Liquefaction potential evaluation in an intermountain Quaternary lacustrine basin (Fucino basin, central Italy): implications for seismic microzonation mapping

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Abstract

We analyzed in detail the susceptibility to liquefaction of the Pozzone site, located in the northern side of the Fucino lacustrine basin in central Italy. The Fucino area was struck in 1915 by a Mw 7.0 earthquake, which produced widespread coseismic surface effects interpreted as liquefaction-related. At the Pozzone site the interpretation of the described phenomena is not straightforward. Moreover the site is characterized by prevailing fine-grained sediments, which are not the typical liquefiable soils. A number of detailed stratigraphic and geotechnical investigations (continuous-coring borehole, CPTu, SDMT, SPT, DPSH, geotechnical laboratory tests) were realized in order to remove uncertainties about the interpretation of the 1915 phenomena and provide insights for the liquefaction potential in a lacustrine environment, dominated by fine-grained sedimentation.

The stratigraphic succession of the first 18.5 m from the ground surface is made up of fine-grained sediments, with four packages of coarser sediments formed by interbedded sand, silty sand and sandy silt. These packages, interpreted as frontal lobes of an alluvial fan system within the lacustrine succession, are highly susceptible to liquefaction. We found evidence of a paleo-liquefaction at 2.1-

2.3 m depths, occurred between 12.1-10.8 and 9.43-9.13 kyrs ago, which together with the geotechnical analyses pointed out that the site is liquefiable for 1915-like earthquakes.

Though we found a broad agreement among CPTu, DMT and shear wave velocity "simplified procedures" in detecting the liquefaction potential of silty sand to sandy silt layers, our results suggest that the use and comparison of different in situ techniques are highly recommended for reliable estimates of the cyclic liquefaction resistance in lacustrine sites characterized by high content of fine-grained soils.

In these geologic environments, where liquefiable layers can be not so obvious to detect, only detailed stratigraphic reconstructions, in situ characterization and laboratory analyses can help recognizing those sites susceptible to liquefaction. This has implications on basic (Level 1) seismic microzonation mapping, which usually relies on empirical evaluations based on geologic maps and pre-existing sub-surface data (age and type of deposits, prevailing grain size, depth of water table).

Commentato [UW1]: REVIEWER'S COMMENT 6

Keywords Seismic microzonation, Liquefaction, Paleoliquefaction, Fine-grained sediments, Lacustrine deposits, Fucino basin, Apennines.

1. Introduction

Coseismic ground failures due to liquefaction phenomena may cause severe damages to structures and infrastructures during strong-to-large earthquakes, as occurred during the 1995 Kobe, 2010-2011 Canterbury and 2012 Emilia Romagna earthquakes. In Italy, in spite of the very large number of liquefaction cases documented in modern, historical and pre-historical times (e.g. Galli, 2000; Fortunato et al., 2012), there are areas where the urban development has paid very little attention to assess liquefaction hazard, such as the Fucino basin (central Italy) which was struck by the 13 January 1915, M_s 7.0 earthquake. In the Fucino epicentral area Oddone (1915) documented a number of geological coseismic effects referable to liquefaction. So far, the urbanization policies (and practice) have not adequately taken into account the liquefaction hazard. This is confirmed by the examination of the small amount of geological, geophysical and geotechnical data collected in the urbanized area of the Fucino basin in the recent past. Ad hoc geological surveys and geotechnical investigations that are needed to assess the liquefaction potential are rare, and in most of the cases the available investigations are not suitable to quantify the susceptibility to liquefaction.

A possible reason for this lack of attention to liquefaction phenomenon in this area might be due to the high fine-grained (silt, clay) content within these lacustrine sediments. Here the presence of clean sand bodies (typically liquefiable deposits) are rare, or very thin and poorly continuous in places. This aspect induced to underestimate the liquefaction hazard, although evidences collected worldwide after the 1994 Northridge, 1999 Kocaeli, and 1999 Chi-Chi earthquakes have highlighted that a significant number of cases of liquefaction occurred in silty and clayey soils containing more than 15% clay-size particles (Bray and Sancio, 2006). For instance Bray et al. (2004) found liquefaction in the silts of Adapazari, Turkey. These soils that were observed to have liquefied during the Kocaeli earthquake did not typically meet the Chinese criteria (Wang 1979) for liquefaction-prone fine-grained soils. These evidences lead to consider the Chinese criteria inadequate and its use today is strongly discouraged (Idriss and Boulanger, 2006). After all, the liquefaction susceptibility of fine-grained material is a topic of broad interest and it has been debated since the last 15 years (Andrew and Martin, 2000; Sonmez, 2003; Cetin et al. 2004; Idriss and Boulanger, 2006; Bray et al. 2014).

The "historical criterion", stating that liquefaction can recur in areas where it is known to have occurred during past earthquakes, is still valid. Nevertheless a possible source of uncertainty in evaluating the susceptibility to liquefaction from historical documents depends on different interpretations of historical accounts. For example, some descriptions by Oddone (1915) after the Fucino earthquake clearly indicate the occurrence of liquefaction (e.g., ground fracturing with water and sand venting, sand volcanoes; see also Galli, 2000). Other surface effects can only be doubtfully related to liquefaction (e.g. ground deformation, water-level variations, water emissions, turbidity in natural lakes), such as for the Pozzone site in the northern side of the Fucino lacustrine basin (Fig. 1).

Nisio et al. (2007) have suggested that at the Pozzone site the 1915 earthquake might have triggered mechanisms of deep piping, significantly different from the shallow-origin mechanisms (<15-20 m depths) that are responsible for liquefaction in strict sense. This additional uncertainty increases the difficulty of liquefaction hazard assessment in the Fucino geologic context.

In this work the Pozzone test site is largely investigated to carry out liquefaction potential evaluation with the purposes of (1) confirming the liquefaction-origin of the phenomena observed after the 1915 earthquake; and (2) contributing to the evaluation of liquefaction potential in lacustrine environments, dominated by fine-grained sedimentation. These have implications on seismic microzonation (SM) mapping, in particular for basic SM (e.g., Level 1 SM according to Working Group SM 2008), which is typically based on geologic mapping and pre-existing sub-surface data, without specific geotechnical analyses.

Commentato [UW2]: REVIEWER'S COMMENT 6

2. Geology, seismic hazard and liquefaction susceptibility of the Fucino basin

2.1 Geological setting

The Fucino basin is a Quaternary tectonic depression located in the core of the central Apennines of Italy. Its evolution is related to the activity of two main fault systems. The first system strikes NW-SE and dips to the SW (Fucino normal fault system); the second system strikes WSW-ENE and dips to the SSE (Tre Monti fault system). Though the SSE-dipping Tre Monti system had an important role during the early evolution of the basin, the master fault of the graben is the SW-dipping Fucino fault system (Galadini and Messina, 1994). Seismic reflection data show a typical half-graben sedimentary infill in the hanging wall of the Fucino fault, with a maximum thickness up to about 1000 m of the Quaternary sediments (Cavinato et al., 2002). The Quaternary continental deposits cover unconformably a bedrock formed by Mesozoic to Middle Miocene carbonates, cropping out in the mountains surrounding the basin, and by Late Miocene siliciclastic turbidites, mostly buried by the Quaternary sediments (Fig. 1).

