Engineering Geology 211 (2016) 1–6

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Review

GPR and high resolution seismic integrated methods to understand the liquefaction phenomena in the Mirabello Village (earthquake ML 5.9, 2012)

Luca Baradello *, Flavio Accaino

Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Borgo Grotta Gigante 42/c, 34010 Sgonico, Trieste, Italy

ARTICLE INFO

Article history:
Received 26 February 2016
Received in revised form 29 June 2016
Accepted 30 June 2016
Available online 1 July 2016

Keywords:
Liquefaction
GPR
Seismic reflection
Seismic tomography

ABSTRACT

We performed a geophysical survey in Mirabello, a village of Emilia Romagna Region of Northern Italy, to study the soil affected by the ML 5.9 earthquake of 2012, specifically the formation of surface ruptures by sand ejection due to the liquefaction of shallow subsurface layers. The investigation was carried out using ground penetrating radar and seismic reflection/refraction techniques. This work confirms the importance of electromagnetic waves to map the shallow subsurface extent of fractures and liquefied sand bodies, while the high-resolution seismic reflection profile allowed us to map the fractures at depth. The result obtained by tomographic inversion of first arrivals of seismic data has been compared with a ground penetrating radar section acquired in the same place, furnishing complementary information for the interpretation of the section.

Contents

1. Introduction

The Northern Italy earthquake of May 20th, 2012 had a magnitude ML 5.9 and was related to the buried active front of the Romagna and Ferrara thrust belt. Co-seismic sand liquefaction was observed along the Reno paleo-river bed. In particular this effect has affected the urban zones of Sant'Agostino, San Carlo, and Mirabello villages (Ninfo et al., 2012; Papathanassiou et al., 2012). The last village is located 20 km NW from the hypocenter and satisfying the typical liquefaction parameters proposed by Galli (2000) was chosen as test site by the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale in Trieste and the Department of Earth Sciences (University of Ferrara) to carry out several geophysical investigations. The shallow geology of the test site is mainly composed of alluvial deposits that form the main hydrogeological units overlying the bedrock which is located several hundred meters in depth (Castiglioni and Pellegrini, 2001). This area could be potentially affected by liquefaction effects (sand boils and fractures) because of the presence of uncompacted saturated sand with a groundwater table near the surface. This can have a possible relationship not only with the litho-stratigraphic settings but also with the diffused artificial man-made hydraulic structures and reclamation activities carried out towards the end of the XVIII century (Cremonini, 1988). Liquefaction is defined by Sladen et al. (1985) as a phenomenon wherein a mass of soil, subjected to strong waves, loses most of its shear resistance, and flows as a liquid until the shear stresses are as low as the reduced shear resistance.

Ground penetrating radar (GPR) profiles and a seismic reflection profile were acquired to analyse this phenomenon. GPR is a suitable tool to detect and map near-surface fractures (Grasmueck, 1996; Gourry et al., 1996; Pipan et al., 2000), while the seismic method allows the investigation of deeper structures and can provide a good link, if

* Corresponding author.
E-mail address: lbaradello@ogs.trieste.it (L. Baradello).

http://dx.doi.org/10.1016/j.enggeo.2016.06.027

existing, between faults and the surface fractures that can be mapped with GPR. There are few case histories of GPR applied to the investigation of seismically-induced fractures in literature. Usually, electrical resistivity and electromagnetic induction methods (Erchul and Gularte, 1982; Wolf et al., 1998; Abu-Zeid, 2016) and geotechnical approaches (such as probabilistic and deterministic cone penetration tests, Moss et al., 2006) are preferred to delineate the earthquake-induced liquefaction. A recently new non-invasive approach to liquefaction investigation based on the applicability of active seismic and passive multichannel surface wave techniques is proposed by Castellaro et al. (2015). In liquefaction studies, the success of the GPR depends on the frequency used, since GPR doesn't work well if soil has high conductivity (Liner and Liner, 1997). Authors used different frequencies: Al-Shukri et al. (2006) located the venting dikes earthquake-relates with 400 MHz antenna in Marianna, Arkansas; Nobes et al. (2013) tested 100 MHz and 200 MHz antennas in Christchurch, New Zealand, to detect sediment mounding beneath the silt ejection (silt volcano) and stratigraphic disruption beneath the piston failure. The 100 MHz antenna did not yield significantly better depth of penetration. Thus, to obtain the best resolution, the survey was completed using the 200 MHz antenna providing good results. Liu and Li (2001) obtained a good image of features associated with seismically induced liquefaction using 100 MHz in Sikeston Ridge, Missouri, since the soil is rather sandy.

Here we show that the GPR technique can map the shallow subsurface extent of both the fractures and the liquefied sand bodies, if proper frequencies are employed. The investigation of these fractures at greater depths has been performed with high-resolution seismic reflection profiling and the tomographic inversion of first arrivals.

