THE PIANURA PADANA EMILIANA EARTHQUAKE

In May 2012, a large area of the Po river plain between the provinces of Ferrara and Modena was affected by a strong seismic event with magnitude greater than 5 (6.1 peak). This portion of the alluvial plain hosts many urban centres and industrial production activities, workshops and intensive farming.
This paper describes these phenomena and their relationship with the stability of buildings. In the urban and suburban centres as well as in rural areas, the earthquake caused the collapse of buildings and surface fracturing with sand liquefaction; this phenomenon occurs when a saturated soil devoid of cohesion passes rapidly from solid to liquid state, in conjunction with a strong earthquake. The sand bodies leaked from underground as large flows affecting the agricultural areas and urban centres located on top of old bumps that are found in ancient riverbeds. The seismic events occurred in rural areas have often used the wells and the irrigation network as a way of escape, whilst when on the inside of a building, the sand is likely to have followed escape routes created by human intervention

Sand liquefaction phenomena induced by the May 2012 Emilia Romagna Earthquake: geomorphological features and relations with the territory and building stability

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The fracturing phenomena was mainly about the Ferrara area, where the ENEA *Technical Unit for Seismic Engineering* of Bologna intervened along with the Civil Protection and municipal technicians for AEDES surveys, and in the geological and geophysical surveys in collaboration with OGS Trieste and the Department of Earth Sciences of University of Ferrara.
This area of the Po Valley hosts many urban centres and industrial production activities, workshops and intensive farming, in addition to an important historical structure made up of old farm buildings and fortifications.

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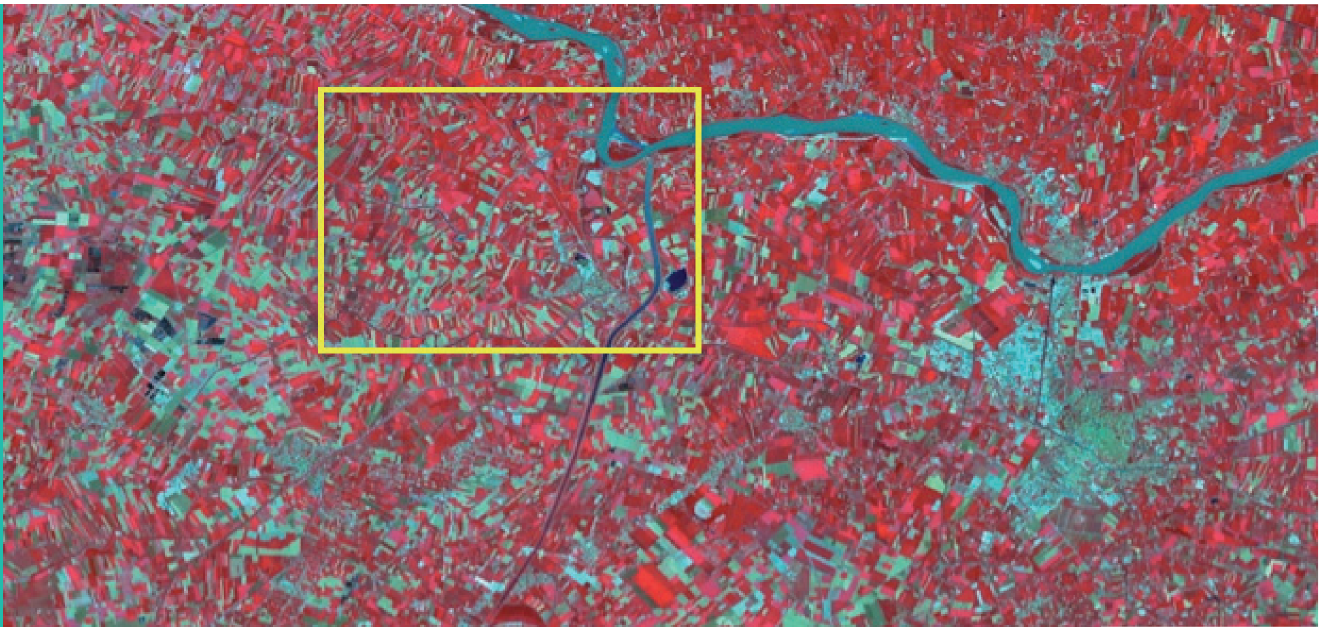

