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The 2012 Emilia earthquake (Italy): Geotechnical characterization and ground response analyses of the paleo-Reno river levees

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ABSTRACT

In 2012 Northern Italy was hit by a seismic sequence with earthquakes of moderate local magnitudes and shallow hypocentral depths. After the main shocks of May 20, collapse of buildings and lifeline ruptures were widely observed in the epicentral area within a distance of about 15 km, where large acceleration values with prevailing vertical component were recorded. Locally, at a greater distance, intense and spectacular liquefaction effects were observed. They mainly affected the earthen embankments of the old Reno river channel (paleochannel), and, to a lesser extent, their immediate surroundings. In these far-field areas, ground surface accelerations were significantly low and not consistent with the spreading and extent of the observed liquefaction effects. A detailed geotechnical survey was performed to identify depth, location and behaviour of liquefied soil layers and to analyse their influence on ground response and surface liquefaction effects. Results from in situ and laboratory tests, performed under static and dynamic loading conditions, are presented herein and a complete geotechnical model of the ancient levees and the underlying soil deposit is proposed for numerical site-specific seismic analyses. More attention was paid to analysing the influence of non-linear behaviour of interbedded liquefied sands on the expected surface ground motion. Implications and limits of the results obtained are discussed with, finally, proposals for adjustments to 1-D linear equivalent models operating in the frequency domain, for taking into account stiffness degradation of liquefiable layers at high strain levels.

1. Introduction

In 2012 Northern Italy was hit by a seismic sequence that lasted over two months with more than 2000 shocks of moderate magnitude and relatively shallow hypocentral depth. They affected a large area extending East-West for nearly 55 km across the Po valley (Fig. 1). The most significant local magnitude (M_L) values, 5.9 and 5.8 were recorded on May 20 and 29 2012, respectively. The main shock of May 20 was followed, in a very short time interval of about 4 min, by two aftershocks of significant magnitude, 4.8 and 5.1, respectively. At this time, only a few permanent recording stations were available in the area affected by the earthquake. The largest macroseismic intensities ($VI < I_{MCS} < VIII$) were observed in the central-eastern part of the Po valley [1]. The greatest damage was observed in the near-fault area, within an epicentral distance of almost 15 km, due to the large acceleration values, with a prevailing vertical component, and to the vulnerability of some industrial facilities and historical monuments. Much lower peak ground accelerations were recorded at distances slightly further from the epicentre (>15 km) with prevailing horizontal components and minor damage to built-up areas.

After the main shock on May 20, widespread liquefaction phenomena were observed over quite a wide area of about 1200 km^2 with the greatest distance from the epicentre of about 30 km [2]. Some reactivation or weaker phenomena (less than 20% of all the observations made) may refer to the second main shock on May 29 [3]. The most intense and spectacular effects were on the earthen banks of the old Reno river channel (paleochannel) [4], and, to a lesser extent, in the vicinity, on reclaimed lands overlying recent alluvial soil deposits. According to definitions from literature [5], the detected effects may be attributed to Level Ground Liquefaction (LGL) and Cyclic Mobility (CM) phenomena, while flow liquefaction (FL) can definitely be excluded [6–10]. Field evidences of LGL were observed throughout the entire affected area and they mainly consisted of sand boils, large ground fissures and intense ejection of sand and water (craterlets) from ground cracks or hydraulic wells. To a lesser extent, CM also took place and induced vertical and horizontal ground displacements (lateral spreading), with some moderate consequences on the stability and serviceability of buildings and buried lifelines.

The major effects, due to soil liquefaction, occurred in the interbedded sandy saturated layers lying within or below the

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ancient levees, followed the main shock on May 20 and, secondarily, the event on May 29. Surveys and studies following these events have highlighted two main issues. Firstly, rather low ground surface accelerations (< 0.1g) on the earthen embankments or in their vicinity have been recorded (or derived from ground shaking maps); their values were not as high as would be expected from the widespread and significant field evidences of liquefaction. On the other hand occurrence of liquefaction phenomena associate to very low PGA values has been also recently documented in literature [11].

Secondly, ground instability phenomena (foundation settlement or tilting, partial or total loss of bearing capacity, overturning, etc.) and consequent structural damage were not particularly serious, despite the number and extent of liquefaction occurrences.

Location, depth and mechanical behaviour of the saturated sandy layers that may have liquefied within the paleochannel therefore needed to be more deeply investigated and their influence on surface ground motion analysed.

The first part of this paper presents and discusses results from available in situ and laboratory tests to define a reliable geotechnical model for the Reno river paleochannel. The second part investigates the influence of interbedded liquefied layers on surface ground motion by means of site-specific seismic analyses and compares its results with the observed effects. Finally, a practicable procedure was proposed to take into account the effects of cyclic degradation of liquefiable soils when using 1-D linear equivalent models.