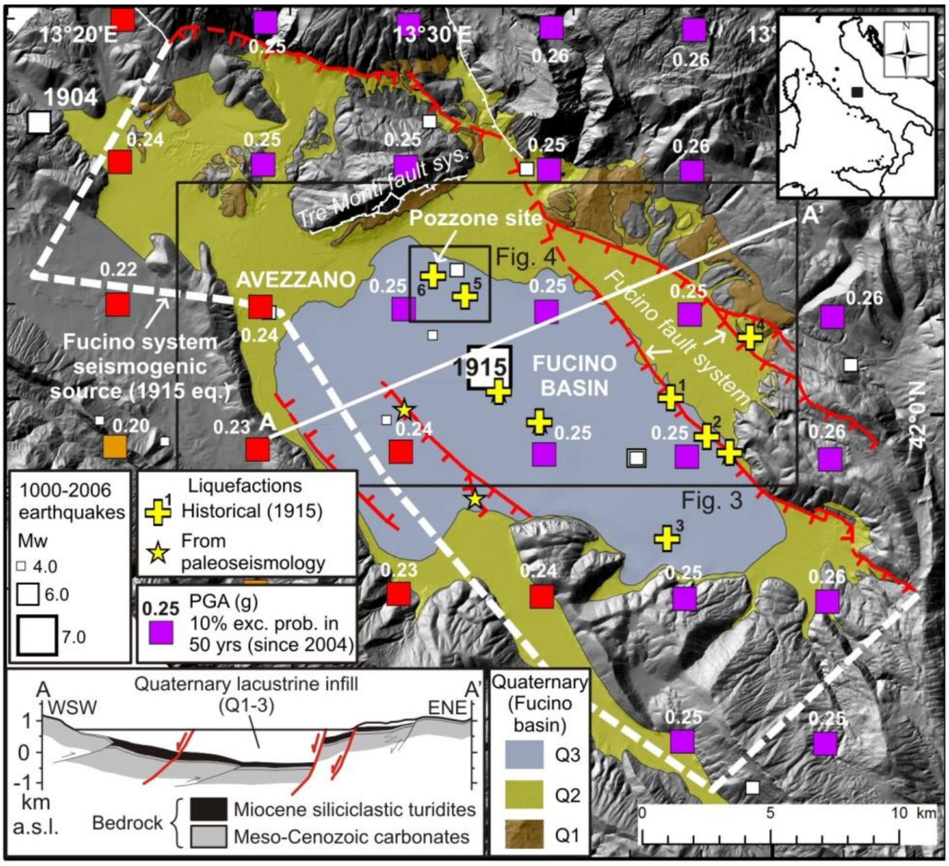

Fig. 1 Map of the Fucino basin in central Italy with location of liquefaction occurrences (crosses = 1915 M 7.0 earthquake from Oddone 1915 and Galli 2005; stars = paleoseismological investigations from Galadini et al. 1997; numbers refer to sites cited in the text). The Quaternary continental deposits of the Fucino lacustrine basin are divided in Q1 (Early-Middle Pleistocene), Q2 (Late Pleistocene) and Q3 (upper part of Late Pleistocene – Holocene). Geologic section is slightly modified from Cavinato et al. (2002). The Fucino normal fault system is in red; other active (Late Quaternary) normal faults are in white. The seismogenic source of the Fucino fault system is from Pace et al. (2011). Historical earthquakes are from CPTI15 Catalogue (Rovida et al. 2016). Points of peak ground acceleration (PGA) are from the probabilistic seismic hazard map of Italy (Working Group MPS 2004).

Concerning the age, stratigraphy and lithology of the Quaternary continental deposits, numerous works have been published in the last thirty years (Zarlenga 1987; Galadini and Messina 1994; Bosi et al. 1995; Cavinato et al. 2002; Centamore et al. 2006). More recently, three main stratigraphic successions have been defined for the drawing of the Geological Map of Italy in the Fucino area

(Sheet 368 Avezzano, available on-line at http://www.isprambiente.gov.it/Media/carg/368_AVEZZANO/Foglio.html):

1) The first succession includes old fluvial and lacustrine deposits, with thick interlayers of slope-derived massive breccia, which crop out in the northern and northeastern side of the basin (Q1 in Fig. 1). They are faulted and uplifted in the footwall of the main boundary normal faults; their age ranges from Early to Middle Pleistocene ("Aielli-Pescina" Supersynthem in the 1:50.000 Geologic Map of Italy, sheet 368 Avezzano);

2) The second succession characterizes the marginal area of the lacustrine depression, where fine-grained lacustrine sediments (silt and clay) are interbedded with coarse-grained (sand and gravel) alluvial, deltaic and shoreline deposits (Q2 in Fig. 1). At the surface the age is Late Pleistocene ("Valle Majelama" Synthem in the 1:50.000 geologic map of Italy; see also Giraudi 1988);

3) The third succession characterizes the central part of the basin, where the stratigraphy is dominated by fine-grained lacustrine sediments (silt and clay), with an increasing percentage of sand layers in the areas close to the margins (Q3 in Fig. 1). This area was occupied by a lake that was completely drained by the end of the XIX century. The age of the first few meters is Late Pleistocene (upper part) - Holocene (Giraudi 1988).

2.2 Historical seismicity and seismic hazard

The seismic history of the Fucino area is characterized by two strong earthquakes occurred during the last millennium (CPTI 15 Earthquake Catalogue; Rovida et al. 2016; Fig. 1). The first event struck northwest of the Fucino basin on 24 February 1904, producing an Intensity of VIII-IX on the MCS scale; the estimated M_w is 5.6. The second shock occurred on 13 January 1915 and was much larger. The epicentre was within the Fucino basin and the instrumental magnitude was M_s = 7.0 (Margottini and Screpanti 1999). Four localities including Avezzano, the largest town of the Fucino area, experienced total destruction (Intensity XI MCS; Locati et al. 2016); the fatalities were roughly 30,000. The earthquake produced several coseismic surface effects, including surface faulting, landslides, liquefaction, ground failure and hydrogeological anomalies (Oddone 1915; Galadini et al. 1999). The evidence of surface faulting documented by Oddone (1915) and by several paleoseismologic investigations performed during the ‘80s and ‘90s demonstrated that the 1915 earthquake ruptured the SW-dipping Fucino normal fault and its prolongation along the Magnola SSW-dipping fault, for a total surface rupture length of ~38 km. Paleoseismologists recognized 8 additional events of similar size ($M \sim 7.0$) between ~19 kyrs ago and 1915, with an average recurrence time ranging between 1400 and 2600 yrs (Serva et al. 1986; Michetti et al. 1996; Galadini and Galli 1999; Galli et al. 2008, 2012).

The probabilistic seismic hazard of the area, calculated on the basis of historical earthquakes, is among the highest of Italy (Fig. 1; Working Group MPS04 2004). The bedrock peak ground acceleration (*PGA*) expected to be exceeded with 10% probability in 50 years in the Fucino area ranges between 0.24 g and 0.26 g. These values do not account for the amplifications due to the lacustrine infill and its 3D geometry, which may be severe according to weak motion and microtremor data (e.g., Cara et al. 2011; Famiani et al. 2015).

2.3 Historical and paleo-liquefaction phenomena

Within the Fucino basin a number of liquefaction features related to the 1915 and other pre-historical earthquakes were recognized thanks to: 1) direct observation of coseisimic surface effects immediately after the 1915 earthquake (crosses in Fig. 1) documented by Oddone (1915; see also Galli 2000); and 2) paleoseismologic investigations (stars in Fig. 1; Galadini et al. 1997):

1) A number of liquefaction evidences on the surface was observed soon after the 1915 earthquake, such as the occurrence of small craters and ground fractures associated with water and sediment venting (sites 1, 2, 3 and 4 in Fig. 1) or the differential settlement of a building associated with the occurrence of loose sediment at the ground surface (site 5). The interpretation of other surface effects is less straightforward, such as for the Pozzone site (site 6). Near Pozzone there is a number of small natural lakes where Oddone (1915) documented ground fracturing, disappearance of a small island

within the largest of the Pozzone lakes, variations of the water level within the lakes, and long-lasting turbidity. Nisio et al. (2007) interpreted the Pozzone lakes as water-filled deep piping sinkholes, originated by processes which are controlled by overpressured fluids flowing up from the deep carbonate bedrock (> 100-200 m). Therefore, the earthquake might have reactivated a mechanism that is significantly different from the liquefaction in strict sense, which is typically of shallow origin (< 15-20 m).

2) The recognition of liquefaction phenomena in paleo-seismological trenches (stars in Fig. 1) are based on the presence of liquefaction-related sedimentary and structural features, such as sand dykes, sand sills, or braking of shallow layers into blocks separated by fissures filled by liquefied material (Galadini and Galli 1999).

