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Electrical resistivity tomography investigation of coseismic liquefaction and fracturing at San Carlo, Ferrara Province, Italy

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1. Introduction

Massive surface fracturing and sand ejection took place during the main shock of the May 20, 2012, earthquake (M_L = 5.9) in the Emilia-Romagna region, northern Italy. These phenomena were induced by the liquefaction of water-saturated sand layers, and they damaged several buildings, as well as many roads and sidewalks. They were clustered between the villages of Sant'Agostino and Vigarano Mainarda, located along a paleo-reach of the Reno River [Papathanassiou et al. 2012, this volume]. The subsurface surrounding two major (several decameters long) ground ruptures was investigated using electrical resistivity tomographies (ERT), as resistivity is strongly affected by the chemico-physical conditions of loose sediments.

Italian regulations require the Municipalities within seismically active areas to develop maps of the potential liquefaction risk. Not all of the territories that are under this kind of risk have been investigated to date. A strong effort to improve this knowledge is therefore needed. Noninvasive geophysical methods can help to fill this gap, as high-resolution techniques are available with good result-to-cost ratios. Among the available methodologies, the most suitable are the methods based on electrical resistivity and permittivity, as they are highly sensitive to the presence of underground water. The ERT method has been carried out successfully across active faults, providing crucial paleoseismological information [Caputo et al. 2003, 2007].

A few weeks after the main Emilia-Romagna seismic event, ERT profiles were carried out at several locations within the affected area. In this study, we discuss two sites: the first in an uncultivated field south of San Carlo (Figure 1, site 1), which is associated with a paleoseismological excavation [Caputo et al. 2012, this volume], and the second within the urbanised area of the same village (Figure 1, site 2). Both of these areas were affected by several ground ruptures, and particularly site 2, by sand volcanoes. The two sites are located in similar morphological, hydrogeological and stratigraphic settings, along the levee flank of the paleo-Reno River. Indeed, since Middle ages and up to the XVIII century the Reno River was flowing towards northeast creating a fluvial system characterized by a channel, natural levees and crevasse deposits. The natural (and partly artificial) levees were progressively urbanized to avoid the effects of the frequent flood events, which were definitely stopped when the river was diverted near Sant'Agostino towards the southeast thus flowing directly into the Adriatic Sea. The witnesses of the past hydrography are still marked in the local topography and well known from stratigraphic investigations of the broader area [e.g. Bondesan 1989, Cibin and Segadelli 2009].

2. ERT data acquisition

The ERT method allows the acquisition of large amounts of apparent resistivity data, which is aligned along profiles and referred to different investigation depths as a function of the quadrupole length [Barker 1981, 1989]. These data are commonly plotted as pseudo-sections that show the distribution of the apparent resistivity, and they are processed by means of nonlinear inversion techniques [Loke and Barker 1996]. Here, we used the ABEM SAS4000/ES464 georesistivity meter. The apparent resistivity data were collected following the Wenner-Schlumberger array.

At site 1, a 115-m-long resistivity profile with 1 m electrode spacing was acquired across some major fractures that were associated with both vertical and horizontal (i.e., opening) displacement, but that lacked any significant sand ejection. The sampled data of apparent resistivity at this site numbered about 700.

At site 2, a 46.5-m-long profile with 0.75 m electrode spacing was acquired, which crossed a highly fractured area that was characterised by important volumes of ejected sands. In this case, the sampled apparent resistivity data are about 208.

Figure 1. Location map of the two sites investigated using electrical resistivity tomography and presented in this study. Satellite picture from Google Earth™.

3. Discussion

Before inversion, all of the apparent resistivity data were checked for quality, and suspected outliers were removed from the datasets. As a second step, we added the topographic information, using the RES2DINV [Loke 2012] inversion software. The inverted resistivity model at site 1 is shown in Figure 2. The main features of the resistivity model are represented by: (i) an electrically irregular 'overburden', from 0 to 60-65 m; (ii) a ca. 10-m-thick high resistivity body, from 65 m northwestwards; and (iii) a highly conductive deeper level, also locally affected by sub-vertical resistive anomalies.

Along the same transect, a 55-m-long paleoseismological trench was dug over the following days [Caputo et al. 2012]. The related simplified wall section is shown in Figure 2 for comparison with the geophysical data. The detailed visual inspections of the trench walls allowed the perfect calibration of the upper part of the ERT, while for the lower portion of the profile, the stratigraphic and geotechnical information was obtained from coring and cone penetration tests carried out a few hundred meters from site 1 (information kindly provided by Servizio Geologico, Sismico e dei Suoli, Regione Emilia-Romagna).