2. Historical background

The area under study lies on a portion of the old Reno river paleochannel running SW-NE for a distance of nearly 10 km across the Po valley (Fig. 1) and includes the small villages of San Carlo and Mirabello (Fig. 2b). In this area, the subsoil is quite heterogeneous and mainly composed of fine sands and silts. It was probably originated from the river's own overbank deposit and was further improved by humans to provide protection from flooding for the rich farmland of the river floodplains [12–15]. Since the XVII century, when the natural course of Reno river was deviated a few kilometres south of the San Carlo village (Fig. 2), intense reclamation work was carried out with three types of intervention: filling, drainage, and mechanical water lifting [16,17]. More recently, the abandoned and reclaimed area has been progressively occupied by growing farm and industrial activities, the top of the embankments and the surrounding alluvial plain have so been intensively populated [18].

From a seismic point of view, the area of interest falls within a region of low-to-moderate activity, which originated from still active compressive movements of the Euro-Asiatic plate towards the African plate along its most north-western border ("Padan-Adriatic" thrust belt) [19,20].

Before the 2012 seismic sequence, several earthquakes of relatively low intensity affected the area in 1346, 1570 and 1796 (Fig. 1), moderate to heavy damage ($I_{MCS} > VII$) was recorded by historical chronicles [21,22]. As a result of the 1570 event, wide spread liquefaction phenomena were experimented a few kilometres north-east of the area under study, as a consequence of a seismic sequence of large duration and moderate intensity [21,23] and, during the 2012 earthquake, they recursively occurred mostly on the old river embankments (Fig. 2b).

3. Geotechnical characterization of the paleo-Reno levees

As reported in literature, the earthen levees, like those of the Reno river paleochannel, could generally be susceptible to liquefaction because they originated from deposition of loose granular soil particles through flooding water or weak compaction of man-made fills [5,24]. Because of its origin and changes over the past centuries, the subsoil in the area under study shows great variability in its properties. An intensive program of surveys, including in situ (boreholes, BH, standard penetration tests, SPT, cone penetration tests, CPT, and down-hole tests, DH) and laboratory tests (classification, CL, oedometric, EDO, resonant column, RC, static, TX, and cyclic, CTX, triaxial tests) were therefore planned to increase the existing database and to carry out detailed geotechnical characterization of the paleo-Reno river banks and the underlying soil deposit [6,7].

3.1. Field testing

Fig. 3 shows the location of bore-holes (BH), CPT and DH tests on the LIDAR high precision digital elevation model of the area of interest. The grey-shaded texture represents the altitude of the ground surface (varying between 11.6 m and 18.1 m asl) and evidences the paleochannel location and its extension.

The area is generally low lying and typically flat, gentle slopes of a few degrees are only encountered at the outer boundary of the two paleochannel levees, where the slope varies from approximately 30H:1V to 60H:1V (horizontal:vertical) with the

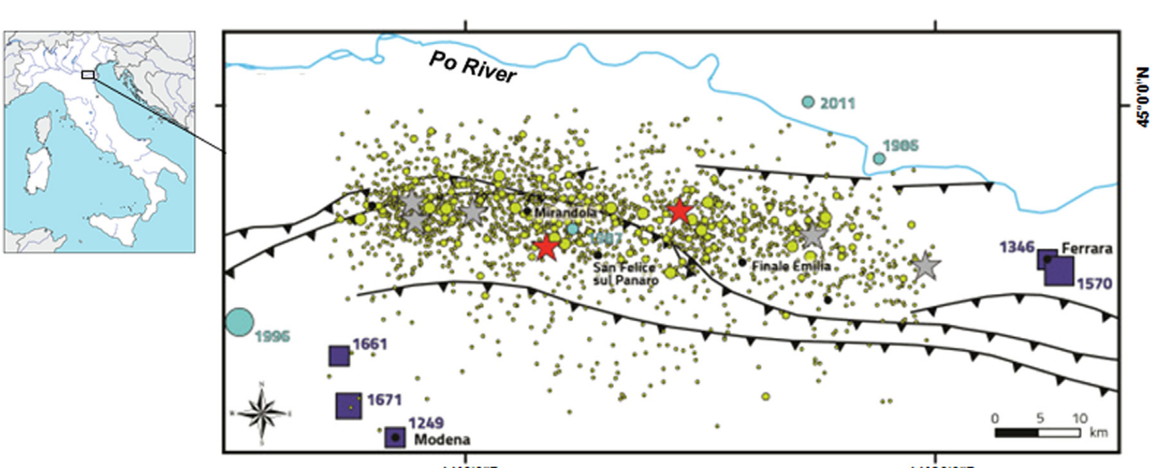

Fig. 1. Location of 2012 seismic sequence in the Po valley and historical earthquakes with year of occurrence (modified from Emergeo W.G. [2]).