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3D geological model reconstruction for liquefaction hazard assessment in the Po Plain

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ABSTRACT: Liquefaction represents one of the effects that may occur during an earthquake. Several controlling factors may influence liquefaction occurrence. In particular, the thickness of the potentially liquefiable layers, the grain size of the sediments, the compaction degree and the interaction between different layers may strongly influence the phenomena. Hence, a deep understanding of the liquefying deposits is fundamental for the seismic hazard assessment. During the Emilia (Northern Italy) earthquake sequence of May-June 2012, several liquefaction phenomena were observed. In this work, a 3D geological model for liquefaction hazard assessment is presented for the Cavezzo municipality, strongly affected by this phenomenon. The study was performed in the framework of the European project Horizon 2020 "LIQUEFACT" using an interdisciplinary methodological approach involving geologists, geomorphologists, sedimentologists, engineering geologists and geotechnical engineers.

1 INTRODUCTION

Liquefaction represents one of the most dramatic effects that may occur during an earthquake (National Research Council, 1985). The liquefaction controlling factors are numerous, such as the earthquake magnitude, the peak ground acceleration, the geological-geomorphological context and the depth of the groundwater table. In particular, the grain size of the sediments, the thickness, geometry and facies distribution of the potentially liquefiable layers, as well as the compaction and the interaction between different layers during the pore water pressure redistribution may strongly influence the phenomena. For these reasons, a detailed characterization of the potentially liquefying deposits is pivotal to evaluate the hazard assessment. The construction of geological models for areas potentially affected by liquefaction is not a common approach, and the hazard assessment in most cases is treated on a point-by-point basis. The aim of this study was the development of a methodological approach in order to build a 3D geological model of the subsoil for liquefaction hazard assessment purposes.

The methodology was developed and tested in the Cavezzo municipality (Northern Italy), which was affected by several liquefaction phenomena during the Emilia earthquake sequence of May-June 2012 (Lo Presti et al. 2013) (more than 1,000 in the epicentral area; Emergeo Working Group, 2013). The site was selected for the large availability of geological-geotechnical investigations and it is representative of a fluvial environment characterized by a complex subsoil architecture. The study was performed in the framework of the European project Horizon 2020 "*LIQUEFACT - Assessment and mitigation of liquefaction potential across Europe: a holistic approach to protect structures/infrastructures for improved resilience to earthquake-induced liquefaction disasters*" (http://www.liquefact.eu/) using an interdisciplinary approach integrating geological engineering, geomorphological, sedimentological, and geotechnical engineering data.

1.1 *Geological and geomorphological setting*

The Cavezzo municipality is located within the northern sector of the Modena province (Italy), on the right side of the Secchia River. From the geological point of view, Cavezzo is on the southern limb of the buried Mirandola antiform (Boccaletti et al., 2004; Martelli et al., 2017). The lithostratigrafic succession of the area is composed by alluvial deposits ranging in thickness from around 130 m in the northern area to 280 m in the southern one (RER-ENI, 1998). The bedrock is constituted by interbedded marls and sands of the Pliocene and Lower Pleistocene "Argille Azzurre" Formation and Middle Pleistocene "Imola Sands" Formation (RER-ENI, 1998).

The seismic hazard of this area is related to the ground motion activity of the buried Ferrara folds. In particular, Cavezzo is located about 3 km away from the epicenter of the 29/05/2012 earthquake (M_w= 5.9; Rovida et al., 2016).

The alluvial deposits in the Cavezzo area are characterized by interbedded fine silty-clayey soils with layers rich of peat and interbedded sands and silty sands. These surficial sediments