2.4 Susceptibility to liquefaction from pre-existing shallow subsurface data

In order to have a first-order evaluation of the areal susceptibility to liquefaction only from pre-existing data, without additional specific investigations, a large number of stratigraphic logs from boreholes and geotechnical and geophysical data were collected in the entire Fucino area. This is the approach usually used in basic SM studies (Level 1 SM according to Working Group SM 2008), which rely on geologic maps and pre-existing subsurface data. Overall the present study gathered: a) 427 stratigraphic logs from boreholes drilled since '50s for hydrogeological exploration/exploitation (water wells in Fig. 2); b) 3 geophysical investigations (mostly Vertical Electric Soundings) for hydrogeological studies performed between '50s and '80s; and c) several in situ geotechnical investigations performed by professional geologists or published in the scientific literature (e.g. AGI 1991; Foti et al. 2006, Totani et al. 2000). The latter data include 69 stratigraphic logs from geognostic boreholes, 133 dynamic penetration tests (Dynamic Probing Super Heavy, DPSH), 8 cone penetration tests (CPT/CPTu), and 6 seismic and flat dilatometer tests (SDMT/DMT) (Fig. 2). The depth of the water table was obtained by using both the borehole data and the hydrogeological map of the Fucino area published by Petitta et al. (2005).

By combining subsurface data with surface geological data (Geologic Map of Italy, http://www.isprambiente.gov.it/Media/carg/368_AVEZZANO/Foglio.html; original unpublished geological maps from an ongoing project of seismic microzonation of the Avezzano Municipality), a number of detailed geological sections was constructed in order to define the geometry and lateral continuity of sedimentary bodies susceptible to liquefaction. In particular, the focus is on the northern side of the Fucino basin, where data are more abundant (Fig. 3). The reconstructed 2D geometries allow to identify areas characterized by water-saturated sand bodies within the first 20 m depth and therefore potentially susceptible to liquefaction.

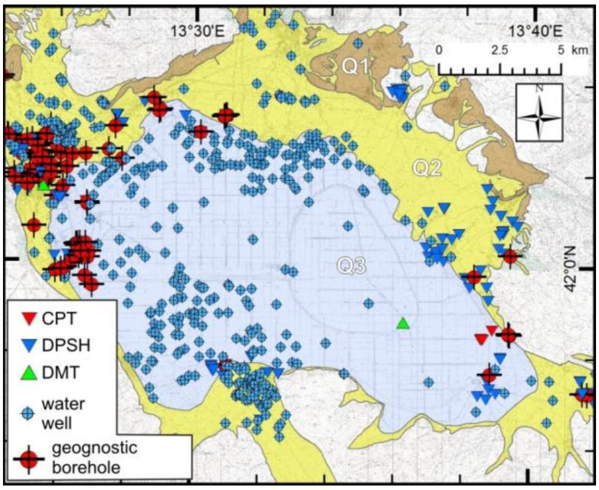

Fig. 2 Pre-existing data collected for estimating the first-order susceptibility to liquefaction. CPT = Cone Penetration Test; DPSH = Dynamic Probing Super Heavy; DMT = Flat Dilatometer Test. Geognostic boreholes often have in-hole SPT. Q1, Q2 and Q3 as in Fig. 1.

Commentato [UW3]: REVIEWER'S COMMENTS 4 and 5

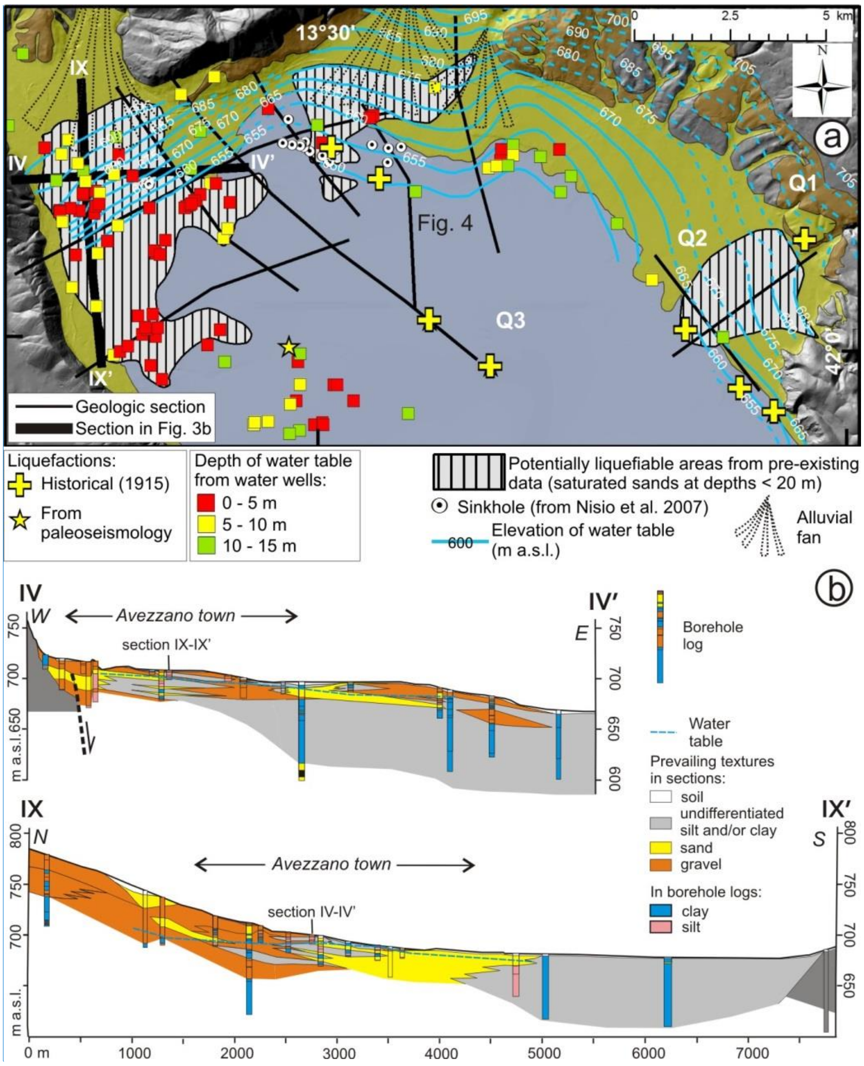

Fig. 3 a) Map of the northern Fucino area with areas potentially susceptible to liquefaction based on pre-existing geological data (areas with water-saturated sand bodies within the first 20 m depth); the elevation of the water table is from Petitta et al. (2005); Q1, Q2 and Q3 as in Fig. 1. b) Examples of geologic sections across the Avezzano town. Note that in the stratigraphic logs of some old water wells clay is not distinguished from silt, and fine-grained soil is indicated as "clay".

Commentato [UW4]: REVIEWER'S COMMENTS 4 and 5

It is interesting to note that most of the sites of historical or pre-historical liquefaction lies outside the potential liquefiable areas. This suggest that a) the features and phenomena interpreted as due to liquefaction must be reinterpreted, or more likely that b) pre-existing data are not sufficient for evaluating the liquefaction potential. Hereinafter the study will be focused on the Pozzone test site (Fig. 4).

3. The Pozzone test site: geological-geotechnical model and liquefaction assessment

3.1 Shallow subsurface geological model

The Pozzone site is located in the northern side of the Fucino lacustrine basin, in a flat area which was occupied by water before the drainage of the lake. Holocene lacustrine sediments of the unit Q3 crop out (Fig. 4). The area is located ~1 km south of the toe of a large alluvial fan (Celano alluvial fan; Q2 in Fig. 3). The fan fed the Fucino basin with coarse-grained material during the cold climatic conditions of Late Pleistocene. The Holocene lacustrine sediments (Q3) cover a thick pile of continental Quaternary deposits that, according to borehole and seismic reflection data, are up to 200-250 m thick (Cavinato et al. 2002; Boncio et al. 2015). At the time of the present work several synthetic stratigraphic logs of water wells drilled during the ‘50s were available (EF water wells in Fig. 4b, maximum depth 90 m). A detailed stratigraphic log from a continuous-coring geognostic borehole was available in the northern side of the area (UdA Paludi borehole in Fig. 4). The stratigraphy of the available EF water wells is coarsely described; silt is not distinguished from clay and pelitic sediments are generically described as “clay”. By comparing the stratigraphy of the EF wells with that defined in this work (S1 Pozzone geognostic borehole, Fig. 5), it is evident that the information from the old wells is insufficient for a liquefaction hazard study. Only discontinuous areas show sand bodies within 20 m depth (Fig. 4a). Below ~20 m depth there are extensive bodies of sands and gravels, but they do not influence significantly the liquefaction hazard.

