin has been affected by the phenomena of subsidence, probably due to the reduction of sediment transport during the long dry period of the optimum medieval. The manifested hydraulic vulnerability of the territory following the two historical earthquakes, occurred in 1165 and 1222, created the conditions for further hydraulic problems that ended in 1240 with the change of the course of the Reno River, that was drifted to Finale Emilia to end in the Panaro River near Bondeno (Ferrara).

The significant alteration of the Reno River was related to routes of 6th February, 1455, when an earthquake of VIII grade intensity (Mercalli) struck the middle valley of the Reno, resulting in damaging the river banks. Such morphological changes did produce a fragile hydraulic system and the overflowing of the Reno River. The significant share variations observed with the recent earthquake of 2012[2] provide guidance on the impact that an earthquake has on the hydrological regime. Furthermore, the events of liquefaction support the hypothesis that similar effects have affected the stability of the banks and associated floods of the Reno River, that affected the area where the most disastrous event occurred in 1459. Since 1497, the Reno abandoned the Panaro changing its course and passing between Cento and Pieve villages.

In the northern part of Sant'Agostino Municipality, the river then free of protective banks had distributed sediments in the swamp waters until it reached the Po River after crossing the marsh areas. In 1522, the extreme climate that evolved towards the cold periods of the little ice age, in addition to the absence of canalization of the river-bed, had favored a disastrous flood of the Reno, with major effects on Mirabello's settlements and agricultural activity. These conditions led the government of Este to accept the intervention of canalization of the river, that resulted in the structuring of the river-bed. The same river-bed was affected by liquefaction after the recent earthquake of 20th May, 2012.

During the late medieval cold climate, the high rainfall and sediment transport created the conditions for structuring the paleo-river bed of the Reno, which was channeled with an almost straight bank from Sant'Agostino to Porotto (8 km NE of Mirabello).

The unfavorable weather conditions of heavy rain and high levels of sediment transport made it hard for the Reno water to enter the Po, causing its rapid silting. This fact is well documented by a letter sent, in 1598, by Gian Battista Aleotti of Argenta to Pope Clement VIII asking for support for the diversion of the Reno River. The diversion of the Reno River towards Sanmartina Valley took place in 1604.

In this period numerous solutions were adopted to reduce the sediment transport in the Reno River and transfer it to overcome subsidence in marshes. A particular intervention aimed at reducing sediment transport during floods is evidenced by the morphological feature of the central-northern part of the Mirabello Municipal area, where the paleo-river bed becomes wide, and in the urban organization traces of panels crossing the river are evident, whose function was to facilitate the sedimentation of soil transported by the flood waters (Fig. 2).

A representative example of these hydraulic works is the Reno Chiavica (II in Fig. 3), constructed in 1723 by Cardinal Aldrovandi, that served to mitigate the burial risk of the Po river once converged to the Reno. This solution proved unfortunate as it favored the occurrence of a number of disastrous routes (e.g., Bisacca, III in Fig. 3), after which it was necessary

FIGURE 2
Reconstruction of the principal anthropogenic structures along the Reno River based on the consultation of the available historical maps
Source: Museum of Rural Life of Mirabello, Ferrara

to divert its course leading to the formation of the present structure of the abundant river-bed. Further to the south of Sant'Agostino, the southwestern portion of the Reno was diverted towards Argenta (SW of Mirabello) with a tight angle. Consequent major interventions took place following the 1949 and 1951 floods, that lead to the construction of the presently known "*Cavo Napoleonico*". In relation to its construction, most of the materials that once were part of the left embankment of the Reno River were excavated and used in the construction of the "*Cavo Napoleonico*" embankments.

Detailed reconstruction of the Reno paleo-river at Mirabello

The co-seismic site effects urge for a systematic microzonation of all the affected areas including Mirabello. In this village, the analysis of these effects has resulted in the subdivision of the territory into five homogenous classes. The observed differences between the different classes are mainly related to both different subsurface lithologies and past anthropogenic activities. These classes are summarized in detail as follows (Fig. 3):

1a) Southern sector: In this area we have identified only the right embankment. The embankment is structured in a waterproofing system mainly composed of terraced clay.

