THE PIANURA PADANA EMILIANA EARTHQUAKE

The Istituto Nazionale di Oceanografia e di Geofisica Sperimentale "OGS" in Trieste, the University of Ferrara – Department of Earth Sciences, Edilgeo and Eurekos Srl, with the supervision of the Emilia-Romagna Region and the Civil Protection Department (CPD), have carried out a geophysical exploration at two test sites located in the villages of Bondeno and Mirabello, both situated in the western and south-western part of the province of Ferrara respectively. The geophysical survey was accomplished by using the Ground Penetrating Radar (GPR) and the seismic reflection techniques. Scope of the survey was to set insights on the uppermost part of the subsoil interested by the co-seismic effects of the May 20, 2012 earthquake (M_L 5.9, hypocenter depth: 6.3 km, INGV) and manifested by the formation of surface ruptures and the ejection of sand due to the liquefaction of sand layers present in the shallow subsurface. The attained preliminary, geophysical results have allowed for the geometrical mapping of these site effects also in depth. Despite the 2D nature of our results, this work has pointed out the ability of the GPR technique, if proper frequencies are employed, to map the shallow subsurface extent of both fractures and, under certain conditions, the liquefied sand bodies too. The possibility to trace back these fractures at greater depths was accomplished thanks to the employment of high resolution seismic reflection profiling. The preliminary results achieved in this work can help geologists get proper characterization of the subsurface below the damaged buildings, which would aid engineers and decision makers in formulating appropriate site-specific solutions. The 3D extension of these results would, surely, provide a better vision of the 3D nature of these fractures at minor costs

Geophysical methods for the assessment of the surface structures in the Mirabello area

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Following the main shock of M_L 5.9 that hit the area whose hypocenter was located at 6.3 km some 20 km NW of Mirabello, sand liquefaction effects have been observed along the entire paleo-river bed of the Reno river between Sant'Agostino and Vigarano Mainarda. In particular, these effects have interested both the urban and industrial warehouse zones of Mirabello village, among others, such as Sant'Agostino and San Carlo (Fig. 1). From the tectonic point of view, the observed seismic activities are related to the buried active front of the Romagna and Ferrara thrust belt. In this area, this folded belt represents the advanced northern rim of the Apennines mountains,

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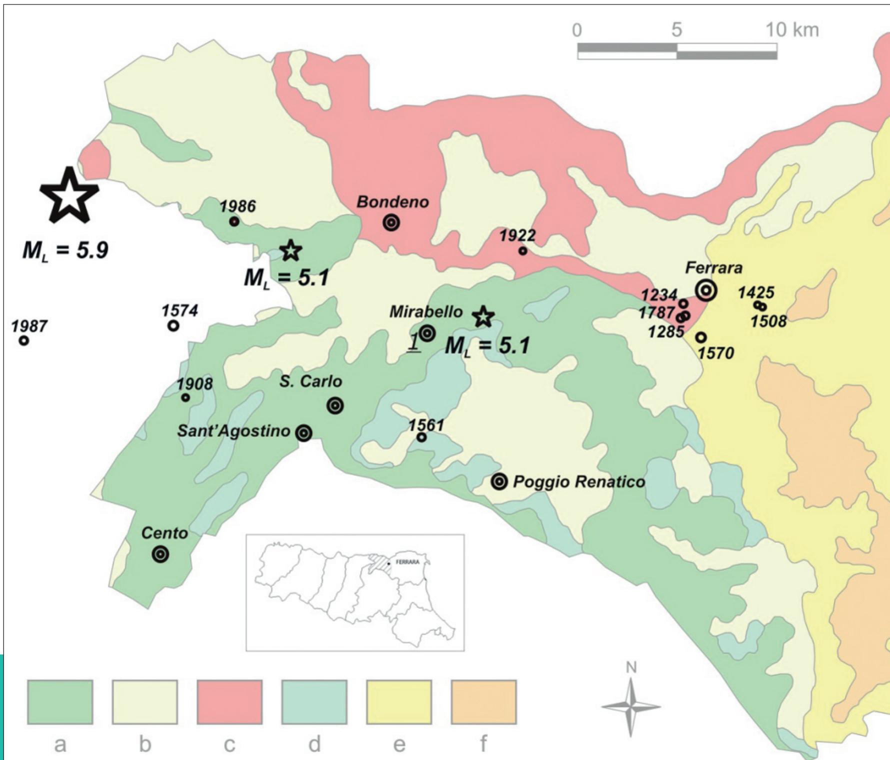
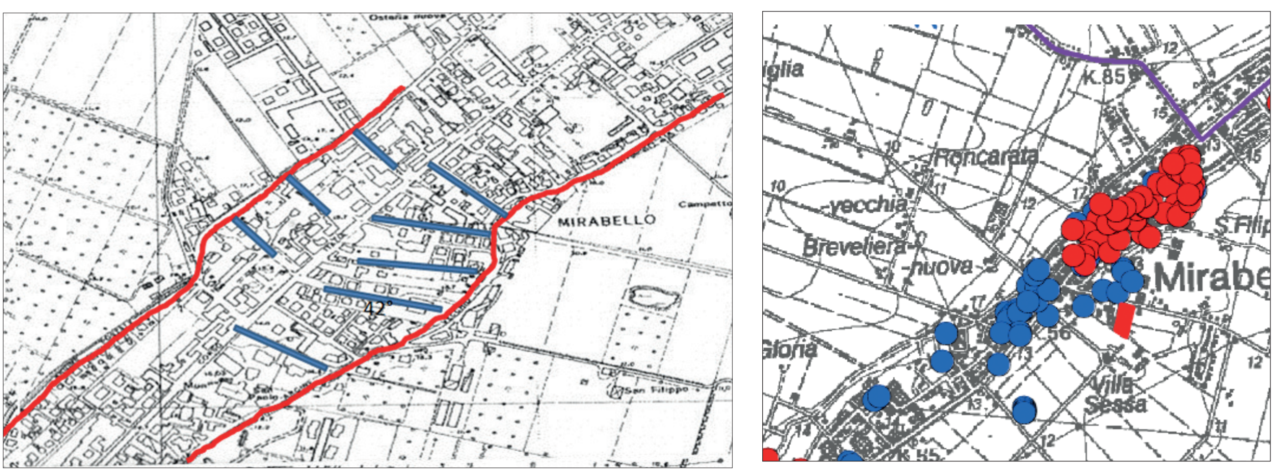