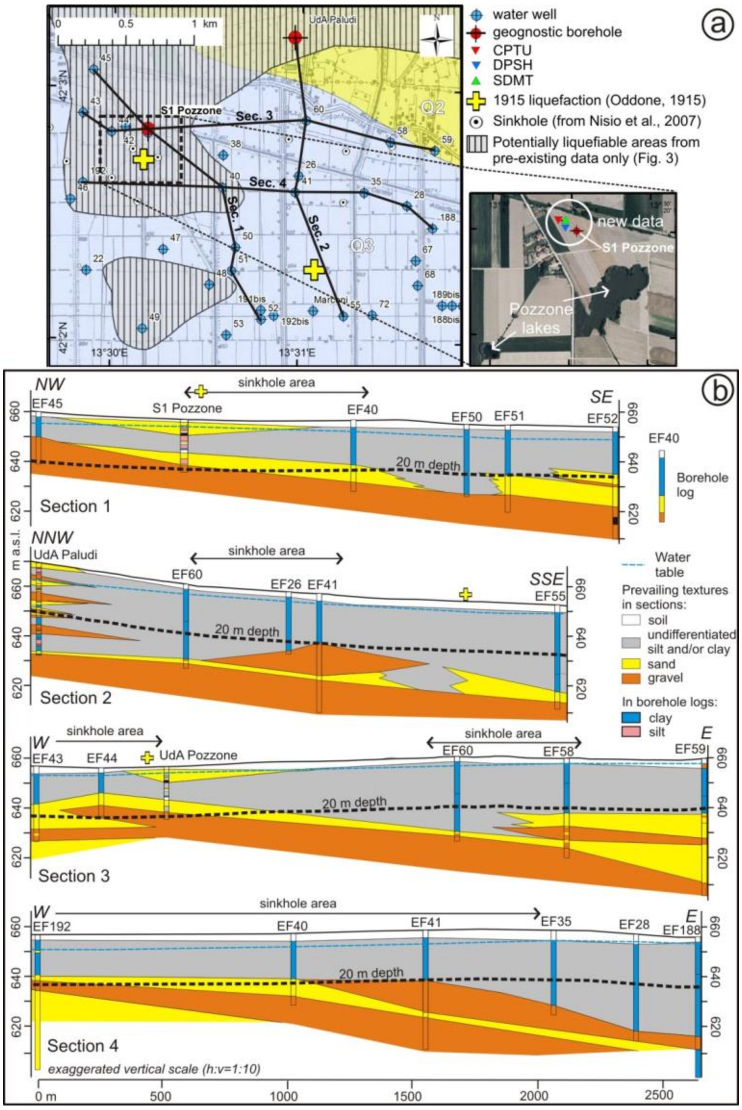

Fig. 4 a) Map of the Pozzone site (location in Fig.s 1, 3) and location of the new investigations. b) Geologic sections across the Pozzone area based on pre-existing borehole logs. Note that the stratigraphy of the EF water wells is coarsely described; clay is not distinguished from silt, and fine-grained soil is indicated as "clay". The detailed stratigraphy in the northern side of section 2 is from an unpublished 40-m deep continuous-coring geognostic borehole («UdA Paludi»). The detailed stratigraphy of the «S1 Pozzone» borehole is in Fig. 5.

In order to define a detailed stratigraphy at the Pozzone site a 21 m-deep, continuous-coring borehole was performed (S1 Pozzone in Fig. 4; location in Fig. 4a). The stratigraphy is illustrated in Fig. 5. At a depth of 18.5 m there is the top of a body of dense gravels which correlates with the gravels drilled by the EF water wells (Fig. 4b). From the surface to 18.5 m depth the stratigraphy is formed by four main strata of fine-grained sediments interlayered with four strata of coarser sediments. The fine-grained strata are 2-2.5 m thick and they are made up of silt or clayey silt, more rarely of silty clay. The coarser strata, 1.3 to 3.6 m thick, consist of decimetric layers of sand, silty sand and sandy silt. Between ~5 and 6.2 m we observed 3 layers of medium-coarse black volcanic sands with large biotite crystals which have been recognized in several places within the Fucino basin, with an age ranging between 27 and 19 kyrs before present (B.P.) (upper part of Late Pleistocene; Galadini and Galli 1999; Giraudi 1999).

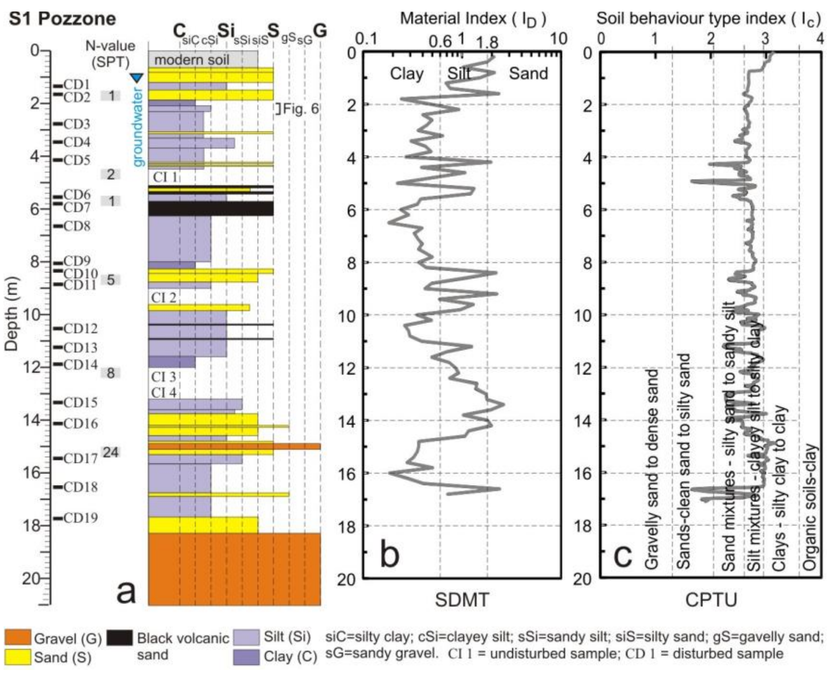

Fig. 5 a) Stratigraphy of the continuous-coring S1 Pozzone borehole from field logging; note that SPT tests were performed in a parallel hole; b, c) lithological characterization of the Pozzone site from SDMT (b) and CPTu (c) tests, located close to the S1 borehole; location in Fig. 4a.

At a depth of 2.13 m we observed an evidence of paleo-liquefaction (Fig. 6). Between 2.13 and 2.33 m there is a layer of gray silt with reddish bands denouncing oxidation or general pedogenic processes. This layer was recognized within the Fucino basin to be related to a period of low water level dated between 12.1 and 10.8 kyrs B.P.. During this period the marginal basin was exposed to subaerial conditions and erosion (Giraudi, 1999). On top of the reddish layer there is a mushroom-shaped body of loose sand formed by an upper lens 1-2 cm thick, convex upwards, connected downward with a curved dyke. This mushroom-shaped body can be interpreted as the remnant of a small sand blow. The top of the reddish layer is interpreted as the ground surface at the time of the liquefaction event (event horizon in the paleo-seismological literature). It is worthy to note that the entire reddish layer is deformed by soft-sediment deformations, consistent with the occurrence of an earthquake-induced liquefaction event.

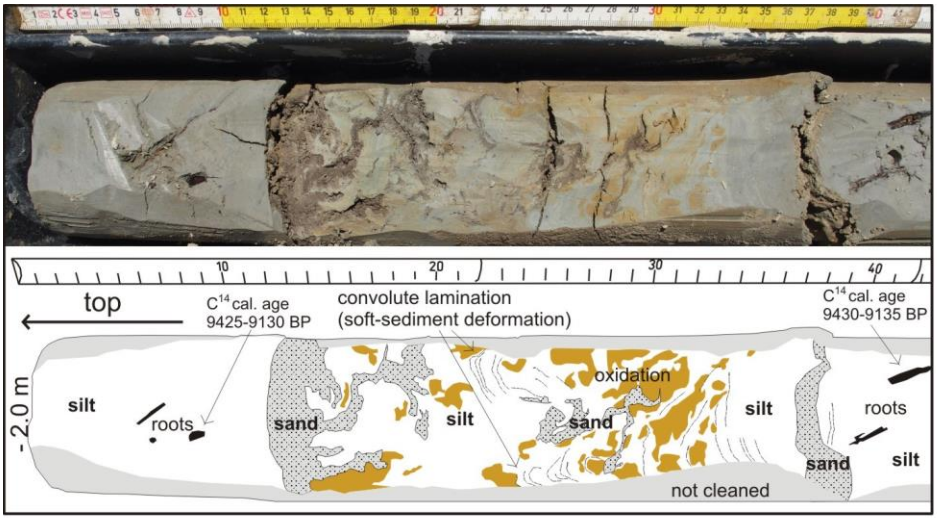

Fig. 6 Detail of the core sampled in the Pozzone borehole between 2.0 and 2.42 m depths showing a mushroom-shaped body of loose sand (2.12-2.20 m interval) interpreted as a remnant of a small sand blow due to a paleo-liquefaction event. The top layer at the time of the paleo-liquefaction is the reddish layer, deformed by soft-sediment structures. Note that the dated roots (ages from AMS C^{14} dating) are only apparently dispersed fragments. From a careful examination of the internal part of the core, they are continuous, nearly-vertical (life position) roots.

