applied GE geophysics for environment and territorial system engineering
7th international conference
Iglesias (Sardinia, Italy), 10 - 12 October 2012

Geophysical characterization of co-seismic fractures due to liquefaction: case study following the Ml 5.9 magnitude earthquake that hit the Emilia on May 20, 2012

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ABSTRACT

Following the main shock (M_L 5.9) that hit North Italy on May 20, 2012 at 4:03:53 considerable coseismic site effects, represented by surface fractures, sand boils and lateral spreading, occurred. These were caused by the liquefaction of a saturated sand layer(s) located at shallow depths (< 15 m). The spatial distribution of these coseismic features follow the limits of the paleo-river beds which are widely present in the Padana Plain. In particular, the villages of Sant'Agostino, San Carlo, Mirabello and Vigarano Mainarda which are situated along the paleo-river bed of the Reno River, were severely affected and considerable damage to both cultural and industrial warehouses occurred while residential buildings suffered less damage. These occupy the western and south western portion of the Province of Ferrara, North Italy (Fig. 1). 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. It is overlain by a thick succession of Pliocene and Quaternary sediments forming a wedge-like shape of sediments underlying the Po Plain. The superficial geology of the test sites is composed mainly of alluvial deposits that has been deposited in different environments comprising: channel and proximal and distal levee, inter-fluvial, meander and swamp (Fig. 1). These sediments form also the main hydrogeological units overlying the bedrock which can be found at depths ranging between several hundreds to few kilometres.

This work focuses on the application of geoelectromagnetic methods including: Electrical Resistivity Tomography (ERT), Induce Polarisation (IP) and Ground Penetrating Radar (GPR) techniques. for the characterisation of the subsurface continuity of these ruptures and possibly the geometry of the liquefied sand layer. The geophysical survey was carried out in three sites where ground ruptures are well visible on the ground surface and at the same time being located in the vicinity to residential and industrial building as well as in free field (1, 2 and 3 in Fig. 1).

High resolution ERT/IP data acquired at the three test sites were accomplished along 2D profiles (1 to 2 meter electrode spacing) employing the ABEM SAS4000 and MPT-DAS1 georesistivity meters, while the GPR data was collected in site 3 using the IDS DAD unit (Italy) attached to 70 MHz sub-ecco monostatic antenna (Sweden). In one site (No. 2) a 50 m long and 5 meters depth paleoseismological trench was excavated in order to map these ruptures and to search for the eventual presence of features belonging to past earthquakes (Caputo et al., 2012).

In the first site (1 in Fig. 1), a small-scale resistivity survey was carried out along a 46.5 m length profile that crossed the densely ruptured public park in the centre of San Carlo Village, North Italy. Here, the resistivity image has captured the depth extent of all the surface cracks (see squares, Fig. 2) which can be easily traced to 2-2.5 m depth. Again, a wide resistive anomaly crosses the conductive substratum (arrows) possibly associated with liquefaction dykes. The source liquefied layer is a sandy level encountered at 7 m depth in a borehole drilled in the same area. The observed irregular morphology of the low resistivity layer (ρ=5-10 Ω.m/arrows in Fig. 2), between 14 and 34 m provide strong clues about the occurrence of

seismically-induced fractures due to liquefaction. It may also suggest the presence of previous weakness zones produced by past seismic events.

In the second site (2 in Fig. 1), where the paleo-seismological trench was excavated, the inverted resistivity image (Fig. 3b), acquired perpendicular to major observed surface ruptures, without sand ejection, before the excavation of the paleoseismological trench, shows the presence of laterally heterogeneous surface electrical layer where the elongated narrow anomalies signs the subsurface continuation of the surface ruptures (Abu Zeid et al., 2012). The sketch of the south western wall of the trench has confirmed this interpretation (Fig. 3a). Moreover, the resistivity model shows the presence of a conductive subsurface below 10/12 meters b.g.l. whose top surface shows irregular morphology which may reflect the occurrence of liquefaction. However, the observed dislocation in the conductive layer, according to the author's opinion, could also be related to past dislocations caused by historic earthquakes (see arrows on Fig. 3b).