The resistivity model (Fig. 4a) identified two resistivity levels denoted as a1 and a2. The former is characterized by resistivity values greater than 25 Ohm.m, while the latter (a2) shows low resistivity values although few heterogeneities are present laterally. These can be associated with clay and silt sediments, while the present heterogeneities (with resistivity values between 20 and 40 Ohm.m) are to be associated with the enrichment of silt and fine sand sediments. This interpretation is in accord with the subsurface lithology obtained from nearby boreholes, where a sandy silt layer has been encountered with its base located at 10.5-11 m b.g.l. It is believed that this layer has undergone liquefaction although very modest quantities of sand have reached the surface.

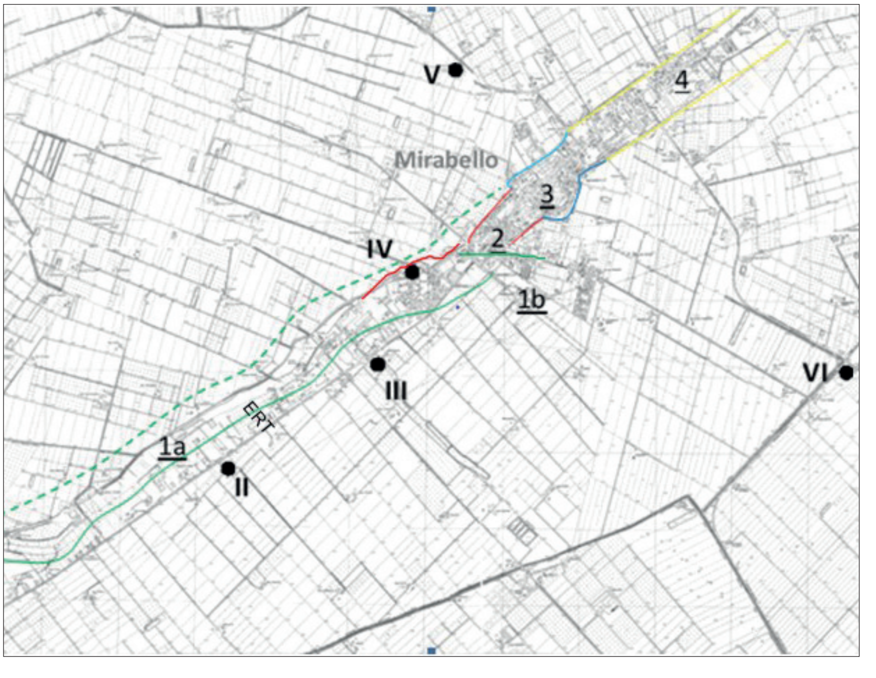

FIGURE 3
Micro seismic zoning of the Mirabello territory. The different colors indicate areas with different geomorphological and lithostratigraphic features. I-VI: principal anthropogenic structures along the Reno River (shown in Figure 2), 1-4: areas with similar site effects