The sediments lying both above and below the paleo-liquefaction are penetrated by nearly-vertical roots 9.43-9.13 kyrs old (AMS C^{14} dating, calibrated ages B.P.). Therefore, the liquefaction event is younger than 12.1-10.8 kyrs ago (the age of the reddish layer) and older than the 9.43-9.13 kyrs-old roots. Interestingly, Galadini and Galli (1999), on the basis of extensive paleo-seismologic investigations, found evidence of two prehistoric earthquakes occurred between 12.7 and 7.5 kyrs B.P. The Pozzone paleo-liquefaction might correspond to the oldest of these two earthquakes.

3.2 Geotechnical and geophysical investigations for liquefaction potential assessment

Geotechnical and geophysical investigations were carried out in order to define a subsoil model and to provide a liquefaction assessment of the Pozzone site. In particular, we performed one seismic dilatometer test (SDMT1 sx+dx), one piezocone test (CPTu1), one dynamic super heavy penetration test (DPSH1), six in-hole standard penetration tests (SPT1, SPT2, SPT3, SPT4, SPT5, SPT6) along a hole close and parallel to the S1 borehole, two seismic noise measurements (POZ1, POZ2), and laboratory tests on 21 disturbed samples (sieve analyses and Atterberg limits). In the seismic tests by SDMT, two shear wave sources in a symmetrical configuration (hammer blows striking the anvil on two opposite sides) were used in order to produce two SH seismic wave trains with opposite polarities (SDMT1 sx and SDMT1 dx). Preliminary information on SDMT, CPTu, DPSH and noise measurements can be found in Amoroso et al. (2015a, 2015b).

Fig. 5 summarizes the borehole log information, together with the recorded SPT N-value (blows to drive the sampler 0.3 m), and the soil type classification from SDMT and CPTu investigations respectively in terms of material index I_D and soil behaviour type index I_c. In situ lithologies mostly correspond to the geological stratigraphy, considering that I_D and I_c are not grain size distribution indexes but reflect the mechanical soil response. In particular the Pozzone site is characterized by a sequence of silty clays and clayey silts with lenses of silty sand and sandy silt at 4.20-5.40 m, 8.40-10.60 m, and 12.60-14.20 m depths according to I_D (Marchetti 1980; Marchetti et al. 2001) and I_c (Robertson 1990, 2010) classifications.

Information on the real soil grain size distribution was obtained by laboratory tests. The results of sieve analyses and Atterberg limits for the disturbed samples are listed in Table 1 in terms of fine content (*FC*), liquid limit (*LL*), plastic limit (*PL*), and plasticity index (*PI*). These data confirm the prevalence of fine-grained material with some lenses of coarser deposits with high fine fraction (*FC* ≥ 19.31 %).

In terms of liquefaction susceptibility, according to Idriss and Boulanger (2008) these silty clays and clayey silts appear to belong to the transition between "sand-like" and "clay-like" behaviour across the fairly narrow range of *PI* ≈ 3-6 % on average. As a consequence the Pozzone fine-grained soils may exhibit an "intermediate" behaviour, that however could be more accurately investigated by performing cyclic triaxial or simple shear tests.

Commentato [UW5]: REVIEWER'S COMMENT 3

Table 1 Results of geotechnical laboratory tests, in terms of sieve analyses and Atterberg limits, on disturbed samples retrieved from the S1 Pozzone borehole (CD samples in Fig. 5).

Sample	Depth (m)	FC (%)	LL (%)	LP (%)	PI (%)
S1-CD1	1.30-1.40	97.80	40.15	34.57	5.57
S1-CD2	1.60-1.70	19.31	-	-	-
S1-CD3	2.75-2.85	99.74	-	-	-
S1-CD4	3.40-3.50	96.53	-	-	-
S1-CD5	4.10-4.20	99.67	39.87	34.52	5.35
S1-CD6	5.50-5.60	99.45	-	-	-
S1-CD7	5.75-5.85	50.54	-	-	-
S1-CD8	6.60-6.70	99.49	47.13	40.21	6.92
S1-CD9	8.00-8.10	99.54	44.57	39.15	5.42
S1-CD10	8.30-8.40	26.88	-	-	-
S1-CD11	8.80-8.90	98.92	37.30	35.47	1.83
S1-CD12	10.60-10.70	99.42	38.81	35.26	3.05
S1-CD13	11.20-11.30	99.87	45.89	39.52	6.37
S1-CD14	11.85 -11.95	98.09	39.31	27.63	11.68
S1-CD15	13.30-13.40	68.67	28.43	24.80	3.63
S1-CD16	14.10-14.20	42.92	-	-	-
S1-CD17	15.40-15.50	88.94	27.03	24.33	2.70

S1-CD18	16.50-16.60	99.62	41.71	34.85	6.86
S1-CD19	17.70-17.80	26.75	-	-	-

Fig. 7 summarizes the results obtained from CPTu1 in terms of corrected cone resistance q_t and sleeve friction f_s, and from SDMT1 sx+dx in terms of constrained modulus M and horizontal stress index K_D (related to stress history/OCR) obtained using common DMT interpretation formulae (Marchetti 1980, Marchetti et al. 2001), as well as measured shear wave velocity V_S. CPTu1 and SDMT1 sx+dx tests reached respectively 16.80 m and 17.10 m depth, where the soundings were stopped due to the presence of a gravelly layer. Both CPTu and SDMT profiles evidence a similar increase in mechanical resistance and stiffness of the soil, particularly in the silty sand and sandy silt at 4.20-5.40 m, 8.40-10.60 m, and 12.60-14.20 m depths according to q_t and M, and partially to V_S. The V_S profiles obtained from the left blow (SDMT1 sx), the right blow (SDMT1 dx) and from the average of the two seismic wave trains (SDMT1 sx+dx) are nearly coincident (Fig. 7). The average relative error estimated comparing SDMT1 sx or SDMT1 dx with SDMT1 sx+dx is roughly 4%. Such low uncertainty supports the use of a "true interval" configuration, striking the shear beam only at one end, adopted in current SDMT testing practice (Marchetti et al. 2008).

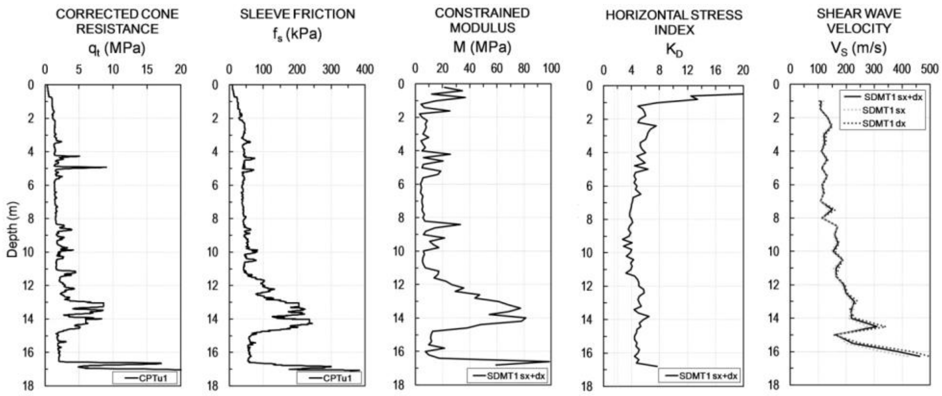

Fig. 7 CPTu and SDMT results at the Pozzone site.