FIGURE 1 Landsat 7 ETM image, RGB 432): the false colour image takes up the land portion of the *alluvial plain,* there is intense agricultural activity. In red is shown the vegetation (cultivated areas); in cyan, *bare soils and urban centres* and economic activities

The area affected by the earthquake is a portion of the river plain between the Po and Panaro rivers and is a fluvial-marsh area. The evolutionary history of this area is very complex because the presence of important structures in the subsurface tectonic compression affects the rate of subsidence, sedimentation processes and the evolution of the rivers. Despite the great contributions of sediment from the Apennines (Reno River and Panaro), in this region there were large marsh areas as tectonics is responsible for high rates of subsidence [3], which not coincidentally correspond with the areas in which we measure negative gravity anomalies. Such marsh areas are interspersed among the areas with the lowest rate of subsidence, corresponding to the high structural, collisional active fronts [4]. Humans from the earliest settlements had been coping with this problem by building riverbed guns and through reclamation of marshlands controlled by overbank (filled).

These interventions of sandy sediment deviation (step flood) into the marshes, documented in historical maps and witnessed by archaeological studies, explain why clayey sediments and peat (typical of wetlands of low energy) intercalations of coarse sands are incompatible with the environment sedimentary swamp.

These areas reclaimed into the morphology of plain fluvial-marsh, are affected by intensive human settlement and highly fragmented land.

Thanks to the reclamation of these areas to flat morphology of fluvial-marsh, they were of particular interest to an intensive human settlement of the agricultural high fragmentation. The false color Landsat 7 ETM image takes up the land part of the Bondeno and Sant'Agostino Municipalities, and shows an intense agricultural activity with strong fragmentation (Fig. 1).

Liquefaction of loose deposits due to earthquakes

Soil liquefaction is the phenomenon obtained when a saturated-unconsolidated soil passes rapidly from

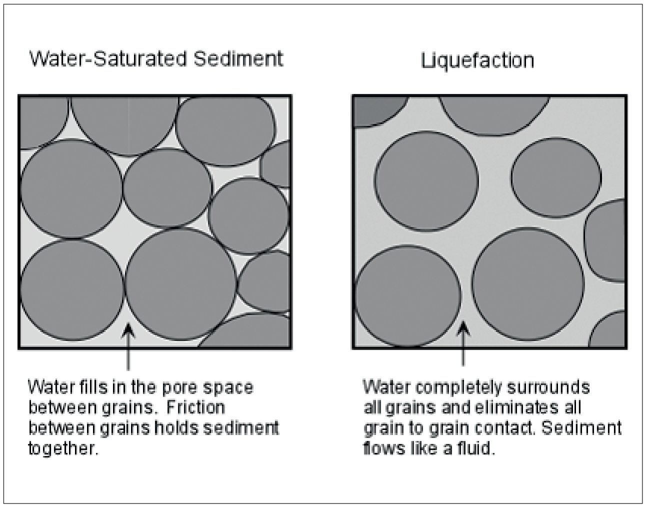

FIGURE 2 Loss of the resistance in a sediment due to liquefaction

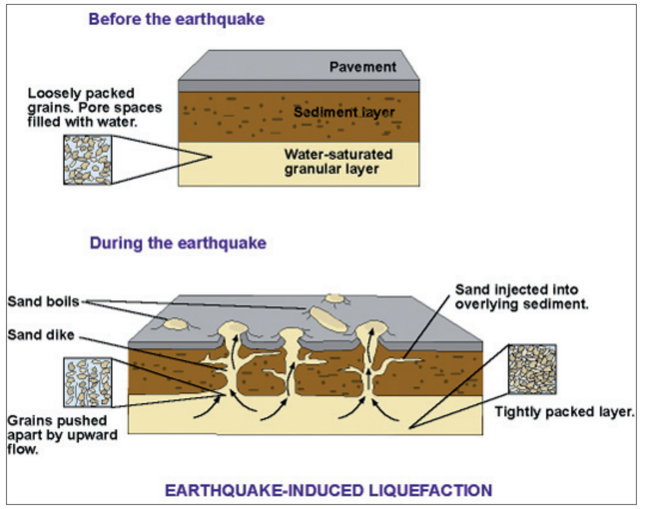

FIGURE 3 Diagram of the liquefaction phenomenon induced by earthquake

solid to liquid state; this transition is mainly due to the increase in interstitial pressure causing the loss of shear strength.