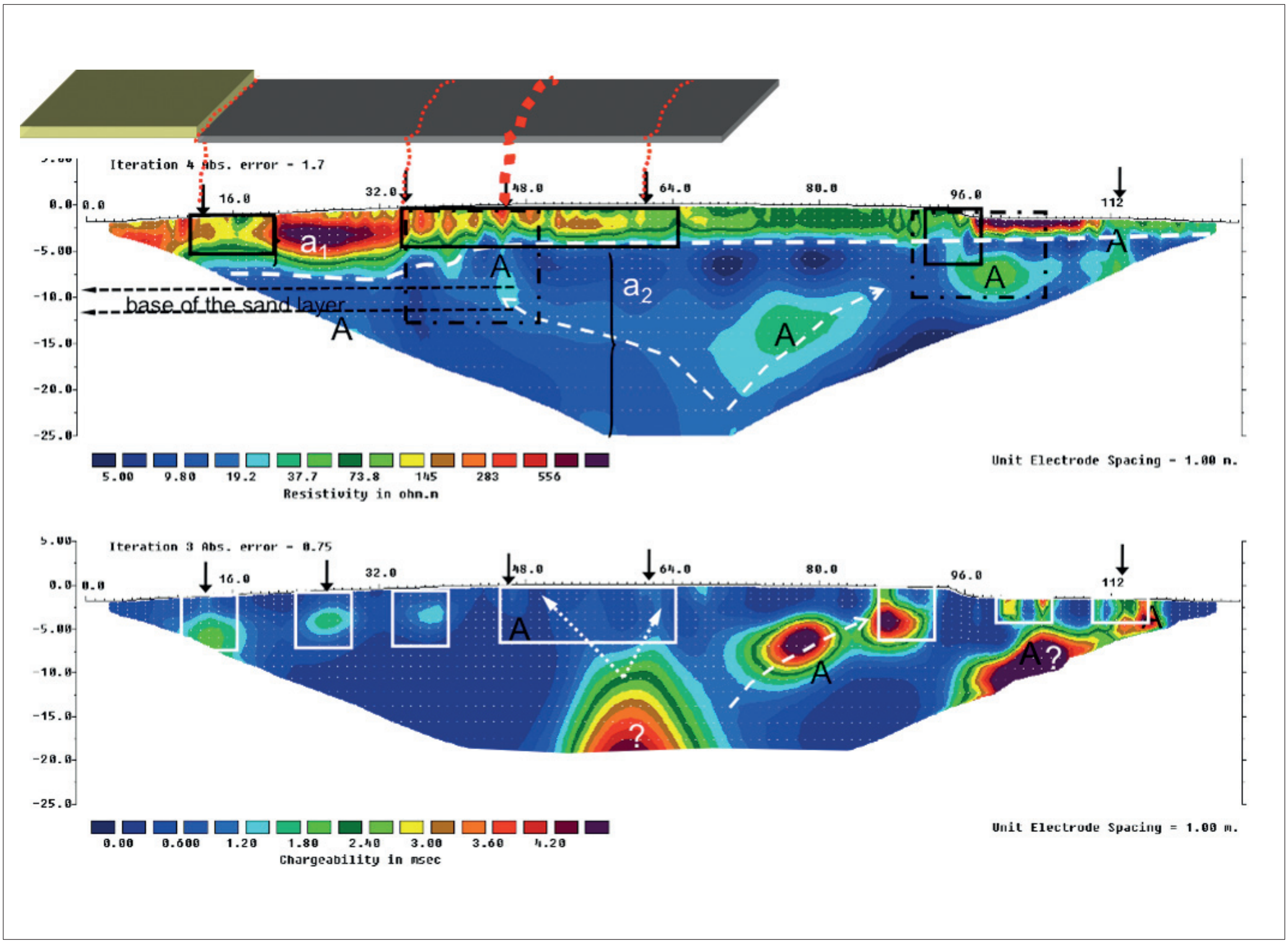

FIGURE 4 2D inverted resistivity (upper) and chargeability (lower) models. a1: resistive horizon and a2: conductive horizon. A: resistivity anomaly due to lithologic variation (silt and fine sand). Dashed white line: possible paleo-soil surface representing the old right embankment of the Reno River. The two shaded areas indicate the extension of the industrial warehouse with respect to the profile. The left one is related to the extreme western portion of the building that was severely damaged and subsequently demolished. ?: further analyses are needed to reveal the nature of these IP anomalies

As regards the first level, the resistivity model suggests the presence of lateral heterogeneities at the following chainages: 12 m, 35-65 m, and around 96 m. These are believed to be associated with subsurface fractures whose traces were visible on the surface at the moment of data acquisition.

One of these main fractures (chainage: 35 meters) has caused major damage to the industrial nearby building located some 25 meters off the resistivity profile towards NE. Moreover, the resistivity anomaly located at chainage 48 was associated with the expelling of modest quantity of fine sand that reached the surface. It is interesting to note the pathway followed by the sand following the liquefaction of the sand layer.