The water table was detected at 1.7 m depth via the pore pressure u_2 obtained from the piezocone and the C-readings (see Marchetti et al. 2001), additional DMT measurements which were acquired only in sandy layers. Instead the water table depth measured in the borehole was found at 1.2 m below the ground surface. This variability can be justified considering the seasonal fluctuations of the water table and the different period of execution of the in situ tests and borehole.

Commentato [UW6]: Per Sara: Rivedere la frase

3.3 *Liquefaction analyses*

Procedures for assessing the liquefaction potential of sands and silty sands have been developed for a number of in-situ tests including SPT (e.g., Youd et al. 2001), CPT (e.g. Robertson and Wride 1998; Idriss and Boulanger 2008), and V_S measurements (Andrus and Stokoe 2000; Kayen et al. 2013). Methods for predicting liquefaction using the horizontal stress index K_D obtained from DMT have also been proposed (e.g., Monaco et al. 2005). Research has shown that K_D is sensitive to factors such as stress history, aging, cementation, and structure, which greatly increase the liquefaction resistance for a given relative density (Monaco and Schmertmann 2007; Monaco and Marchetti 2007). However at present these methods are supported by a limited liquefaction case history database.

The use of "redundant" correlations, based on different in situ techniques/parameters, is commonly recommended for a more reliable estimate of the cyclic liquefaction resistance *CRR*. For instance, Robertson and Wride (1998) recommended to estimate *CRR* by more than one method for medium- to high-risk projects, while *CRR* from CPT-only (preferred to SPT) may be adequate for low-risk, small-scale projects. The 1996-98 NCEER Workshops (Youd et al. 2001) recommended that, where possible, two or more tests should be used. Idriss and Boulanger (2004) warned that using a number of in situ tests should be the basis for standard practice and the allure of relying on a single approach (e.g. CPT-only) should be avoided.

At the Pozzone site the liquefaction analyses were carried out according to the "simplified procedure" introduced by Seed and Idriss (1971), based on the comparison of the seismic demand on a soil layer generated by the earthquake (cyclic stress ratio *CSR*) and the capacity of the soil to resist against liquefaction (cyclic resistance ratio *CRR*) for a reference magnitude 7.5. The liquefaction safety factor F_L was calculated as the ratio between *CRR* and *CSR*. In addition, the liquefaction potential index I_L

was calculated according to Iwasaki et al. (1982) to estimate the liquefaction susceptibility of the whole soil profile.

The cyclic stress ratio *CSR* was estimated by using the Seed and Idriss (1971) formulation, evaluating the Magnitude Scaling Factor *MSF* and the shear stress reduction coefficient r_d according to Idriss and Boulanger (2008) for CPTu and DMT data, and according to the procedures proposed by Andrus and Stokoe (2000) and Kayen et al. (2013) for V_S measurements.

For the seismic input assessment both probabilistic and deterministic approaches were considered. The probabilistic approach was based on the official seismic hazard map of Italy used for building design (Working Group MPS 2004; NTC 2008), while the deterministic approach considered the seismogenic source of the 13 January 1915 earthquake. Though the deterministic approach is the most reasonable for the back-analysis of phenomena associated to the 1915 earthquake, we also decided to explore the results from a probabilistic approach as it is commonly applied in the professional practice.

The probabilistic approach provided a value of the peak ground acceleration (PGA) of 0.34 g. This value was obtained as the product of the design peak ground acceleration a_g for a probability of exceedance of 10% in 50 years (return period of 475 years) on stiff soil (type A) and a stratigraphic amplification factor (S_S) and a topographic amplification factor (S_T), according to the Italian Building Code (NTC 2008). At the Pozzone site a_g is 0.25 g (Fig. 1; Working Group MPS 2004). S_S was estimated equal to 1.339 considering a ground type "C", as indicated by the V_S profile (Fig. 7), and S_T was considered equal to 1 as Pozzone is located in a flat area. The magnitude scaling factor *MSF* was calculated for a moment magnitude M_w = 5.66, obtained from the mean value of the magnitude (M) – distance (D) couple that mostly contribute to the probabilistic hazard of the site, as obtained by the disaggregated PGA in the interactive version of the Italian seismic hazard map (M = 5.66, D = 7.6; Working Group MPS, 2004; http://esse1-gis.mi.ingv.it/s1_en.php).

The deterministic approach estimated a value of the PGA of 0.5 g. This value is a mean of the PGA obtained from four different ground motion prediction equations (GMPEs; 1 = Bindi et al. 2011; 2 =

Akkar et al. 2014a, 2014b; 3 = Boore et al. 2014; 4 = Cauzzi et al. 2015), considering the distance (R) from the Pozzone site to the 1915 seismogenic source and the V_S profile of Fig. 7 (ground type "C"). The GMPEs 1 to 3 use the Joiner-Boore distance (R_{jb}, shortest distance from the site to the surface projection of the rupture), which was set equal to 0 as the Pozzone site is located within the surface projection of the 1915 rupture (Fig. 1). The GMPE 4 uses the R_{rup} distance (shortest distance from the site to the rupture surface), which was calculated to be 3.8 km by assuming an average dip of 50° for the seismogenic source. The magnitude scaling factor *MSF* was calculated for a moment magnitude $M_w = 7.0$, corresponding to the instrumental magnitude of the 13 January 1915 earthquake in Rovida et al. (2016).

The cyclic resistance ratio *CRR* was derived from CPTu and SDMT results. For CPTu data the Idriss and Boulanger (2008) approach was used, introducing the normalized cone tip resistance q_{c1N} for "sand-like" soils, and the s_u ratio, equal to s_u / σ'_{vc} (where s_u is the undrained shear strength and σ'_{vc} is the effective overburden stress), for "clay-like" soils. In absence of cyclic triaxial or simple shear test results, the limit between "sand-like" and "clay-like" behaviour was assumed to correspond with a soil behaviour type index I_c equal to 2.6. The Pozzone soil deposits were considered as sand-like for $I_c \leq 2.6$, and clay-like for $I_c > 2.6$. Instead DMT and V_S liquefaction assessment methods are available only for sand-like soils. The DMT-based correlations used to derive *CRR* from the horizontal stress index K_D were those proposed by Monaco et al. (2005), Tsai et al. (2009) and Robertson (2012). *CRR* was also estimated from the overburden stress corrected shear wave velocity V_{S1} according to Andrus and Stokoe (2000) and Kayen et al. (2013), introducing the fine content *FC* obtained from sieve analyses combined with *FC* estimated from CPTu. Both in the *CRR*-K_D and *CRR*-V_{S1} methods the Pozzone deposits were considered as sand-like when the DMT material index was $I_D \geq 1.2$.

Commentato [UW7]: REVIEWER'S COMMENT 3

The water table was considered equal to 1.2 m below the ground surface, which is the value directly measured in the S1 Pozzone borehole.

The results of the liquefaction analyses carried out using the probabilistic and deterministic seismic inputs are illustrated in Figs. 8 and 9, respectively. Each diagram shows the profiles with depth (z) of the soil behaviour type index I_c or the material index I_D, the parameter used in each case for evaluating CRR (q_{c1N}, K_D or V_{S1}), CSR compared to CRR multiplied by MSF, the liquefaction safety factor $F_L = CRR/(CSR /MSF)$, and the liquefaction potential index I_L.

The magnitude scaling factor is very sensitive to the used liquefaction assessment method and to the input magnitude. In particular, in the probabilistic approach, assuming $M_w = 5.66$, the calculated MSF values were $MSF = 1.62$ for CPTu and DMT sand-like soils (Idriss and Boulanger, 2008), $MSF = 1.10$ for CPTu clay-like soils (Idriss and Boulanger 2008), $MSF = 2.06$ for V_S sand-like soils (Andrus and Stokoe 2000), and $MSF = 1.46$ for V_S sand-like soils (Kayen et al. 2013). Instead in the deterministic approach, assuming $M_w = 7.0$, the calculated MSF values were $MSF = 1.14$ for CPTu and DMT sand-like soils, $MSF = 1.02$ for CPTu clay like soils, $MSF = 1.19$ for V_S sand-like soils, and $MSF = 1.10$ for V_S sand-like soils.