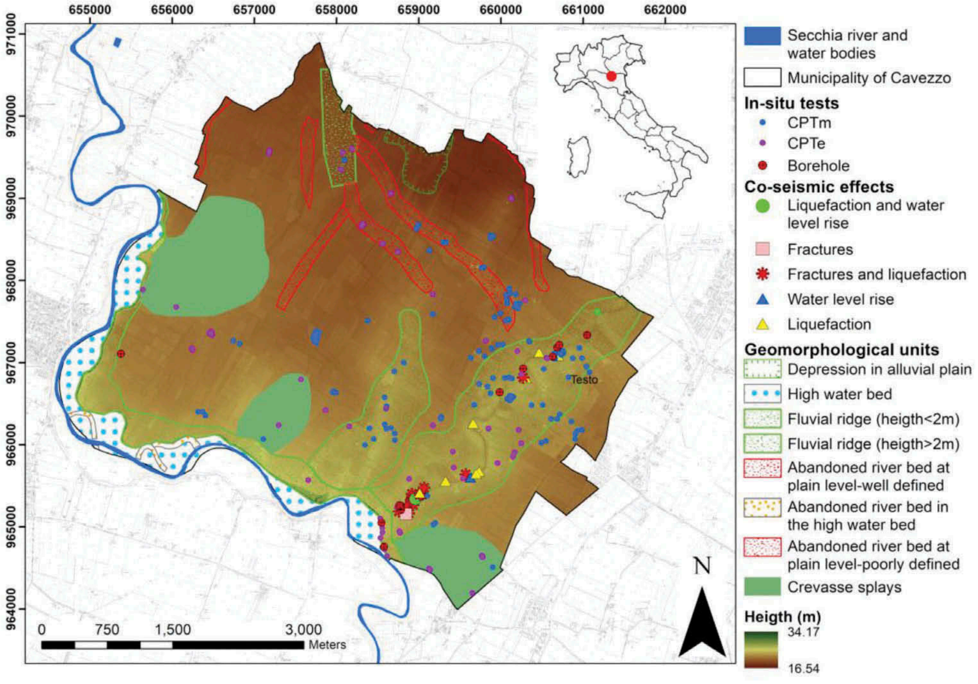

Figure 1. Geomorphological sketch of the study area with the location of the co-seismic phenomena and *in situ* investigations.

were deposited by the Secchia River, whereas the deeper sand layers were deposited by the Po River (Castaldini, 1989). From the morphological point of view, the study area is located in the alluvial plain of the Secchia River, ranging in elevation from 34 m a.s.l. in the southern and western sector to around 20 m a.s.l. in the northern part. It is worth noting that the highest topographic level is reached in correspondence of the modern artificial levees of the Secchia River, which raise about 7–8 m above the surrounding area (Figure 1).

The study area includes different geomorphological features interpreted as floodplain, fluvial ridges and crevasse splays. The subsoil of Cavezzo is mainly characterized by silty-clayey sequences including channel-filling and crevasse splay sand layers (Pellegrini & Zavatti, 1980).

Liquefaction phenomena were observed in Cavezzo after the 29th May 2012 earthquake (Lo Presti et al. 2013) along an abandoned ancient channel of the Secchia River (Castaldini 1989) running NW-SE. In particular, this ancient course was active during Roman and Medieval times until the 13th century (Lugli et al., 2007). Liquefaction phenomena were represented by sand boils, sand ejection from water wells and bulging and cracking of canal bed with sand ejection.

2 DATA AND METHODS

2.1 *In situ and laboratory test data*

The ground characterization in Cavezzo municipality was performed using in situ tests acquired during previous field surveys and investigations ad-hoc implemented in the framework of the LIQUEFACT project, from the following sources:

1. Database of the Regione Emilia Romagna (RER) (http://ambiente.regione.emilia-romagna.it/geologia/cartografia/webgis-banchedati/sezioni-geologiche-prove-geognostiche-pianura),
2. LIQUEFACT investigation campaigns,
3. post-2012 earthquakes data (MUDE -Modello Unico Digitale per l'Edilizia- database),
4. Investigation campaign funded by *Comune di Cavezzo* and *Regione Emilia-Romagna* in the framework of *Ordinanza del Capo Dipartimento della Protezione Civile n. 293/2015*.