In geotechnics, the term 'liquefaction' is used to describe a loss of load-bearing capacity in water-saturated terrain under static or dynamic stress, in consequence of which the deposits reach a state of fluidity equal to that of a viscous mass.

The soils susceptible to liquefaction are those in which the deformation resistance is only due to the friction between particles (granular deposits, e.g. sand and silt).

A cyclic load applied to a saturated deposit can cause, for each cycle, an increase in pressure of water filling the pores between soil grains; if the water has not time to flow out before the next cycle, the hydraulic pressure can rapidly increase up to exceed the contact stress between grains (Fig. 2) with the consequent loss of shear strength. In this case, a soil layer can be unable to bear any weight and may be observed to flow like a liquid.

The most important phenomena that accompany liquefaction are therefore:

1) changes in pressure systems within the soil, with simultaneous effects of enhancement, redistribution and dissipation of the pore pressure;
2) changes in structure and relative position of soil layers during and after the phenomenon (Fig. 3).

The appearance of seismo-induced liquefaction in an area depends both on local geotechnical and hydrogeological characteristics of deposits (inducing conditions) and on the dimension of earthquake loadings (setting-off condition).

Between the inducing conditions it is worth mentioning: deep and thickness of potentially liquefiable deposits (less than 15-20 m from the ground surface); deep of water table (less than 5 m); relative density, average diameter and contents in fine fraction of fill material.

The setting-off conditions depend on the characteristics of the seismic action, which can be summarised in: magnitude (generally greater than 5.5); peak ground acceleration (PGA greater than 0.15g); duration of dynamic loading (more than 15-20 s). All these conditions are strictly related to the magnitude of inducing earthquake and to the distance from the epicentre.

In Italy, the distribution of magnitude vs epicentral distance values of earthquakes causing soil liquefaction (Fig. 4) shows that the level of magnitude reached by the May 2012 Emilia Romagna earthquake sequence can induce liquefaction phenom-

ena up to 40 km from the epicenter. Indeed, geological surveys found that the May 20th event (Mw 5.9) produced liquefaction phenomena up to about 25 km from the epicenter.
The phenomenon of liquefaction in the seismic areas of the event sequence being considered involved mainly the levels of sandy riverbed (Mirabello, St. Agostino, San Carlo), but also the marsh areas where fill interventions have made significant thicknesses of sandy sediments interbedded with clays.
In some cases the sand rose through the wells that are fed from the first confined aquifer, for which we cannot exclude contributions from this deeper body of water.
Generally in the phenomena of liquefaction the gases present in the subsurface are not involved, but in this case the abundance of peat levels within the sediments favors the formation of layers rich in methane and CO_2 present in solution in the water, which can increase the thrust upwards of the sands and therefore favor the triggering of liquefaction phenomena.
In support of this possibility occurred evident residues of peat in the sediments erupted in the liquefaction features, along with the emanation of malodorous gases from some of the fractures. It should be noted that they were already known phenomena of type "sinkhole" in the territory of Finale Emilia [7,8].
Considerable evidence indicates that liquefaction events were preceded by elevations of the piezometric level in the aquifer "pitched rid" of the seismic areas [7] and increase the enactment of gas from the ground, on which some blame the fish kill in the irrigation canals of the area; for this reason, in the future it would be important to build a network for monitoring these important precursors.

Geomorphological features

The phenomenon of liquefaction of the ground is quite common in the area affected by the earthquake (lower alluvial plain of Modena and Ferrara provinces), where there are deposits of silty-sandy riverbeds of the rivers Po, Panaro and Reno.
The first confrontations between the geomorphologic characteristics of the area and the location of the effects observed have shown a clear correlation with the presence, in the subsoil, of the riverbeds of the Secchia, Panaro and Reno rivers.

FIGURE 4
Relation between magnitude and epicentral distance for liquefaction effects in Italy
Source: Galli, 2000