FIGURE 1
Simplified geological map of the western portion of the Province of Ferrara. The map shows the location of the main earthquakes of May 20th, 2012 (stars) and the location of the test site discussed in this paper (1). The main lithological units, of Holocene age, are: (a) medium to fine sand (channel and proximal levee deposits); (b) silty clay (distal levee deposits); (c) sandy silt, fine sand and silty clay (distal levee deposits); (d) medium to coarse grained sand (alluvial plain and meander deposits); (e) medium to fine grained sand (distribution channel and levee deposits); (f) silt, clayey silt (swamp deposits). (Modified after Data Base of the Emilia-Romagna Region (URL: geo.regione.emilia-romagna.it/geocatalogo/).
This sector, according to historical documentation –the profiles of Cardinal Aldovrandi's projects– and to toponomastic, is still characterized by the presence of two levees in good state of conservation



(a)

(b)

FIGURE 2 Relationship between the urban texture of the central part of Mirabello village and man-made hydraulic protection structures (left). These structures created the conditions for the deposition of sand sediments that underwent liquefaction following the main shock of May 20, 2012 (right), where the distribution of liquefaction manifestations is shown in red and blue solid circles (STB Reno River, STB Tributaries of the PO River, "Geo-Pro-Civ" non-profit Association). Modified after the Emilia-Romagna Region Geological Survey, 2012 which is overlain by a thick sequence of Pliocene and Quaternary sediments forming a wedge-like shape of sediments beneath the Po plain. The superficial geology of the area, including the test site, is mainly composed of alluvial deposits that have been deposited in different environments comprising: channel and proximal and distal levee, inter-fluvial, meander and swamp. These sediments also form the main hydrogeological units overlying the bedrock, which can be found at depths ranging between several hundreds to few kilometres. The heterogeneity of damage distribution is, therefore, controlled firstly by the geological and geomorphological characteristics of the territory, and secondarily by the building's vulnerability.

The distribution of sand boil manifestations, and the fracture's distribution and orientation in relation to the observed damage severity have pointed out the existence of a possible relationship not only to the litho-stratigraphic settings but also to the diffused artificial man-made hydraulic structures and reclamation activities carried out in different historical periods.

As an example, in Fig. 2 we show the reconstruction of the past hydraulic structures with the twofold aim to decrease sediment transport and to help in low land reclamation. It is interesting to observe that these reclaimed areas were heavily affected by liquefaction effects (sand boils and fractures).