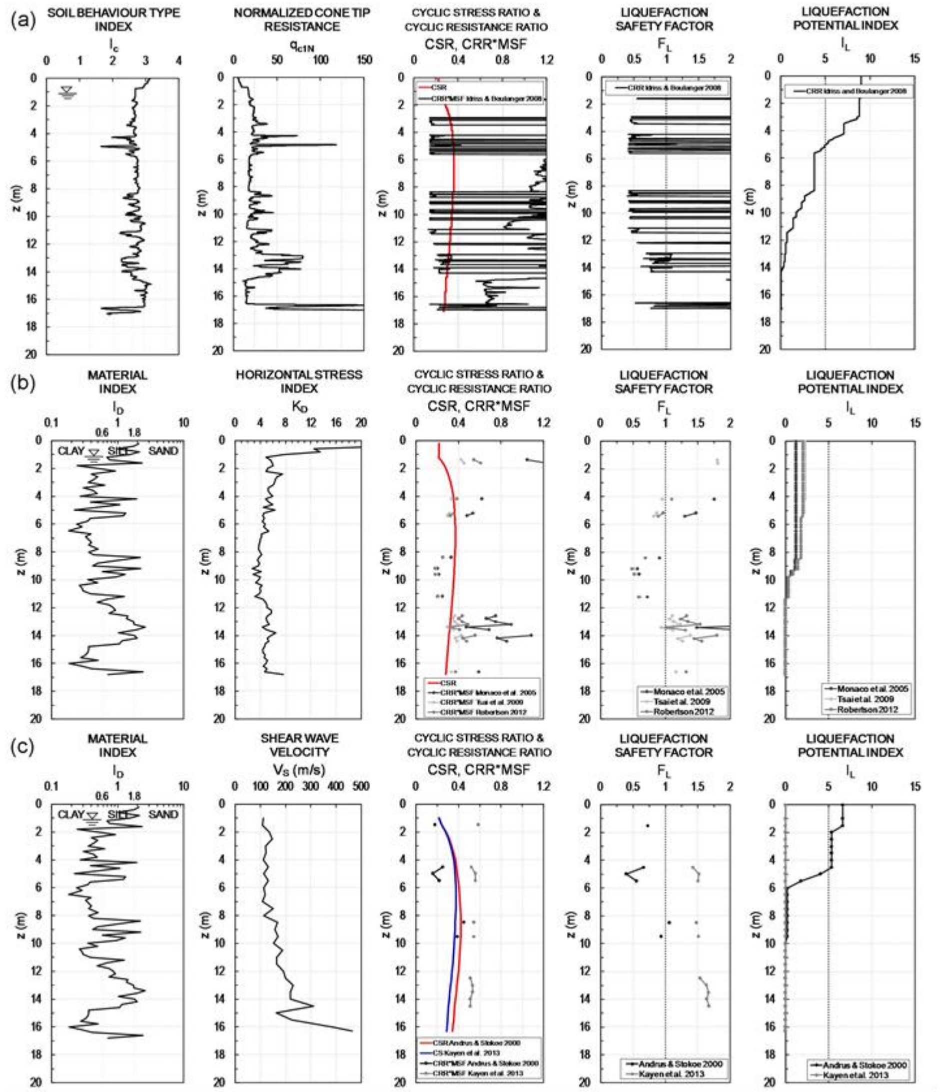

Fig. 8 Results of liquefaction analyses based on CPTu (a), DMT (b) and Vs (c) at the Pozzone site with seismic input defined by a probabilistic approach (Mw = 5.66, PGA = 0.34g).

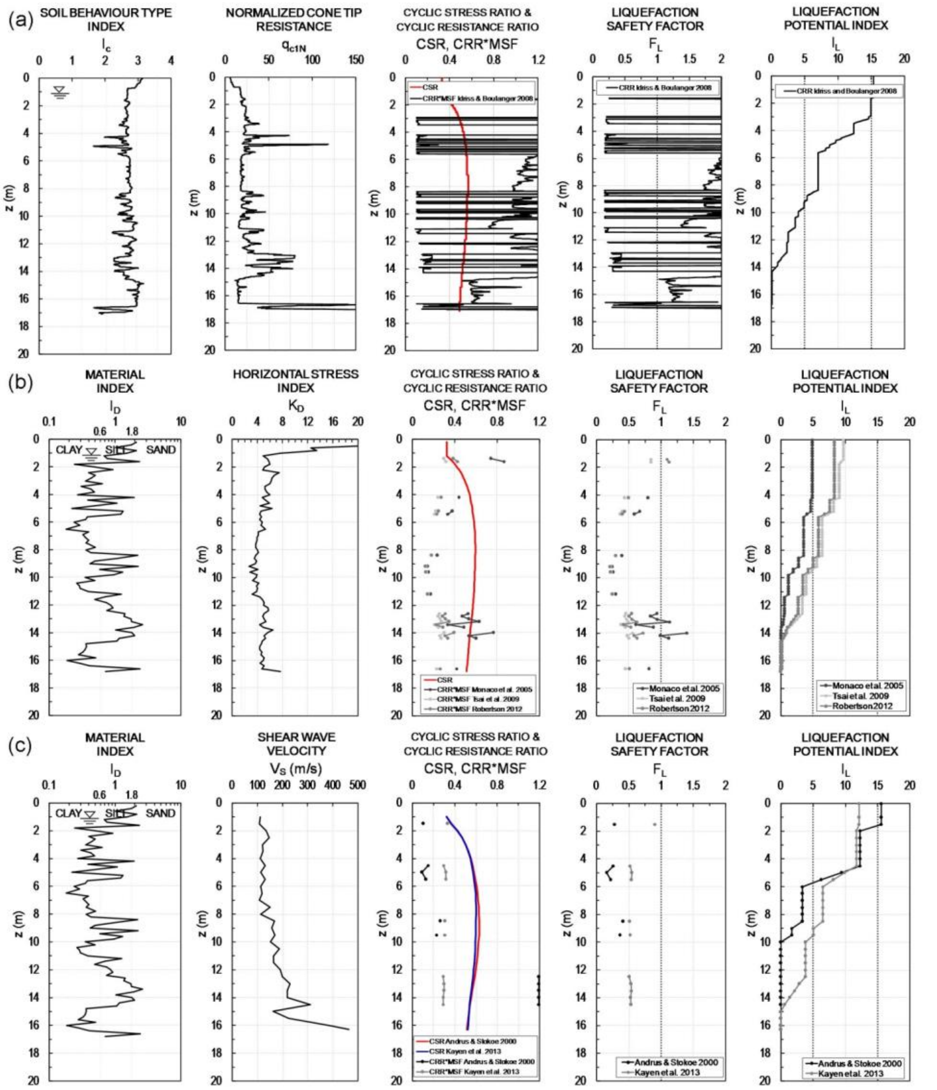

Fig. 9 Results of liquefaction analyses based on CPTu (a), DMT (b) and Vs (c) at the Pozzone site with seismic input defined by a deterministic approach for the 13 January 1915 earthquake (M_w = 7.0, PGA = 0.5 g).

The comparison of the results obtained at the Pozzone site indicates a broad agreement between the methods based on CPTu, DMT and V_S. In general the silty sand and sandy silt layers at 4.20-5.40 m, 8.40-10.60 m and 12.60-14.20 m depths are potentially liquefiable, even though CPTu, DMT and V_S

measurements provide variable I_L. For the scenario earthquake determined using a probabilistic approach (M_w = 5.66, PGA = 0.34g) I_L varies from 0.0 (Kayen et al. 2013) to 9.0 (Idriss and Boulanger 2008), while using a deterministic approach, for the 13 January 1915 earthquake (M_w = 7.0, PGA = 0.5 g), I_L varies from 4.9 (Monaco et al. 2005) to 15.6 (Andrus and Stokoe 2000).

It should be noted that at the Pozzone site, although the CPTu-based method (Idriss and Boulanger 2008) provided the highest estimates of I_L, such I_L value is not dependent on the contribution of "clay-like" soils in liquefaction assessment. In fact, by considering only the contribution of "sand-like" soils, the calculation provided the same I_L values.