In third site (3 in Fig. 1), located in the vicinity of an industrial building south of Mirabello Village (North Italy), both resistivity and Induced Polarisation (IP) techniques were undertaken along a profile crossing the paleo-river ridge. The inversion results are shown in Fig. (4a,b). The resistivity model (Fig. 4a) identified two resistivity levels denoted (a1, a2). The former is characterized by resistivity values greater than 25 Ohm.m while the second (a2) of low resistivity values intercalated by few lateral heterogeneities. The low resistivity values (a2) can be associated to clay and silt sediments, while the lateral heterogeneities (A) with resistivity values between 20 and 40 Ohm.m) are to be linked to 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 being located at 10.5-11 m b.g.l. (borehole level at -1.8 m with respect to the ground surface of the ERT profile). It is believed that this layer has undergone liquefaction although very modest quantities of sand have reached the surface.

Concerning 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 anomalies, indicated by rectangles) which indicate variations in 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 produced by the seismic event. The most significant one is located between chainages: 45 – 64 m where the trace of the nearly vertical fractures can be inferred. Similar features indicating possible up word movements of sediments which can be seen at 7 meters depth between chainages 75 and 90 m.

In the same area one GPR profile was accomplished some 20 meters to the north of the ERT profile. The collected data undergone simple processing procedure including the following steps: trace normalisation, removing time shift, dewowing, vertical BP filter, linear and logarithmic gain application and finally an horizontal BP filter was applied. The processed radar section is shown in Figure (5).

