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Brief communication
"Ground failure and liquefaction phenomena triggered by the 20 May 2012 Emilia-Romagna (Northern Italy) earthquake: case study of Sant'Agostino–San Carlo–Mirabello zone"

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Abstract. The basic aim of this study was to observe and report the earthquake-induced ground deformation of the $M_\mathrm{W} = 6.1$ Emilia-Romagna (Northern Italy) event that occurred on the 20 May 2012. The event caused widespread structural damages in a large area of the Po Plain, while the most characteristic geological effects were ground failure, lateral spreading and liquefaction. This post-earthquake reconnaissance report focuses on secondary effects within the area between the villages of Sant'Agostino, San Carlo and Mirabello located along a former reach of the Reno River. Our field observations started just few hours after the main shock until the 28 May 2012.

1 Introduction

On the 20 May 2012 (04:03 local time), a strong earthquake ($M_\mathrm{w} = 6.1$) with a focal mechanism showing E–W trending, *S*-dipping reverse faulting occurred in the eastern sector of the alluvial plain of the Po River close to the border between Emilia-Romagna and Lombardy regions (Northern Italy). The activated tectonic structure is completely blind, though it was well known from a dense grid of seismic profiles for hydrocarbon explorations (Fig. 1; Pieri and Groppi, 1981; Toscani et al., 2009), while its recent activity was suggested by drainage anomalies (Burrato et al., 2003; Basili et al., 2008; DISS WG, 2010). The event induced extensive geological effects at the surface and structural damages in the broader epicentral area, up to a distance of 20 km. According to the *Istituto Nazionale di Geofisica e Vulcanologia* (INGV), the hypocenter was located at 44.89° N, 11.23° E at a depth of 6.3 km.

In this brief communication, we report and map ground failures triggered by the earthquake within a zone 8 km-long and 0.5 km-wide mainly corresponding to an abandoned reach of the Reno River. The developed maps were separated in liquefaction manifestations and surface cracks, respectively, and reproduced on a Google (2012) base layer (Fig. 2). In addition, a preliminary evaluation of the macroseismic intensity in the studied area is performed based on environmental seismic intensity scale (Michetti et al., 2007).

The villages in this area, Sant'Agostino, San Carlo and Mirabello (WSW of Ferrara), were constructed upon a former river channel and its related crevasse bodies and artificial levees; they suffered severe damage due to both lateral spreading and liquefaction. Similar secondary effects, within old and/or former river channel zones, were generated, for instance, during the 1992 Roermond, Netherlands–Germany (Trifonov et al., 1994); 1990 Luzon, Philippines; 2007 Niigata Chuetsu-oki, Japan; and 2010 Darfield, New Zealand earthquakes (Wotherspoon et al., 2012), showing that this type of morphological setting is favourable to earthquake-induced ground cracks and liquefaction phenomena.

2 Earthquake-induced ground deformations

Few hours after the event, a post-earthquake field survey was organized in order to report the secondary effects and to compile a map of their spatial distribution. The fact that this

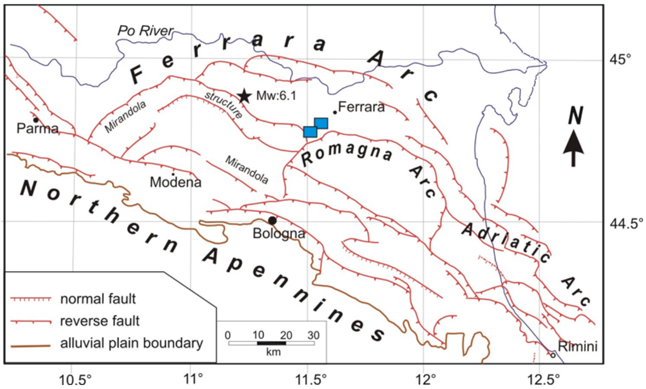

Fig. 1. Simplified tectonic map of the buried northern Apennines showing the studied area (blue boxes SW of Ferrara. Modified from CNR-PFG, 1991).