The corresponding chargeability model (Fig. 4b) evidences the presence of chargeability anomalies, indicated by rectangles, which are caused by variations in the sediment texture (i.e., presence of silt and fine

sand). The location of these anomalies is very near to the fractures, where some of them indicate the presence of "dykes" that may have been associated with the seismic event. The most significant is located between chainages: 45–64 m, where the trace of the nearly vertical fractures can be inferred. Similar features indicating possible upward movements of sediments can be seen at 7 m depth between chainages 75 and 90 m.
Finally, the integration of both geoelectric models and available subsurface lithology indicates that the area beneath the geoelectric profile belongs to the right embankment, which was constructed following the splay of the Reno River occurred in 1526;

1b) The eastern part of the ancient Reno River: This sector is mainly composed of clay sediments alternated with sand only in the superficial levels of the swamps.
These superficial sand sediments are related to the artificial filling operations during the lock construction and opening of a masonry drainage canal in the Reno River embankment for the distribution of sediments in the nearby plains. This hydraulic structure functioned also as a water mill in dry periods, while during the floods it was used to disperse sediments in the nearby marshes;

2) Town sector of Mirabello: In this area, portions of the two embankments are still preserved. The northern limit of this sector lays on the ancient paleo-river bed of "*Spron Mavezzi*", that marked the limits between the territories of Bologna and Ferrara during the Este Duchy; the urbanization of Mirabello occurred in this area on the border of the Reno River, and when the river was abandoned, the expansion of the urban area favored the preservation of the fluvial morphology. In the paleo-left embankment there is a strong morphological jump towards the alluvial flood plain.
Conversely, the right embankment evolves gradually towards the plain morphology due to the presence of sand sediments accumulated after flooding episodes. These differences could have contributed to the observed site effects differences caused by liquefaction;

3) The central-northern area of Mirabello: This sector represents the area of recent urbanization. It is characterized by a greater width of the paleo-river bed which served for the protection of the embankments. This has led to the accumulation of sand sediments that being saturated underwent liquefaction. Further to the north, there is a narrowing in the width of the paleo-river bed where liquefaction events are rarer;

4) The north portion of the urbanized area of Mirabello. In this sector, the paleo-river bed is of minor width and height, most probably due to the reduced supply of sediments that were blocked by the hydraulic structures belonging to sector 3.

Conclusion

The depressed morphology of the territories nearby the paleo Reno River course urged for the construction of artificial embankments against flooding. However, the suspended bed has favored, on the one side, the repeated occurrence of disastrous floods, while on the other it helped in the reclamation of the diffused marshes in the nearby territories. The paleo-river portions of the Reno treated in this study were reconstructed thanks to the availability of historical archives and geomorphological maps.
The paleo-river bed in the seismic zone 1a, belonging to the industrial warehouse area of Mirabello, shows the presence of only the right embankment while the left one has been destroyed. Towards east, its main flexure was identified by the "*Corso Italia*" street connecting Mirabello to Sant'Agostino towards south. This road separates the paleo-river embankment from the eastern, most depressed lands, where past anthropogenic activities had resulted in progressive altitude increase. This plain should be studied in order to identify the texture distribution of these sediments.
The use of the indirect and non-invasive ERT/IP technique, employed in the subsurface lithologic characterization of the industrial warehouse area (ERT in Fig. 3), evidenced the presence of 10 meters of sediments characterised by lateral lithologic variations.

These variations are related to the transition from the river bed sands to loamy soils of the right embankment. These overlay clay sediments rich in peat, that extend and interdigitate with the nearby sediments of the lowland areas. Within these, clay intercalating sand sediments are present. The combined use of resistivity and induced polarization methods allowed, also, for tracing the surface ruptures down to a depth of 10 to 12 meters.

However, the IP section (Fig. 4b) provided indications about the probable presence of deep zones (chainage: 60m, depth: 20 m), which may be related to the presence of silty sand sediments that may underwent liquefaction.

This interpretation is supported by the observed surface ruptures at chainage 92-94 m (Fig. 4a,b). East of these ruptures, the ERT/IP models suggested that liquefaction has also interested the former swamp lands. In this case, liquefaction is due to the accumulation of sand deposited after the repeated floods.

This constitutes an important element for the vulnerability of historic buildings and should be considered in any study dealing with the microzonation of these territories.

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