The data collected and exploited for this study derive from boreholes, mechanic and electric cone penetration tests (CPTm and CPTu) and the laboratory analyses such as granulometric curves and Atterberg limits. The laboratory tests were performed by the Laboratory of Engineering Geology and Geotechnics of the Department of Earth and Environmental Sciences of University of Pavia and by Elletipi s.r.l. Furthermore, two field surveys were performed in Cavezzo the 03/04/2018 and the 04/09/2018 to measure maximum and minimum piezometric levels, respectively. These informations are fundamental to distinguish the most precautionary framework for the analysis of the liquefaction potentials.

The final database includes 13 boreholes and more than 450 cone penetration tests reaching the depth of 30 m.

2.2 *Methodological overview*

The developed methodological approach is focused on the construction of a three-dimensional geological model of the Cavezzo subsoil in order to identify and characterize the geometry (depth, thickness and lateral extension) of the sandy layers susceptible to liquefaction phenomena within the 30 m of depth using boreholes, cone penetration tests and laboratory classification tests.

The research was developed in five phases:

Phase 1. Data source collection and harmonization in GIS environment. Geomorphological map, superficial lithological map, man-made deposits map, map of the water table depth and geotechnical survey: Maps were produced through remote sensing and field surveys.

Phase 2. Lithological classes identification obtained through borehole stratigraphic profiles simplification and laboratory soil classification.

Phase 3. Lithological classes identification through CPTu and CPTm. The main issues of this step were the differences between CPTm and CPTu results and capabilities and their interpretation in term of subsurface stratigraphy. CPTu have a higher resolution and may detect even very thin liquefiable layers (measurements with piezocone, as well as those with electrical tip, are repeated every 2 cm). On the other hand, the reduction of the diameter of the tip above the cone, as in the mechanical penetrometer, leads to qc measurements greater than those obtained from CPTu in loose sand and soft clay; fs values measured with the mechanical bit are always greater than those measured with the electrical bit. Therefore, the interpretation of the stratigraphical, mechanical and electrical cone penetration test results was performed using different approaches, such as using the classification chart of Robertson (1990) and Schmertmann (1978), for CPTu and CPTm, respectively. The first approach allows to distinguish the SBTn (normalized Soil Behaviour Type) classes and the Ic values. The Schmertmann (1978) approach allows distinguishing the different lithotypes. To implement these classifications, the CPTu and CPTm measurements were analysed using the Geologismiky Geotechnical, CPeT-IT and GeoStru-Static Probing software, respectively. A correspondence table among the lithotypes of the Schmertmann (1978) classification and Robertson (1990) SBTn classes was implemented in order to harmonize the lithological classes obtained using CPTu and CPTm data (Meisina et al. 2017). The geotechnical properties of the identified lithological classes were investigated in detail and characterized by means of an exploratory data analysis of qc, fs and Ic values.

Phase 4. Geotechnical characterization of the geomorphological units through CPTu and CPTm. A visual inspection of the graphical representations of the qc, fs and Ic was performed to identify patterns and to spot anomalies selecting data on the basis of the geomorphological context. The analysis constitutes the first step in the identification of homogeneous lithological units characterized by a representative Ic trend (see Phase 6).

Phase 5. 3D engineering Geological model. The geological model was built up using the lithological classes identified by borehole, CPTu and CPTm data. The model was created by means of the "horizons to solids" algorithm via the Groundwater Modelling System (GMS) Aquaveo software. Firstly, the stratigraphic informations were imported and processed by GMS software, and then the solids were obtained using a conceptual model and the geological cross-sections as guide.

Phase 6. Lithological units for liquefaction hazard assessment (MOPS) identification. The lithological units represent homogeneous areas from the geomorphological and lithological point of view and are characterized by a stratigraphic profile representing the stratigraphic sequence (thickness and stratigraphic stacking pattern) and boundaries of the different lithological classes. The detection of the lithological units was achieved using to the stratigraphic logs obtained from boreholes and cone penetration tests, and by analyzing the Ic trends. In particular, the analysis of the stratigraphic profiles was performed using the 3D geological model and the geomorphological map in order to visualize the subsoil architectures and to distinguish the different depositional environments. First, for each landform, the lithological classes in the surface and in the first 30 m from the ground level was determined. Subsequently, the boundaries of the lithological units were manually drawn following the boundaries of the landforms and the subsoil architecture.