The three DMT-based liquefaction methods provided different estimates of I_L, depending on the different CRR-K_D formulations. I_L predicted by Tsai et al. (2009) usually fits better I_L predicted by CPTu than Robertson (2012) and Monaco et al. (2005). Monaco et al. (2005) provided the lowest values (I_L < 5.0) for both seismic inputs. Nevertheless, in general it may be helpful to use all the three CRR-K_D correlations, as long as a more consistent CRR-K_D liquefaction curve, based on an enlarged case history database and considering also the influence of fine content (not taken into account by current CRR-K_D correlations, valid only for clean uncemented sand), is not available.

Also CRR-V_{S1} methods gave different evaluations of I_L. In particular, the Andrus and Stokoe (2000) formulation provided more conservative results than Kayen et al. (2013) and suggested that only the shallower sand layers would liquefy. Among all methods, Kayen et al. (2013) shows the largest variability, ranging from I_L = 0.0 (very low liquefaction potential according to Iwasaki et al., 1982) for the probabilistic approach earthquake, to I_L = 12.1 (high liquefaction potential) for the deterministic back-analysis of the 1915 earthquake.

4. Discussion

The detailed analysis of the Pozzone site helps in settling a number of issues, such as the sources of the uncertainty related to the interpretation of the phenomena observed after the 1915 earthquake

(Oddone 1915), and more in general the susceptibility to liquefaction of the Fucino lacustrine deposits, which are mostly fine-grained, with implications on SM mapping.

- The stratigraphy, the geologic evidence of paleo-liquefaction at 2.1-2.3 m depth and the geotechnical analyses indicate that the site is liquefiable under 1915-like earthquakes. Thus the 1915 coseismic phenomena can be interpreted as due to liquefaction in strict sense, and it is not necessary to invoke other mechanisms of deep origin (e.g., deep piping sinkholes, Nisio et al. 2007). The Pozzone lakes and the other sinkholes described by Nisio et al. (2007) are probably the result of multiple settlements cumulated over several seismic cycles.
- The concentration of sinkholes near Pozzone and their approximate E-W alignment (Fig. 3) can be related to the presence of the buried frontal lobe of the alluvial fan which fed the lacustrine basin from the north (Celano alluvial fan) during periods of large sediment supply which enhanced the prograding of the fan within the basin, increasing the ratio of coarse- (sand) to fine-grained sediments and consequently increasing the susceptibility to liquefaction (i.e., the four strata of coarser sediments recognized in the Pozzone borehole).
- Therefore in geologic environments dominated by fine-grained sedimentation, such as lacustrine basins, where no obvious liquefiable layers are detected, only accurate stratigraphic reconstructions can help discriminating those sites that are susceptible to liquefaction. Stratigraphic reconstructions must be particularly careful along marginal areas, where high-energy sedimentary systems might have fed the lake with coarser sediments (e.g., sand strata in frontal lobes of alluvial fans). The ratio of coarse to fine sediments is not easily predictable from surface or very shallow subsurface data, as it might have changed through time due to a combination of climatic and tectonic conditions. Thus, only adequately deep drilling and continuous coring, combined with accurate in situ testing, may significantly help in estimating the liquefaction potential.
- In spite of the average high content of fine-grained soils along the stratigraphy, the liquefaction analyses converge in classifying the site as susceptible to liquefaction, due to the cumulative

contribution of sandy silt-to-silty sand interlayers. There is a broad agreement between the used CPTu, DMT and V_S "simplified approaches", despite some differences in the calculated values of the liquefaction potential index. The presented results do not enable the authors to define which one is the best method/correlation. Instead it appears evident that for the Pozzone site and for areas with similar stratigraphic features (continental lacustrine environment, proximity to alluvial fan) the use of different in situ techniques/parameters seems to be strongly recommended for a more reliable estimate of the cyclic liquefaction resistance. In fact the use of redundant tests helps in reducing the uncertainties of empirical correlations for complex sites such as those characterized by interbedded layers with variable grain size and high fines content.

- The probabilistic and deterministic approaches provided different values of I_L, with maximum I_L varying from 9.0 (probabilistic, CPTu-based) to ~15 (deterministic CPTu- and Vs-based). The deterministic approach is considered here as the most reasonable in terms of back-analysis of the 1915 earthquake. Nevertheless, it is worthy to note that the probabilistic approach (probability of exceedance of 10% in 50 years, stratigraphic and topographic amplification according to the Italian Building Code; NTC 2008), which is the most commonly applied approach in the professional practice, is able to identify the susceptibility to liquefaction of the soil, even though the resulting liquefaction potential is underestimated.
- The results of this work have implications on basic SM mapping (e.g., Level 1 SM; Working Group SM, 2008). Basic SM is mostly based on detailed geologic maps and pre-existing subsurface data. Usually, specific geognostic, geotechnical or geophysical investigations are not carried out during this phase. Areas potentially susceptible to liquefaction are defined thanks to historical data (evidence of liquefaction during past earthquakes) and empirical evaluations constrained by the available pre-existing data (age and type of deposits, prevailing grain size with particular attention to clean sands, depth of water table). Therefore, this approach, without careful stratigraphic reconstructions, might be inadequate for mapping areas potentially susceptible to liquefaction in lacustrine sedimentary environments similar to the Fucino basin.

Commentato [UW8]: REVIEWER'S COMMENT 6

5. Conclusions

The accurate stratigraphic reconstruction and geotechnical analysis with in situ tests of the Pozzone site allowed us to define the susceptibility to liquefaction of a lacustrine sequence dominated by fine-grained sediments (Fucino lacustrine basin, central Italy).

- The first 18.5 m depth is formed by prevalent silty deposits with four main strata, 1.3-to-3.6 m thick, of decimetric interlayers of sand, silty sand and sandy silt. We interpreted these strata as the distal part of an alluvial fan which fed the lacustrine basin with coarser sediments during periods when climatic/tectonic factors favoured the prograding of the fan within the basin.
- Based on in situ geotechnical analyses, the cumulative contribution of coarser-grained strata determines a liquefaction potential ranging from very low to very high, depending on the method/correlation used for estimating the liquefaction susceptibility and on the selected seismic input. The majority of methods/correlations indicate a liquefaction potential from low to high for a scenario earthquake determined using a probabilistic approach for a return period of 475 years (M_w = 5.66, PGA = 0.34g), and from high to very high using a deterministic approach to back-analyze the 13 January 1915 earthquake (M_w = 7.0, PGA = 0.5g).
- A number of coseismic phenomena of ambiguous interpretation (ground deformation, water-level variations, turbidity in natural lakes) observed after the 1915 Fucino earthquake, can thus be interpreted as liquefaction-related.
- Soft-sediment deformations and small layers of loose sand observed in the core drilled at 2.1-2.3 m depth are interpreted as remnants of a paleo-liquefaction event occurred during a large earthquake between 12.1-10.8 and 9.43-9.13 kyrs B.P. This corroborates the hypothesis that the site suffered repeated liquefaction events during 1915 and previous earthquakes.
- From a geotechnical perspective, there is a broad agreement between the CPTu, DMT and V_S methods in detecting the liquefaction susceptibility of silty sand and sandy silt layers. The results

of the analyses and the particular features of the site (prevailing fine-grained sediments) suggest that the use of "redundant" correlations, based on different in situ techniques/parameters, is highly recommended for reliable estimates of the cyclic liquefaction resistance.

- A seismic input obtained from a probabilistic approach (probability of exceedance of 10% in 50 years) is sufficient to identify the susceptibility to liquefaction of the soil, but the resulting liquefaction potential is underestimated compared to that obtained from a deterministic approach (1915-like earthquake).
- Laboratory tests may attribute an intermediate behaviour (from sand-like to clay-like) to the Pozzone fine-grained soils. Cyclic triaxial or simple shear tests on those low-plasticity silty clays and clayey silts could significantly improve the accuracy of the liquefaction assessment, which cannot be attained by relying only on existing in situ simplified methods. In this respect, cyclic triaxial tests on undisturbed samples from the Pozzone site, as well as further investigations in lacustrine sedimentary environment affected by historical and paleo-liquefactions, have been planned in order to improve the knowledge of the liquefaction behaviour of fine-grained soils and of the level of the seismic hazard of the area.
- In the absence of accurate stratigraphic reconstructions, basic SM mapping (i.e., Level 1 SM) in lacustrine environment, dominated by fine-grained sedimentation, might underestimate the presence of areas potentially liquefiable if only simple empirical evaluations (age and type of deposits, prevailing grain size, depth of water table) are used.

Commentato [UW9]: REVIEWER'S COMMENT 6

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