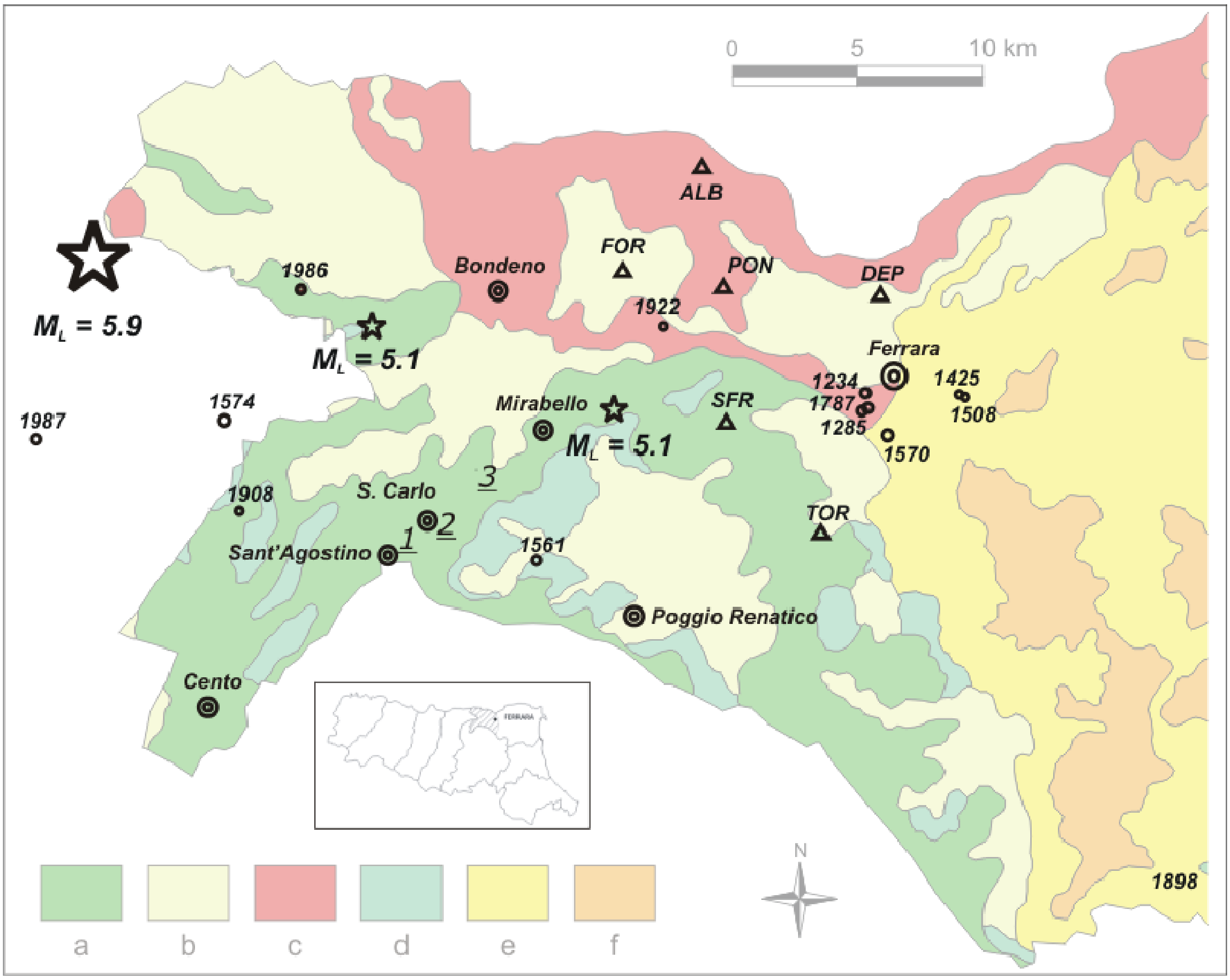

Figure 1: Simplified geological map of the western portion of the Ferrara of the Province of Ferrara. The map shows the location of the permanent local microseismic network (Ferrara Municipality) and administrated by the University of Ferrara (triangles), the main earthquakes of the 20th of May 2012 (stars) and the location of the three test sites discussed in this paper (1, 2, 3). The main lithologic units of Holocene age are: a) medium to fine sand (channel and proximal levee deposits); b) silty clay (distal levee deposits); d) medium to coarse grained sand (alluvial plain and meander deposits); e) medium to fin grained sand (distribution channel and levee deposits); silt, clayey silt (swamp deposits). (Modified after Data Base of the Emilia-Romagna Region (URL: geo.regione.emilia-romagna.it/geocatalogo/).

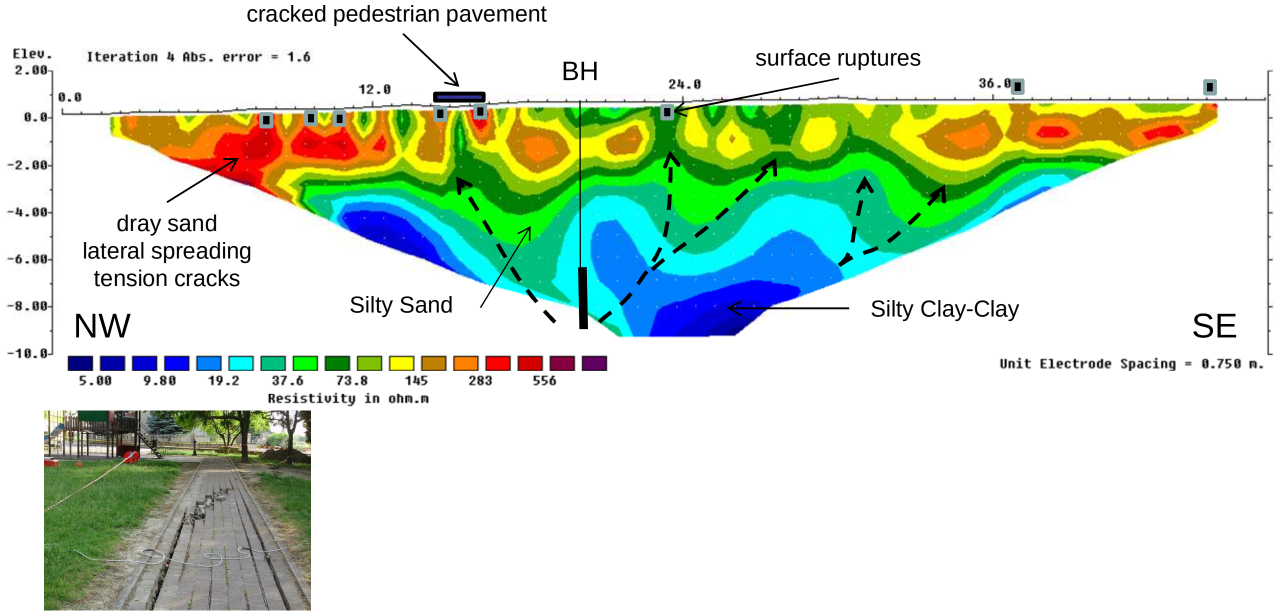

Figure 2: 2D inversion model of the ERT profile carried out at site 1. The photograph in the insert shows one of the surface ruptures crossing the profile at chinage 14-15m. BH: borehole with continuous coring, thick line below the BH: depth to the top of the liquefied sand layer, arrows: possible propagation of the subsurface fractures towards the ground surface.