The analysis and interpretation of a series of georadar (GPR) and seismic reflection profiles supported by geomorphologic and geologic interpretations are presented and discussed in this paper.

The geophysical survey

The test site (1 in Fig. 1), represented by a residential building that was affected by surface ruptures (Fig. 3), is situated in Via Argine Postale, 57 (southwestern part of the village centre). In this site we accomplished several 2D GPR and seismic reflection profiles. Details regarding the employed techniques can be found in specific literature[1]. Concerning the GPR application for the investigation of seismically-induced fractures, we came across

FIGURE 3 Side view of the investigated building with structural damage. The residential building is situated in Via Argine Postale, 57, Mirabello village (Italy). Near the fence, the seismic cables with geophones can be seen

few and sporadic examples in the literature[2]. A brief summary of the main finding shall be presented and discussed hereafter.

GPR Survey

The GPR profiles were carried out along the building sides in a direction perpendicular to the surface ruptures.

GPR data acquisition was accomplished using the GSSI SIR 2000 Georadar, equipped with 100 MHz, 200 MHz and 400 MHz antennas. As it is widely known, resolution is function of the antenna frequency: higher frequences provide higher detail, while low frequences result in greater penetration with less resolution[3,4].

The penetration depth of the radar signal (electromagnetic wave) is also function of materials' resistivity. In fact, all the recorded profiles using the higher frequency antennas were affected by low penetration and ringing, most probably caused by the presence of conductive material in the uppermost part of the section. As an example, we show a GPR section recorded by a 200 MHz antenna (Fig. 4), where ringing problems are evident apart of the high attenuation of the E.M. signal, which has reduced the depth of

exploration. This profile was recorded over the left embankment going towards the lowland area.
The interpretation of processed sections shows the presence of reflectors characterized by several horizontal unconformities and phase changes that could be associated to fractures or infiltration of sand (red lines). Reflectors associated to clay/sand interfaces are in general not parallel to the surface but show undulated geometries, probably associated to alternances of paleo erosion and sedimentation surfaces. It could also refer to the sediments used in the contruction of the embankments. For the transformation of time sections to detph, a velocity of 8 cm/ns – typical of this type of soil (relative dielectrical permitivity "$\square_r$": 14-15) –, has been applied.
It is worth mentioning that, upon request of the National Civil Protection Department and the Geological Survey of the Emilia Romana Region, pre-earthquake GPR sections have been compared[5]. Both radar images were similar, with the only difference that vertical unconformities are present in our data. These features are characterized by phase changes associated to seismically-induced fractures such as those reported in Fig.5.

Seismic investigation

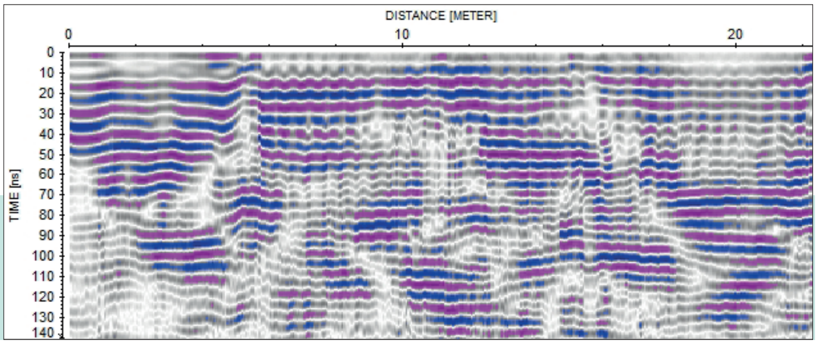
A seismic line has been recorded from the alluvial plain (west) perpendicular to the paleo-river bed (east) (Fig. 1, insert in Fig. 5). The characteristics of this profile were:

- length of the line 75 m;
- geophone spacing 2 m;
- geophones' natural frequency: 100 Hz;
- shooting interval: 2 m;
- energy source: hammer;
- sampling: 0.5 ms.