The principal resistivity anomalies that affected the 'overburden' level mimic a pinch-and-swell structure, which is characterised by high resistivity volumes that alternate with narrow sub-vertical lower resistivity zones. The position of the latter features perfectly matched the sub-vertical fractures and sand-filled dykes that were directly observed in the trench walls. This resistivity distribution is induced by high resistivity, with medium-to-coarse grained sand dykes crossing lower resistivity beds. It is also possible that the pressure exerted by the rising fluids during the injection phenomena has slightly compacted the deposits bordering the dykes.

Based on the comparison between the direct trench observations and the ERT, the resistive anomalies that affected the underlying conductive substratum (i.e., below the trench) are also possibly associated with liquefied sandy material rising from a deeper, water saturated, layer. Although the resolution of the ERT does not allow the source level to be sharply imaged, its occurrence is clearly documented by cores that were drilled s few hundred meters from the investigated site, which providing evidence of a 1-3-m-thick sand layer.

The irregular morphology of the low resistivity layer (Figure 2, ρ = 5-10 Ω.m/A), between 30 m and 60 m provided evidence of the liquefaction phenomena. The ERT section does not clearly reveal a sand source level. We can speculate that its thickness might be of the order of 2 m, at a depth greater than 10 m, with a thickness-to-depth ratio close to the resolving power of the ERT method.

At site 2, the fractures crossed by the resistivity profile are represented by black arrows in Figure 3, and are associ-