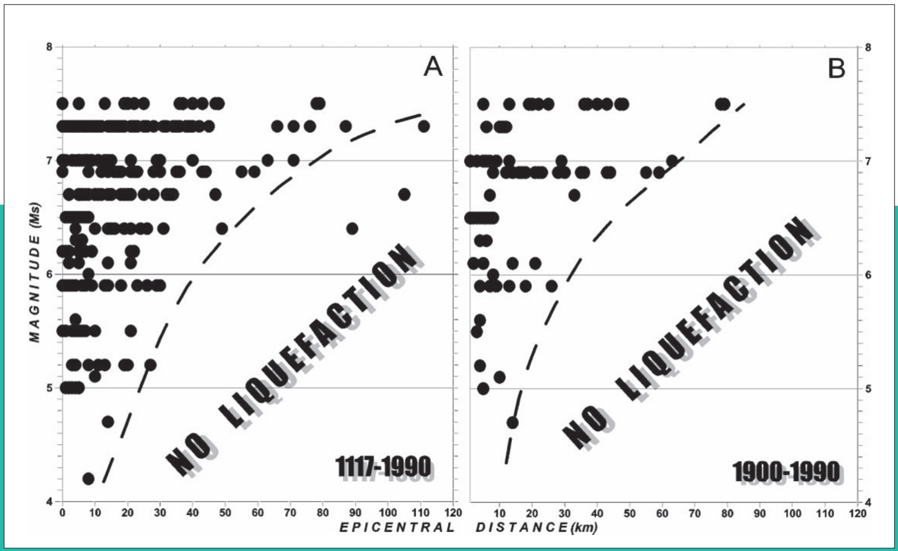

FIGURE 5 Sand liquefaction phenomena within an agricultural area

FIGURE 6 Morphological structures of casting sand

FIGURE 7 The structures are characterized by large sandy plateau

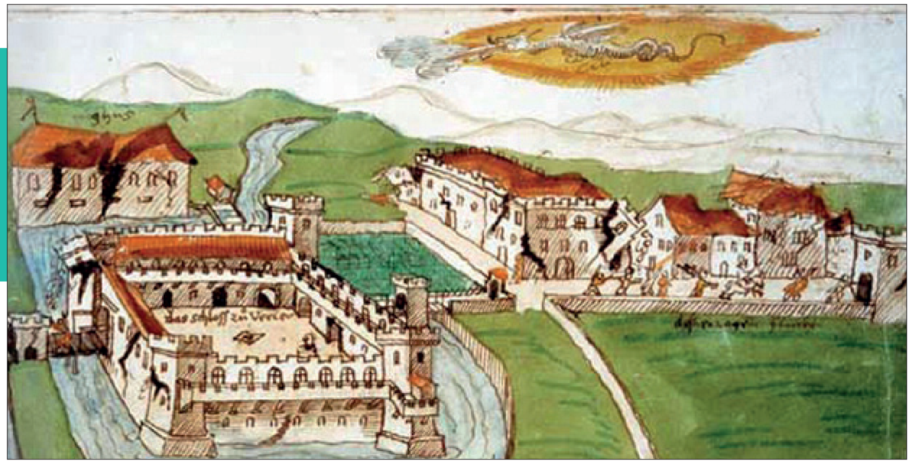

FIGURE 8
Ferrara destroyed by the earthquake of 1570
Source: H. J. Helden, Zurich, University Library

The phenomenon of sand release has manifested a series of en echelon iso-oriented fractures, that despite the modest extension (usually around meters) are expression of local environmental geo-tectonics. From the geomorphology point of view, the structures are characterized by large sandy plateau with a central ridge along the fracture line and with very light slopes to the outside (Figs. 5-6-7).
The sand release has manifested as casting sand and often has taken on the typical morphology of sand volcanoes. In many cases, the activity was polyphasic with changes of the grain size in the sediment issued. Often, at the base we have a strong presence of sand and silt fraction on top. The sand leakage from these large fractures (Figs. 6-7), that opened up the land after the big quake, is very fine and with well classed grain size, because it represents a large part of the layer of alluvial sediments in the subsurface, which deposited during the historic floods that have affected the area in the past centuries.

Liquefaction phenomena and buildings stability

Soil liquefaction cases in Italy

The phenomenon of soil liquefaction is not unknown to Italian geologists and seismologists, who over the years have developed complex risk studies involving the stability of buildings in the affected area.
The liquefaction phenomena usually occur in conjunction with a strong earthquake that causes drastic impact in the underground and on the stability of buildings; this event has accompanied the greatest earthquakes in the last century that have characterized the history of Italy: Calabria and Messina with the disastrous earthquake of 28 December 1908 up to the strong shocks in recent years that have affected the Apennine area. Indeed, during the great earthquake of Calabria in 1783, the phenomenon, as described in the chronicles of the time, forever changed the morphology of the territory, between the Serre and the Aspromonte massif. The destruction of Tedalto Castle and the San Paolo Church is attributed to liquefaction phenomena occurred during the Ferrara earthquake of 1570 (Fig. 8) and described by Pirro Ligorio [11].
In the case of the recent earthquake in Emilia Romagna, the sand liquefaction covered the land portion and buildings located on top of old bumps that are found in the ancient riverbeds.