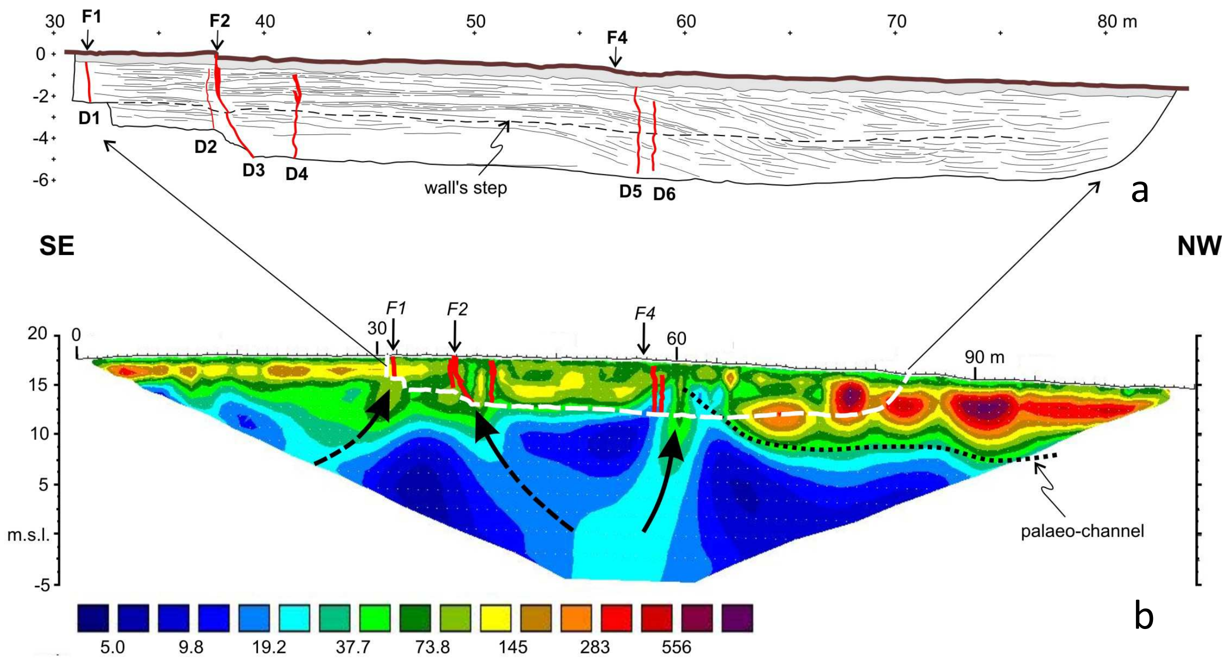

Figure 3: ERT section at site 1 (b) compared with the reconstructed architecture of the subsurface obtained by the visual inspection of the trench wall (a). F1: location of ruptures with sand ejection.