3 RESULTS

3.1 *Lithological classes identification through boreholes and CPTu and CPTm*

Thirteen borehole logs were examined, their depth ranges from 9 to 30 m from the ground level and they are mainly localized along the fluvial ridge of the Secchia River. The boreholes simplification was performed by interpreting the stratigraphic log. The lithological classes with a thickness lower than 40 cm were included in the lithological classes located at the top or at the bottom showing similar properties.

The results of the analysis indicate seven dominant lithologies (the lithological classes): man-made deposits (R), silty sand (S_l), sandy silt (L_s), clay (A), clay with peat (A_t) and sand (S). The CPTu and CPTm stratigraphic profiles were interpreted on the basis of the lithological classes identified from the boreholes. The table of correspondence adopted for the analyses and the identification of the lithological classes is shown in Table 1.

Table 1. Table of correspondence among the lithologies of Schmertmann (1978) and Robertson (1990) classifications and the lithological classes detected using the borehole logs.

Schmertmann (1978)	SBTn Robertson (1990)	Lithological classes from boreholes
Organic clay and mixed soils	2	Clay with peat (A_t)
Insensitive non fissured inorganic clays	3	Clay (A)
Sandy and silty clays	4	Clayey silt (L_a) and Sandy silt (L_s)
Clayey sands and silts	5	Sandy silt (L_s)
Silt – sand mixtures	6	Sandy silt (L_s) and silty sand (S_l)
Sands	7	Sand (S)

3.2 *Geotechnical characterization of the lithological units*

The CPTu and CPTm were also exploited to characterize from a geotechnical point of view the geomorphological contexts of Cavezzo by means of a visual inspection of the Ic trends.

In the fluvial ridge corresponding to the urban zone of Cavezzo (Figure 1), the analysis of the cone resistance (q_c) and sleeve friction (f_s) gives insight about a complex geological setting with a high lateral and vertical lithological variability probably due to the facies variations between fluvial channel and levee sediments. Therefore, the values of q_c of the superficial (5–10 m depth from the ground level) sandy layers are very different in the northern and the southern fluvial ridge area, ranging from 1,5 to 5 MPa. In deeper sands, from 15 to 20 m deep, the q_c values are higher than in the shallow ones, ranging from 2 to 15 MPa. The abandoned river bed areas are characterized by sandy layers with q_c values of the superficial sands similar to the fluvial ridge. The thickness of these soils is lower than the sandy layers detected in the fluvial ridge. Regarding the crevasse splays, the scarcity of geotechnical investigation affects their geotechnical characterization. However, the available cone penetration tests permit to identify interbedded thin layers of sandy silt and silty sand with qc value similar to the values observed in the fluvial ridge and in the abandoned river bed. The floodplain is characterized by shallow (0 to 2 m) sandy layers with values of q_c ranging from 0.58 to 4 MPa.

3.3 *3D engineering geological model*

To build the geological model of Cavezzo 47 cross-sections were used as guide in order to correlate the lithological classes using geological criteria considering the different depositional environments.

In particular, the following depositional environments were detected:

- UNIT A: heterogeneous deposits, lithological classes clayey silt (L_a) and sandy silt (L_s), with interbedded thin silty sand (S_l) corresponding to the recent floodplain;
- UNIT B: lithological classes sand (S), silty sand (S_l) and sandy silt (L_s) corresponding to the channel filling sediments;
- UNIT C: clay (A) and clay with peat (A_t) corresponding to lacustrine depositional environment;
- UNIT D: clay (A) of the ancient floodplain;
- UNIT E: dense sands (S) of the abandoned fluvial channel fill.