Seismic data processing was based on: definition of the geometry of acquisition; calculation of static corrections, to obtain a horizontal reference plain for both energization and recording points; application of NMO (Normal Move Out) corrections for Common Depth Points (CDP) and further Stacking. Data was filtered in the FX domain allowing for a better visualization of the reflections. In Figure (6b), we show the final stacked section (the horizontal scale represents CDP, whereas the vertical time scale represents the TWT (Two Way Time). This section shows the presence of two reflectors: the first one is well delineated (0.06-0.075 s) along the whole section, whilst the second one is less continuous, located at 0.15 seconds towards west and increasing to 0.2 sec towards east (embankment). The most interesting feature regards the presence of seismic attributes associated to interruptions of the reflection surface(s). These interruptions signal the location of the seismically-induced subsurface ruptures. The visual comparison with the GPR profile, that superimposes part of the seismic reflection profile (Fig. 6), shows a good correlation at least for the common depth section investigated by both methodologies. Further analysis of the seismic section suggests the presence of deep fractures that may not be correlated with the seismic event of May 20th, but may provide a clue about the occurrence of past seismic events that had produced seismically-induced fractures. However, more analyses are required

FIGURE 4

GPR profile acquired with a 200 MHz antenna. Structures are masked by ringing effect



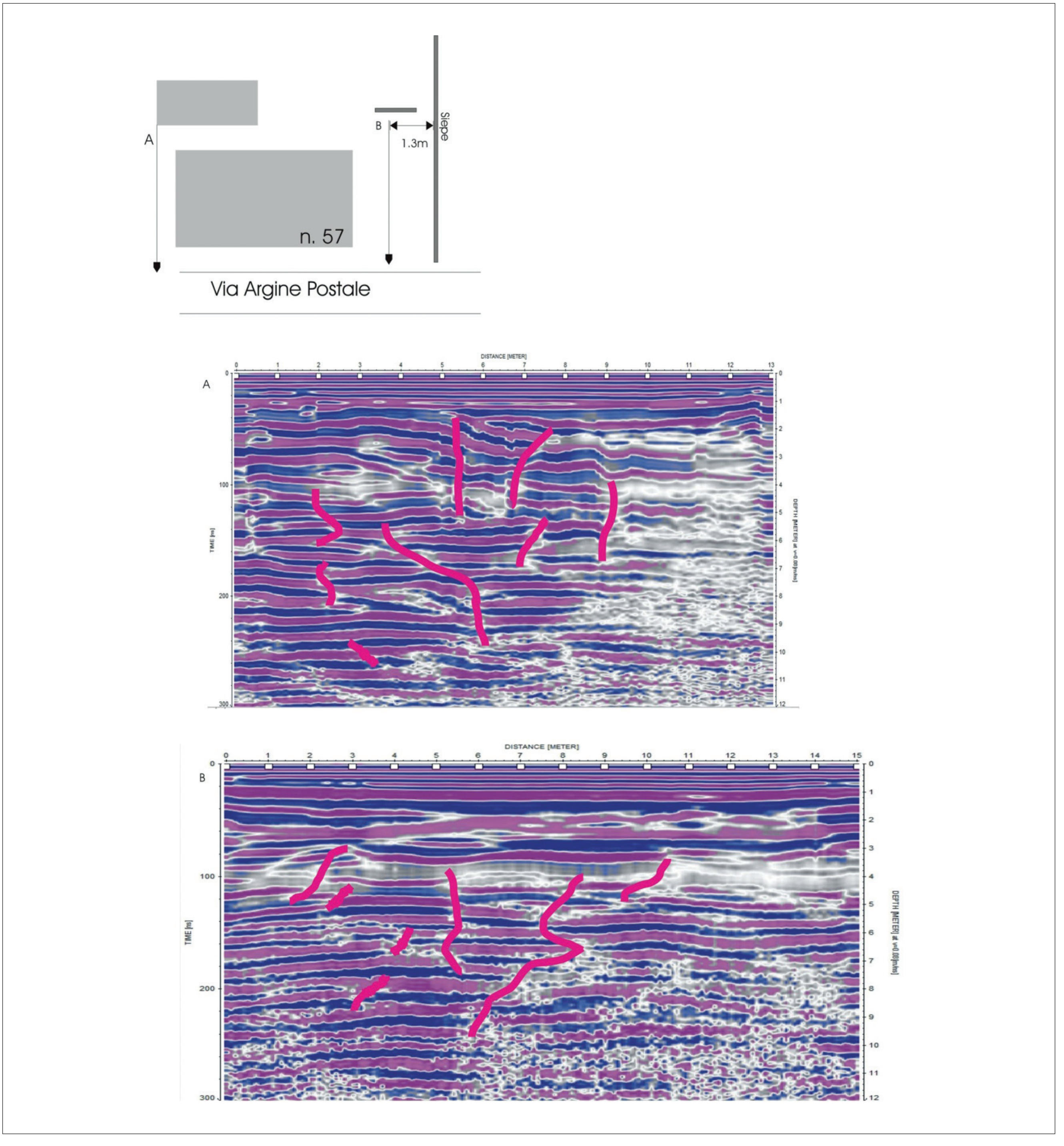


FIGURE 5 Example of GPR sections, 100 MHZ, recorded on the side of building in via Argine Postale 57 at Mirabello. Possible fractures and/or sand intrusions are highlighted in red. The upper left insert shows the position of the GPR and seismic profiles with respect to the building. A and B: GPR sections. Thick vertical line: seismic reflection profile