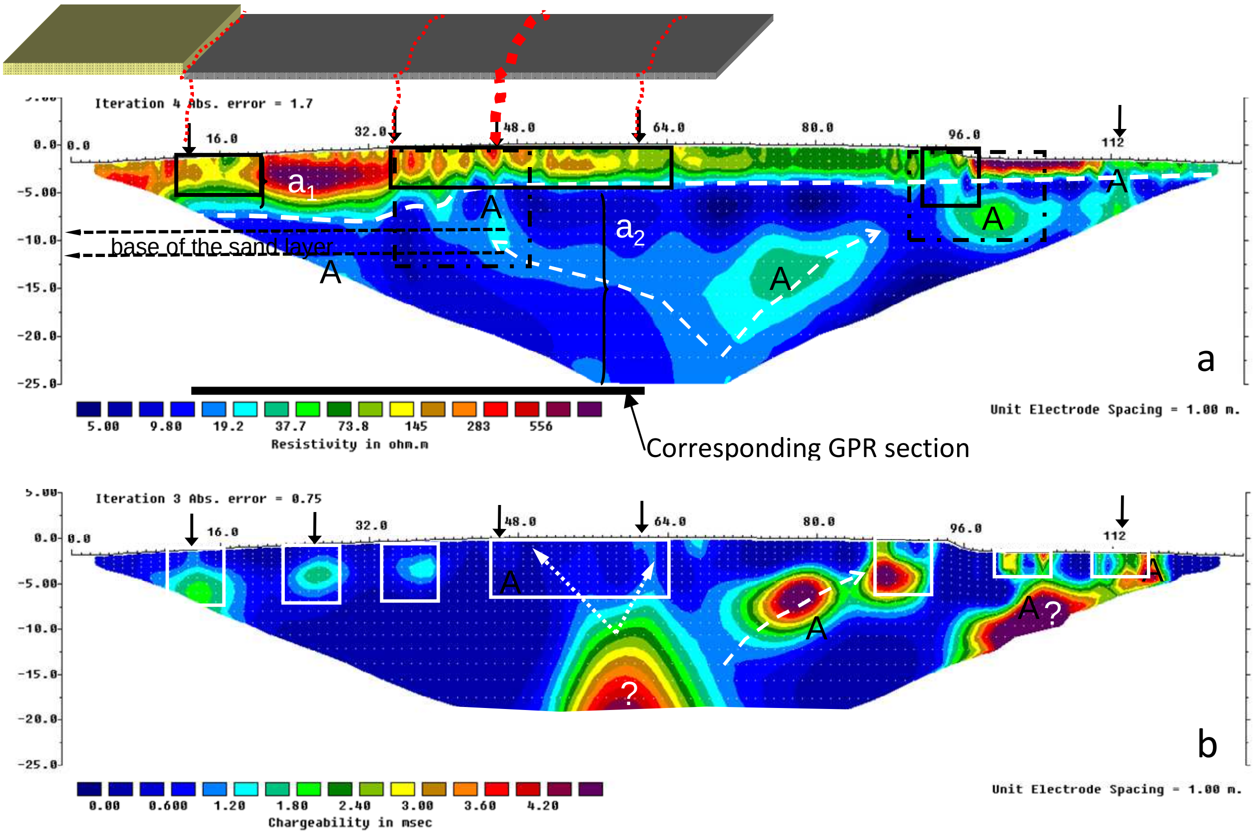

Figure 4: 2D inverted resistivity (upper) and chargeability (lower) models. a1: resistive horizon and a2: conductive horizon, A: resistivity anomaly due to lithologic variation (silt and fine sand), Dashed white line: possible paleo-soil surface representing the old right embankment of the Reno River. The two shaded areas indicate the extension of the industrial building 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.

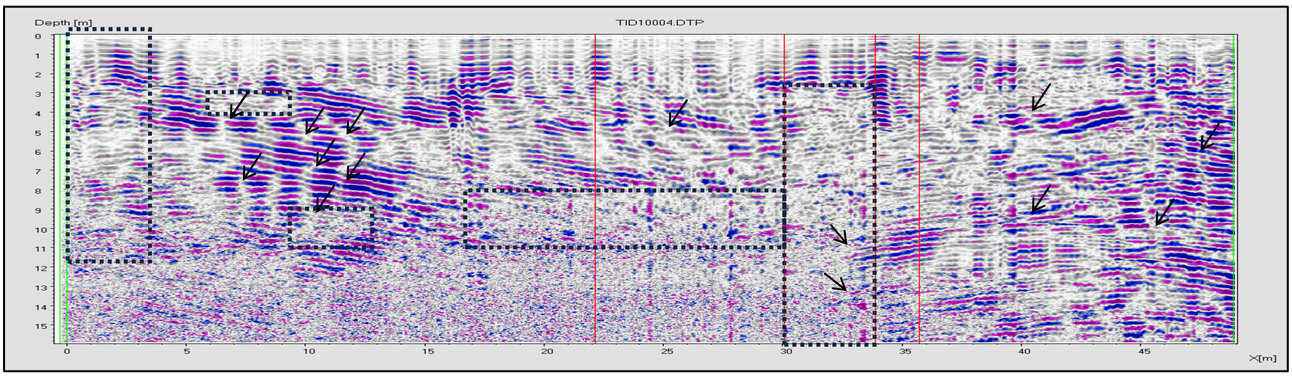

Figure 5. GPR section acquired, some 20 meters to the north, parallel to the ERT/IP. Dashed rectangles: possible liquefied sand layers/levels, arrows: subsurface ruptures.

The above reported results suggests that the combined use of electric and electromagnetic techniques can help in mapping the spatial and vertical distribution of coseismic ruptures. The contribution of the induced polarisation technique is highly stressed as it was able to trace the subsurface possible pathways for subsurface fractures and to highlight the portions of the sand layer undergone liquefaction. The observed agreement with the GPR section suggests that, under favourable conditions, detailed analysis of the reflection attributes can identify the fractures and map their pathway to the surface. The main outcome of this work concerns the usefulness of these geophysical techniques to thorough more insight in the subsurface characterisation of liquefied sites before the commencement of the reconstruction phase. Moreover, the possibility to use the same technique as a monitoring tool after soil stabilisation can also be addressed.

References:

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