2. Methods

At the Mirabello test site, the liquefaction phenomena caused by the earthquake severely damaged many buildings due to uplift, subsidence, and tilting of the soil. One month after the earthquake, in an area bounded by old embankments built on the alluvial plain, a geophysical survey was carried out along the side of a building in the Argine Postale street (Fig. 1) in order to map the subsoil. The geophysical profiles were acquired perpendicular to the direction of the surface ruptures.

The GPR data was collected using the GSSI SIR 2000 Georadar, equipped with 100 MHz, 200 MHz and 400 MHz monostatic antennas. The resolution and penetration are function of the antenna frequency; higher frequencies provide higher detail, while low frequencies provide greater penetration but lower resolution (Davis and Annan, 1989; Jol, 1995). Wunderlich and Rabbel (2013) studied the GPR absorption and the spectra frequency shift depending on clay content and water in the soil, the typical situation where the liquefaction occurs. The penetration depth of the electromagnetic waves is also a function of the material resistivity (Smith and Jol, 1995). In this study, all the recorded profiles, collected at Mirabello using the high-frequency antennas, were affected by low penetration and coherent noise, dominated by a single frequency due to the more conductive finer-grained soils. In Fig. 2 we show the GPR profiles obtained with 200 MHz and 100 MHz antennas collected over the left embankment going towards the lowland area. The strong coherent noise signals, evident at high frequencies, mask the targets and reduce the depth of penetration. We tried to remove this coherent noise with several techniques (background removal, predictive deconvolution, and FK-filtering, as suggested in Kim et al., 2007) but all the algorithms have not preserved the real features, and have introduced artefacts and spurious phase changes. The introduction of phase changes with processing can lead to an erroneous interpretation of the fractures. In fact the phase change is an important indicator to detect fractures.

Olhoeft (2000) showed how the GPR images of linear structures, such as the fractures, depend on many factors, including the Fresnel zone and the scattering angle. Another important factor in the investigation of subsurface structures is the shape of the lobes of electromagnetic energy propagation, and therefore how electromagnetic waves change in the near field (e.g., Yarovoy et al., 2007). To better understand the location, size, and orientation of sand-filled feeder dikes, we collected GPR data by towing the antenna using two orientations: transverse and

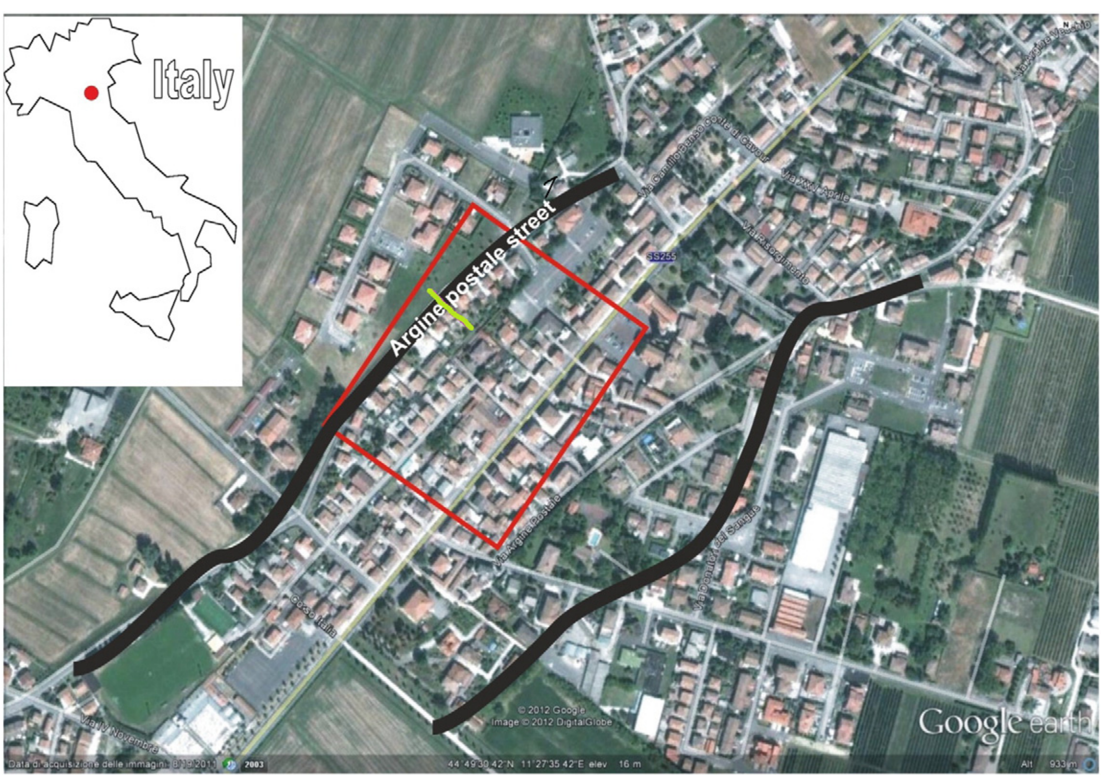

Fig. 1. Map of the geophysical investigation area (red rectangle) in Mirabello village. The black lines show the embankments (old Reno River). The green line indicates the seismic profile.