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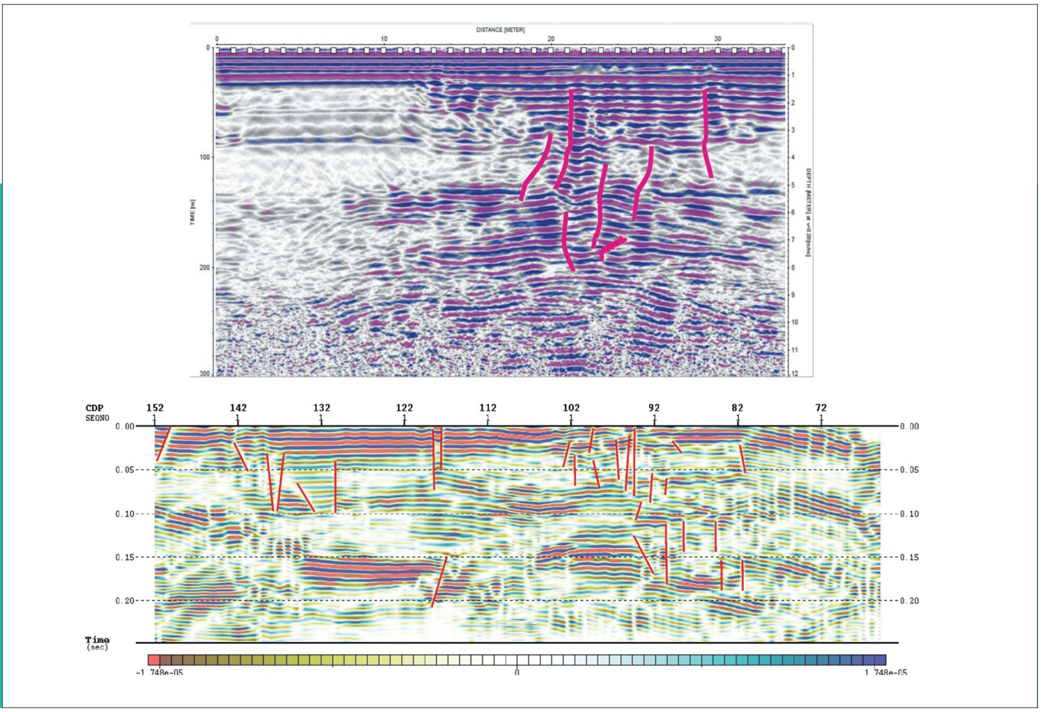
FIGURE 6
a) GPR (100 MHZ) and b) seismic reflection section. Fractures and sand intrusions are highlighted in red colour



Discussion and conclusions

The territory of Mirabello can be subdivided into four areas characterized by different levels and types of damage due to different geo-lithological conditions and anthropogenic interventions.
The application of GPR and seismic reflection geophysical techniques for the study of shallow structures has permitted to precisely define the areas where hidden fractures could be a factor of risk. The combined use of both methods proved to be very useful as it permitted to map the presence of deep structures, not reachable by the electromagnetic signals, down to a depth of about 100 m, maintaining a comparable high resolution from the surface to the bottom. The combination of the two methods pointed out the presence of deep dislocations that need to be further investigated in order to identify both probable causes and formation time period. The latter is very important for the paleo-seismic characterization of this area.
The results achieved, albeit in two dimensions, can help geologists and engineers construct more accurate geological models upon which technical solutions, for the stabilization and mitigation of the seismic risk, can be based. Finally, the extension of these techniques from 2D to 3D is feasible, especially as to the characterization of the subsurface beneath residential and industrial buildings. The integration with the 3D Electrical Resistivity Tomography is also feasible as these methods are sensitive to sediment texture variation.

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