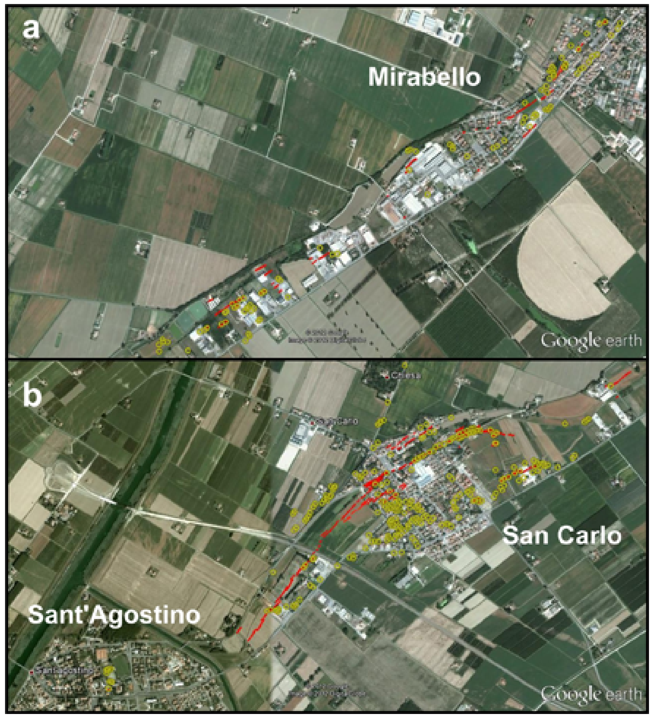

Fig. 2. Maps showing the liquefaction sites (yellow circles) and surface cracks (solid red lines) in the area of Mirabello **(a)** and San Carlo with Sant'Agostino **(b)**.

survey began few hours after the occurrence of earthquake provided the opportunity to observe, photographically record and map the sites where the sandy material was ejected, before the citizens and the local authorities started to remove the liquefied sandy material from their courtyards and roads.

In addition, short interviews with the villagers were realized by the authors concerning the ejection of water and sand and particularly the time of the ejection relative to the occurrence of earthquake, the duration of the phenomenon and the height of the ejection. According to these witnesses, the majority of the sandy material within the three urban areas focused on during the survey was ejected through large diameter water wells. The ejection of sandy material started almost at the same time with the shaking; at the beginning of the phenomenon, clear water came to the surface subsequently mixed with sand. The duration of the phenomenon was variable between few minutes and some tens of minutes, though in one case it was reported to have lasted for several hours.

Concerning the height of the ejection, the most characteristic report is relative to a water well, within the centre of San Carlo (44°48′15.39″ N, 11°24′35.14″ E), where the liquefied material was ejected up to 2 m above ground surface and the associated pressure damaged the well. Taking into account that the villagers reported a depth of water before the earthquake of approximately 6 m, it can be assumed that the total height of the ascent was more than 8 m (i.e. almost 1 bar or 0.1 MPa). Similar ascent and ejection of sand through wells was triggered by the 1976 Friuli, Northeastern Italy, earthquake and described by Sirovich (1996).

During this post-event investigation, more than 150 locations were surveyed and the parameters of liquefaction surface manifestations were measured and carefully recorded. In particular, the length and the width of vent fractures and the diameter of sand craters were measured, while samples from ejected materials at representative sites were collected in order to evaluate their grain characteristics. The length of the liquefaction-induced ground cracks varies, as it was expected, from few centimetres to more than 10 m. In Fig. 3a, it is shown a 10 m-long ground crack reported at a cornfield close to San Carlo (44°48′20.39″ N, 11°24′57.20″ E), where the ejected sandy material covers an area of about 40 m^2. On the other hand, the width variation of the cracks is not so wide and mainly ranges from few centimetres to 30 cm while at few sites the width is more than 50 cm. Most of the ejection of sandy material occurred through fractures and cracks on fields and roads pavements; thus, the number of sand craters and volcanoes is significantly lower than the vent fractures. The diameter in these cases ranges from 4 cm up to 40 cm. Furthermore, structural damages due to soil liquefaction were induced within these areas, such as broken pipelines as well as small-scale (∼ 3 cm) settlement and shifting of houses (Fig. 3b; 44°49′29.09″ N, 11°27′26.37″ E).

An area deserving particular attention is between the cemetery of Sant'Agostino and the village of San Carlo, where, at the top of the levee, a major system of surface cracks was generated, locally showing en echelon geometries, small grabens and oversteps (44°47′51.86″ N, 11°24′00.90″ E; Fig. 3c). At this locality a trench was excavated by the local authorities in order to repair a damaged pipeline (44°47′55.62″ N, 11°24′04.52″ E). As it is shown in Fig. 3d, at the southwestern wall of the trench, two vertical dikes of sandy material penetrated upwards the clayey brown cap layer trying unsuccessfully to reach the surface.