The results of the modelling give insight about 24 horizons present in the Cavezzo subsoil that represents the stratigraphic units. The horizons are numbered consecutively following the depositional sequence in the order that the strata are deposited coinciding with solids characterized by a defined lithological class. The first horizon is the man-made deposit that shows a homogeneous thickness across the study area. The deeper horizons are sand mixtures (sandy silt and silty sand) that are very discontinuous across Cavezzo and are mainly localized in the area of the fluvial ridge along the NE-SW direction. This area is characterized by lens of sandy mixtures in the first 15 m from the ground level. Locally these lenses are covered by clayey deposits. The lithological variability is lower in the floodplain mainly constituted by

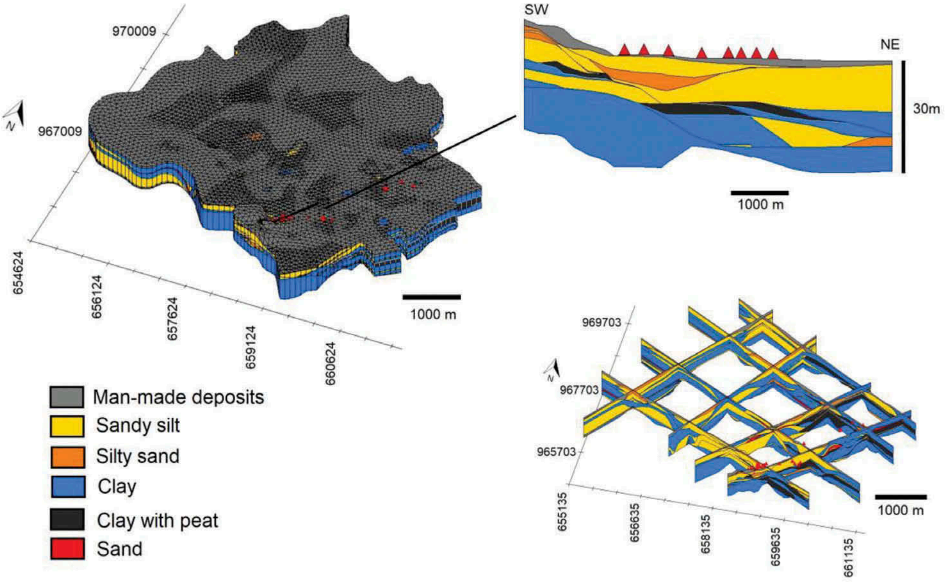

Figure 2. Solids of the 3D Geological model of Cavezzo and cross-sections of the model. Liquefaction phenomena are also reported as red triangles. A detail of a representative cross-section is reported.

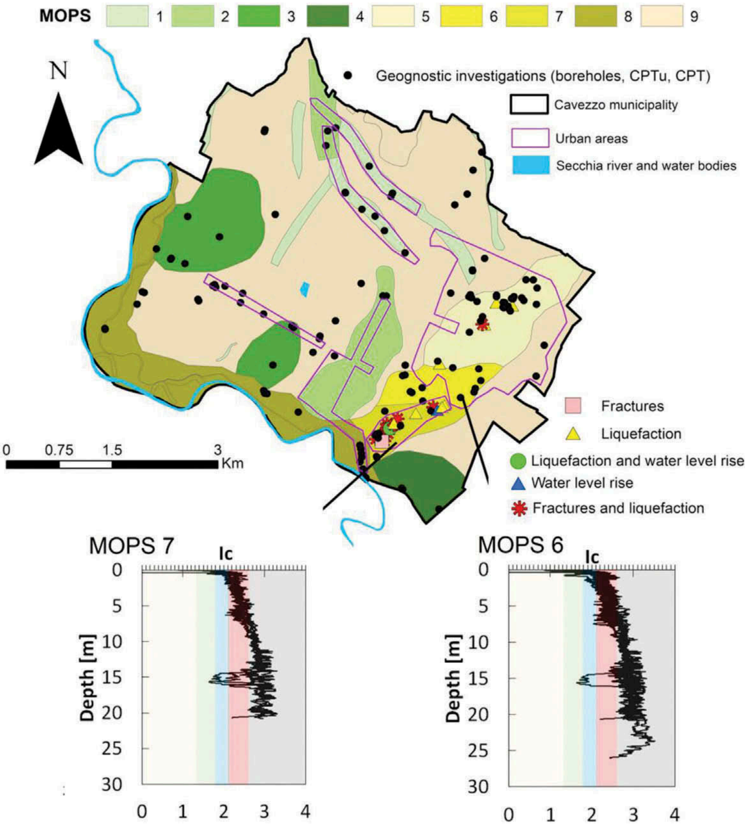

Figure 3. Lithological units (MOPS) in Cavezzo. The Ic trend for LU 6 and LU 7 is also reported.