Effects on building structures in the affected area: preliminary considerations

The release of the sands occurred in agricultural areas is often used as a way of escape for irrigation wells, in the cases occurred on the inside of buildings, the sand probably formed escape routes followed by human intervention. Figure 9 shows the effects of the sand liquefaction phenomena on the

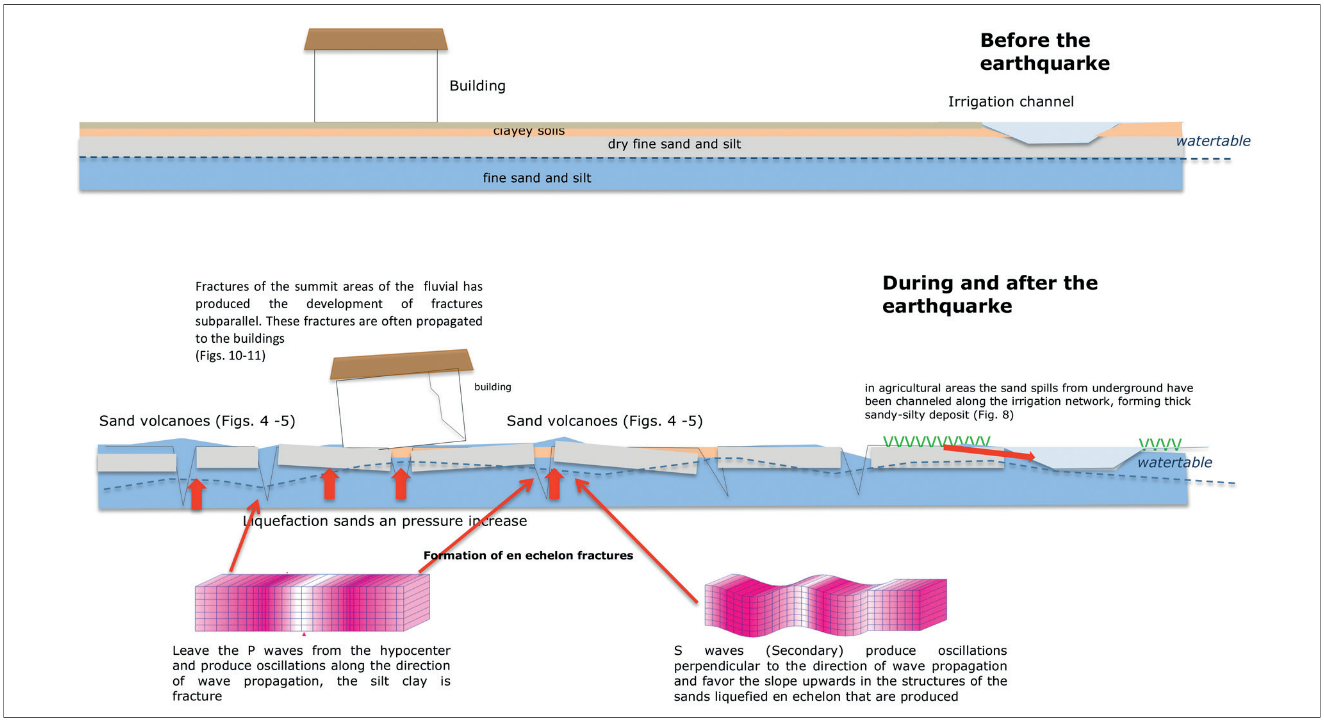

FIGURE 9 Soil liquefaction and effects on the stability of man-made structures: up) before the earthquarke; low) during and after the earthquake
Souce modified from: Institution of Professional Engineers of New Zealand) [10]

stability of man-made structures built before, during and after an earthquake.
The phenomenon is most evident in Sant'Agostino, particularly in the urban area of San Carlo (Fig. 10), the most damaged by the May 20th earthquake, where a great fracture has affected the city centre. During the main shock, the underground aquifer has raised sharply upwards to embrace the thick layer of sandy sediments present in the subsoil; the viscous sandy bodies then created have pressed strongly upwards until they escaped to the surface, through the fractures open in the ground. In agricultural areas the sand spills from un-

FIGURE 10 Sant'Agostino Municipality: one of the most damaged town by the earthquake of May 20th