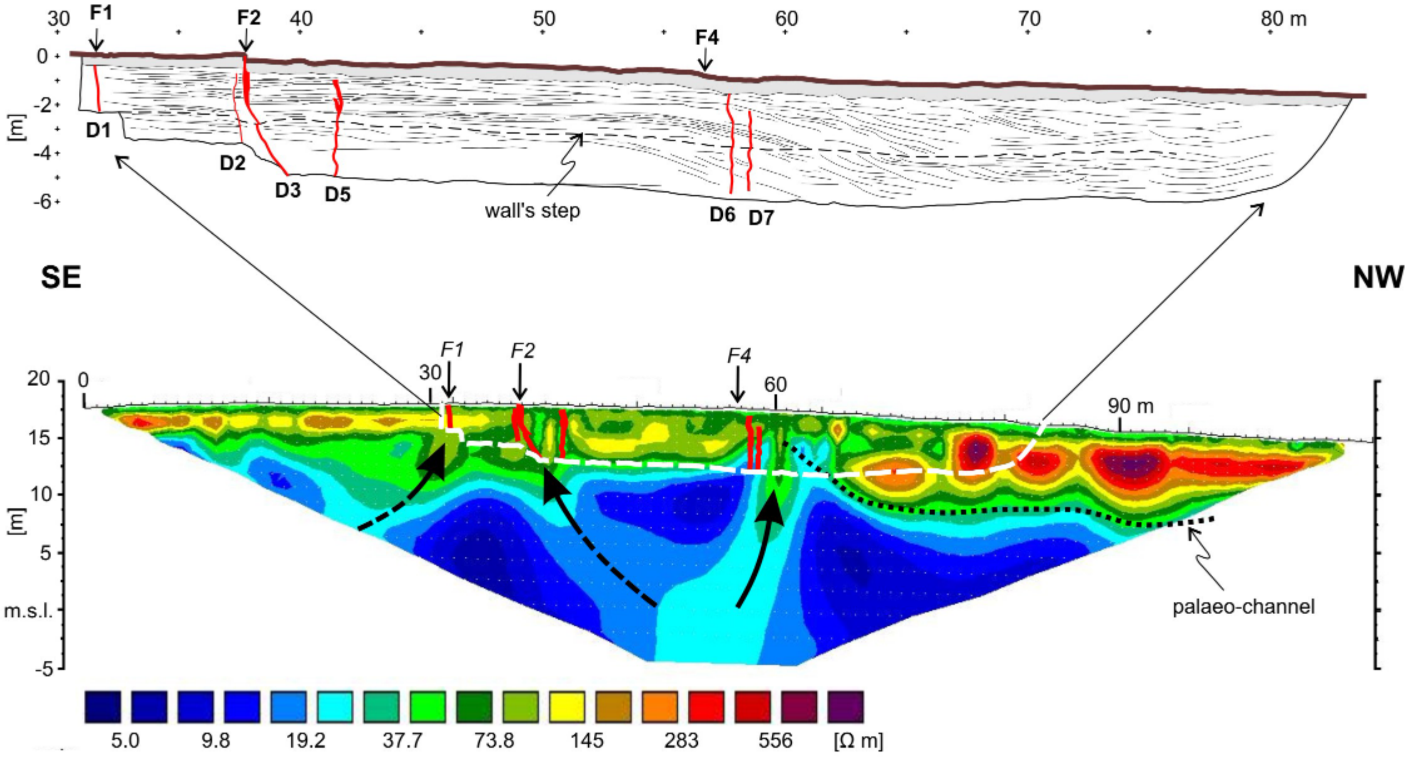

Figure 2. Two-dimensional resistivity model reconstructed at site 1 (bottom) compared to a simplified stratigraphic section (top) obtained from direct observations of the southern wall of the paleoseismological trench (Caputo et al. 2012). Red lines represent the sandy dykes observed in the trench (D1-D6) and associated with paleoliquefaction events. F1, F2 and F4 indicate the positions of the seismically induced fractures due to the May 20, 2012, Emilia-Romagna earthquake, as a consequence of lateral spreading. The high-resistivity body located beneath the northwestern part of the profile corresponds to the sandy infilled river bed of the paleo-Reno River. The large black arrows suggest the mobilisation pathways of the liquefied material in the subsoil.

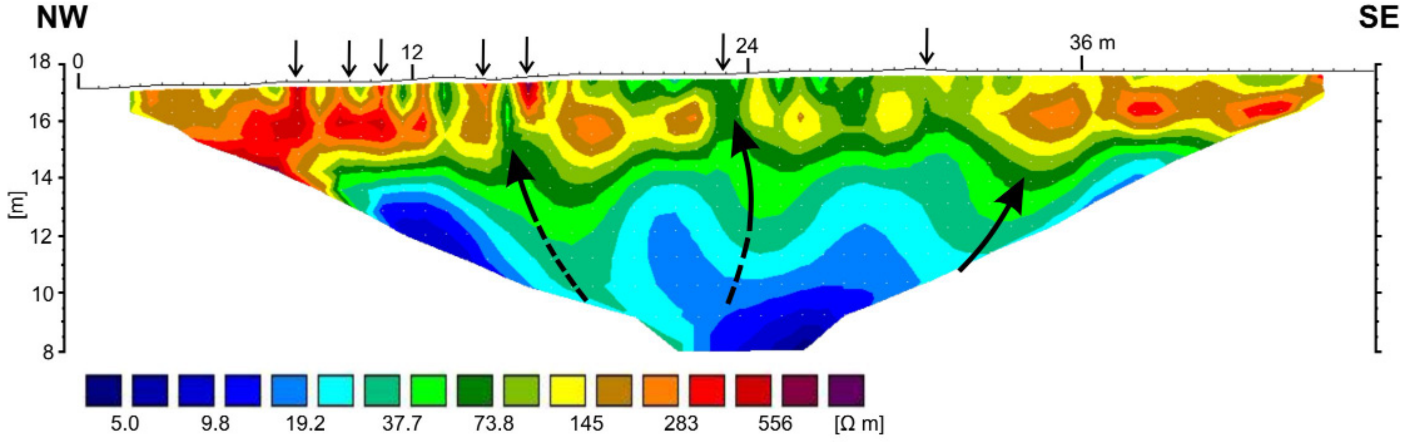

Figure 3. Two-dimensional resistivity model conducted at site 2 in San Carlo. The small arrows at the top of the profile indicate the positions of the ground ruptures, while the larger arrows suggest the mobilisation pathways of the liquefied material in the subsoil.

ated with a local resistivity maximum. This behavior is observed in depth for the first 2.0 m to 2.5 m and for a horizontal distance of less than 38 m. A wide resistive anomaly crosses the conductive substratum (Figure 3, arrows), and is possibly associated with liquefaction dykes. The source layer is a sandy level drilled at the same location, to a depth of about 7 m (information kindly provided by Servizio Geologico, Sismico e dei Suoli, Regione Emilia-Romagna). The irregular morphology of the low resistivity layer (Figure 3, $\rho = 5\text{-}10\ \Omega.m/A$), between 15 m and 34 m suggests the occurrence of seismically induced liquefaction phenomena.

Further investigations will be carried out on the site for a better understanding of the complex depositional architecture and the coseismic deformation. The interdisciplinary integration of geophysical data, geotechnical investigations, subsurface stratigraphy, and coseismic deformation studies is needed for an understanding of the liquefaction phenomenon and for mitigating the associated risk.

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