Table 2. Lithological and geomorphological characteristics of the MOPS in Cavezzo.

Lithological units	Main lithostratigraphic features for microzonation studies	Landforms
1	Liquefiable sandy silt layers between 2 and 9 m from ground level	Abandoned river bed
2	Liquefiable sandy silt layers between 2 and 12 m from ground level	Abandoned river bed and ancient fluvial ridge
3	Liquefiable sandy silt layers between 2 and 9 m from ground level	Crevasse splay
4		
5	Liquefiable sandy silt and silty sand layers between 2–9 m and 9–12 m from ground level, respectively	Abandoned river bed and ancient fluvial ridge
6	Liquefiable sandy silt and silty sand layers between 2 and 8–9 m from ground level	Abandoned river bed and ancient fluvial ridge
7	Liquefiable sandy silt and silty sand layers between 2–9 m and 9–15 m from ground level, respectively	Abandoned river bed and ancient fluvial ridge
8	Liquefiable sandy silt layers between 9 and 14 m from ground level	Levees and present day river bed
9	Non-liquefiable silt/clayey soils	Floodplain

clayey soils. It is worth noting that plotting the location of the observed liquefaction phenomena of the 2012 earthquake within the 3D geological model, it is evident that the phenomena occurred where laterally confined lens of silty sand are present (Figure 2).

3.4 *Lithological units for liquefaction hazard assessment (MOPS)*

Lithological units for liquefaction hazard assessment (MOPS) were identified (Figure 3). All these units are characterized by a peculiar stratigraphic profile and by a typical trend in depth of Ic parameter. Liquefiable layers are identified in all the MOPS, except for the MOPS 9 corresponding to the floodplain sector (Table 2).

These layers are present at depths between 2 and 15 m from ground level and are composed of sandy silts or silty sands. Liquefiable deposits are separated or are alternated with clayey layers, generally at depths between 7 and 10 m from ground level. Despite the presence of liquefiable sediments in all the MOPS, the field evidence of coseismic events occurred in 2012 shows that only MOPS between 5, 6 and 7 had the potential of causing liquefaction (Figure 3): A similar result was detected in the San Carlo area (Fontana et al., 2015). In MOPS 5 and 7, these materials were silty sands and sandy silts present at depths between 2 and 12 m from ground level, which sometimes are overlain by 1 m-thick clay layers. In MOPS 6, silty sands and sandy silts responsible of liquefaction are not overlain by clayey deposits. Moreover, the 3D geometry of the silty sands and sandy silts layers in MOPS 5, 6 and 7 show that these sediments are comprised between clayey and silty deposits, both vertically and laterally, and form relatively confined bodies with moderate lateral extension, generally few hundreds of meters. Differently, sandy silt and silty sand layers identified in the other MOPS where liquefaction phenomena did not occur form continuous bodies within fine-grained units.

4 CONCLUSIONS

The paper described an innovative approach that allows to build an engineering geological model using cone penetration test and borehole data in order to identify liquefiable layers and to improve the knowledge on their distribution and geometry. This method was applied in a complex geomorphological and lithological context located in northern Italy. It corresponds to an alluvial plain characterized by different depositional bodies, some of which are prone to liquefaction induced by seismic events. The procedure allows to integrate field data collected through different direct and indirect surveys, such as boreholes, CPTm and CPTu using a correspondence among the lithological classes and different geognostic investigations. The results give insight on the possibility to recognize potentially liquefiable lithological units, important for hazard assessment (MOPS) using Ic trends. The proposed methodology identifies confined sandy silts and silty sands bodies as the most susceptible layers to liquefaction. The 3D model built integrating the data of different surveys highlights the arrangement of these bodies in the subsoil, with a reliable correspondence to the liquefaction events that actually occurred during the seismic sequence in 2012.

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