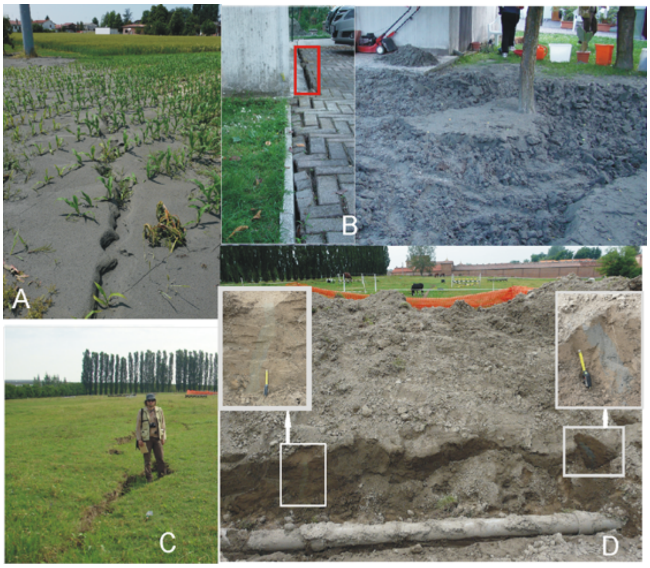

Fig. 3. Vent fractures with ejected sandy material **(a)**, sandy material covering the courtyard of a settled and shifted house **(b)**, surface ruptures **(c)**, evidence of a penetration of a clayey cap layer by a sandy material **(d)**.

However, 150 m to the southwest, large volumes of sandy material were instead ejected from a water well completely covering the courtyard of a house. In order to compare these two different cases, samples of soil material were collected and analysed in the laboratory for evaluating their grain size characteristics. The laboratory outcome is that both samples are classified as fine sands, while the fines content is 8 % and 18 % for the trench dike and the ejected material, respectively. The probable source layer should be the same since the variation in the fines content is more likely due to the upward flow through the silty-clayey cap layer. Preliminary results from a palaeoseismological investigation carried out in the same locality in a parallel trench suggest the occurrence of dikes associated with palaeo-liquefaction events (i.e. older than the 2012 earthquake; Caputo et al., 2012).

Furthermore, in order to assess the macroseismic intensity in the studied area, we applied the ESI scale (Michetti et al., 2007) due to the fact that the generated geological effects were widespread and extensive. Thus, taking into account the length and width of the ground cracks and the dimensions of vent fractures and sand boils of liquefaction phenomena, we conclude that macroseismic intensity should be evaluated as VIII in the area of San Carlo. In particular, according to the ESI definition of intensity degrees (Michetti et al., 2007), a value VIII is appropriate in areas where fractures up to 50 cm-wide and up to hundreds meters-long are commonly observed in loose alluvial deposits; decametric cracks are common in paved roads and liquefaction may be frequent in the epicentral area, localized lateral spreading and settlements (up to ca. 50 cm). In this case, the most typical effects are sand boils up to ca. 1 m in diameter. It should be mentioned that, due to the shock of the 29 May 2012 (whose effects are however not described in this note), failure and settlement phenomena in San Carlo were possibly reactivated and the opening of the fractures locally reached more than 100 cm thus suggesting a cumulative degree of almost IX in the ESI scale.

3 Conclusions

On the 20 May 2012, a strong earthquake occurred in the area of Emilia-Romagna, triggering extensive liquefaction-induced surface manifestations and structural damages within an epicentral distance up to 20 km. Few hours after the event, a post-earthquake field survey was organized in order to report the secondary effects within the area of Sant'Agostino–San Carlo–Mirabello, a zone 8 km-long and 0.5 km-wide. The aims were to observe the phenomenon, measure the effects and compile a map of their spatial distribution.

According to our observations, the length of the liquefaction-induced ground cracks varies from few centimetres to more than 10 m, while the opening of the cracks was commonly ranging from few centimetres to 30 cm (exceptionally up to 50 cm). In addition, as it was stated by local habitants, the ejection of sandy material mainly occurred through water wells large in diameter within the urbanized areas. According to witnesses, the ejection of the material started almost at the same time as the main shock; in the first seconds/minutes of the ejection process, clear water came to the surface and only afterwards did it mixed with sand.

Furthermore, laboratory analyses of soil samples collected from a liquefied site and from a dike in a trench located few meters away document that both materials are classified as fine sands, with fines content of 8 % and 18 %, respectively.

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