FIGURE 11 Bondeno Municipality: sand spill that affected the irrigation channels in rural areas

FIGURE 12 Sant'Agostino Municipality: cracks with sand spill that affected the buildings and the road surface, and the sports field of San Felice

derground have been channelled along the irrigation network, forming thick sandy-silty deposits (Fig. 11).
Once the sandy mud was lying on the ground below the earth's surface without the previous sedimentation transferred, this process has greatly changed the structure of the subsoil, endangering the stability of buildings. Some other consequences of the soil liquefaction are:

- Loss of support to building foundations (Figs. 11-13);
- Fracturing of the summit areas of the banks of the old river, that has produced the development of fractures subparallel to its trend. These fractures are often propagated to the buildings and in the cemetery of San Agostino, in buildings of San Carlo and Mirabello and in the sports field of San Felice sul Panaro (Fig. 12);
- Near streams and rivers, the dry surface soil layers

FIGURE 13 San Carlo, Sant'Agostino Municipality: damage in residential buildings

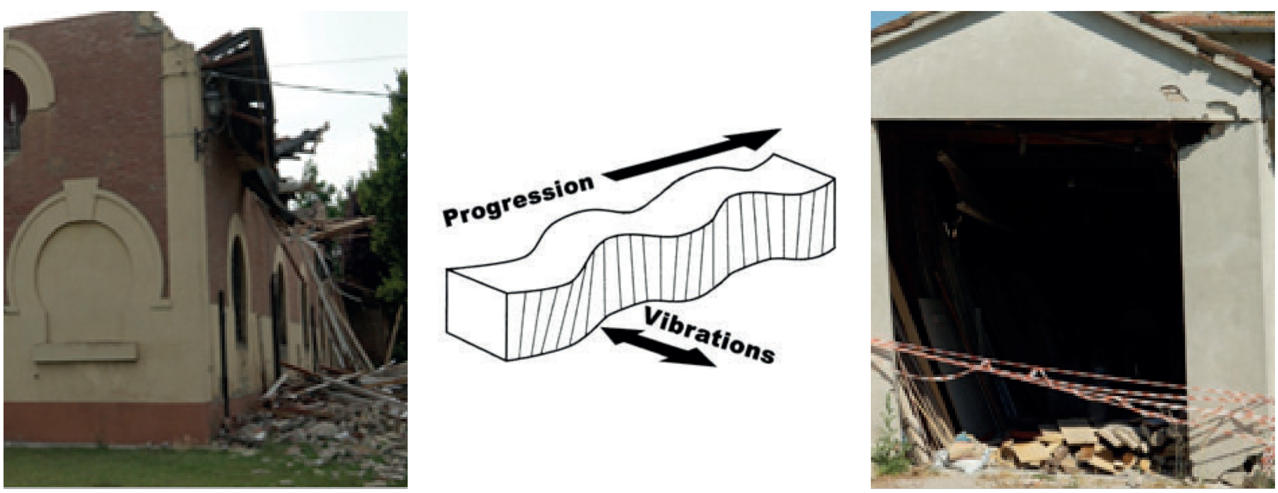

FIGURE 14 Deformation by P waves due to L wave: rural buildings damaged in the Sant'Agostino area

can slide sideways on the liquefied soil towards the streams; this is called lateral spreading (Fig. 9); this could be the cause of the damage to several rural settlements and can severely damage a building. It typically results in long fractures and cracks occurring in the soil surface and they resemble a classic fault line. Not every foundations of a building can be affected by liquefaction, as the affected area may shrink or be pulled sideways by lateral spreading and can seriously damage the building.

Conclusion

The seismic sequence that affected large areas of the alluvial plain of the Po river, on the border between the provinces of Ferrara, Modena, Mantova and Rovigo, has revealed the fragility of the area due to amplification phenomena and site effects that can be assessed by identifying morphological elements, and especially with a detailed reconstruction of the ex-

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treme variability of the subsurface lithology. In this work, demonstration activities in areas of significant tests have revealed the relationship between building structure, geomorphology and seismic phenomena (Fig. 9).

The damage observed (Fig. 14) may be mainly due to the amplification of S waves and L waves in alluvial sediments and their proximity to urban areas present in the earthquake hypocenter.

Moreover, important and visible structural damage reported by buildings due to the sands liquefaction phenomena may be a secondary sand erosion phenomena affecting the construction materials of foundations.

Acknowledgements

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