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ORIGINAL RESEARCH PAPER

Evaluation of liquefaction potential in an intermountain Quaternary lacustrine basin (Fucino basin, central Italy)

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Abstract In this study, we analyse the susceptibility to liquefaction of the Pozzone site, which is located on the northern side of the Fucino lacustrine basin in central Italy. In 1915, this region was struck by a M 7.0 earthquake, which produced widespread coseismic surface effects that were interpreted to be liquefaction-related. However, the interpretation of these phenomena at the Pozzone site is not straightforward. Furthermore, the site is characterized by an abundance of fine-grained sediments, which are not typically found in liquefiable soils. Therefore, in this study, we perform a number of detailed stratigraphic and geotechnical investigations (including continuous-coring borehole, CPTu, SDMT, SPT, and geotechnical laboratory tests) to better interpret these 1915 phenomena and to evaluate the liquefaction potential of a lacustrine environment dominated by fine-grained sedimentation. The upper 18.5 m of the stratigraphic succession comprises fine-grained sediments, including four strata of coarser sediments formed by interbedded layers of sand, silty sand and sandy silt. These strata, which are interpreted to represent the frontal lobes of an alluvial fan system within a lacustrine succession, are highly susceptible to liquefaction. We also find evidence of paleo-liquefaction, dated between 12.1–10.8 and 9.43–9.13 kyrs ago, occurring at depths of 2.1–2.3 m. These data, along with the aforementioned geotechnical analyses, indicate that this site would indeed be liquefiable in a 1915-like earthquake. Although we found a broad agreement among CPTu, DMT and shear wave velocity "simplified procedures" in detecting the liquefaction potential of the Pozzone soil, our results suggest that the use and comparison of different in situ techniques are highly

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recommended for reliable estimates of the cyclic liquefaction resistance in lacustrine sites characterized by high content of fine-grained soils. In geologic environments similar to the one analysed in this work, where it is difficult to detect liquefiable layers, one can identify sites that are susceptible to liquefaction only by using detailed stratigraphic reconstructions, in situ characterization, and laboratory analyses. This has implications for basic (Level 1) seismic microzonation mapping, which typically relies on the use of empirical evaluations based on geologic maps and pre-existing sub-surface data (i.e., age and type of deposits, prevailing grain size, with particular attention paid to clean sands, and depth of the water table).

1 Introduction

Coseismic ground failures caused by liquefaction phenomena can severely damage structures and infrastructures during strong-to-large earthquakes, as observed in the 1995 Kobe, 2010–2011 Canterbury and 2012 Emilia Romagna earthquakes. In Italy, despite 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 in which urban development has put very little effort into assessing liquefaction hazards, such as the Fucino basin in central Italy, which was struck by a M_s 7.0 earthquake on 13 January 1915. In the Fucino epicentral area, Oddone (1915) documented a number of geological coseismic effects likely caused by or related to liquefaction. Despite these results, current urbanization policies (and practices) have not yet adequately incorporated these liquefaction hazards. This statement is confirmed by the presence of a small amount of geological, geophysical and geotechnical data collected in the urbanized area of the Fucino basin during the last few decades. Only a few ad hoc geological surveys and geotechnical investigations have been undertaken to assess the liquefaction potential of this region. In most cases, the available geological, geophysical and geotechnical investigations are not suitable to quantify the liquefaction hazard.

One possible reason for the lack of attention paid to liquefaction in this area may be due to the high content of fine-grained particles (i.e., silt and clay) within its lacustrine sediments. Here, clean sand bodies (which are typically liquefiable deposits) are rare as well as thin and poorly continuous. Although this factor has been cited as a possible reason to overlook liquefaction hazards in this area, evidence collected worldwide after the 1994 M 6.7 Northridge, 1999 M 7.6 Kocaeli, and 1999 M 7.6 Chi-Chi earthquakes have demonstrated that a significant number of liquefaction events have indeed occurred in silty and clayey soils containing more than 15% clay-size particles (Bray and Sancio 2006). For example, Bray et al. (2004) observed liquefaction occurring in the silts of Adapazari, Turkey. Additionally, soils that were determined to have liquefied during the Kocaeli earthquake did not meet the typical Chinese criteria (Wang 1979) for liquefaction-prone, fine-grained soils. These results have led researchers to deem these Chinese criteria inadequate, and their use today is strongly discouraged (Idriss and Boulanger 2006). In general, the liquefaction susceptibility of fine-grained material is a topic of broad interest that has been fiercely debated over 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", which states that liquefaction can recur in areas where it is known to have occurred during past earthquakes, is still considered to be valid. Nevertheless, a possible source of uncertainty in evaluating liquefaction susceptibility based on historical documents is that historical descriptions can be interpreted in different ways. For example, some descriptions of the Fucino earthquake published by Oddone (1915) clearly indicate the occurrence of liquefaction (e.g., observed ground fracturing and water and sand venting as well as sand volcanoes; see also Galli 2000). Other observed surface effects can only be tentatively related to liquefaction (e.g., ground deformation, water-level variations, water emissions, and turbidity in natural lakes), such as those observed at the Pozzone site on the northern side of the Fucino lacustrine basin (Fig. 1). Nisio et al. (2007) have suggested that, at the Pozzone site, the 1915 surface effects may have been caused by deep piping mechanisms triggered by the earthquake. These mechanisms are significantly
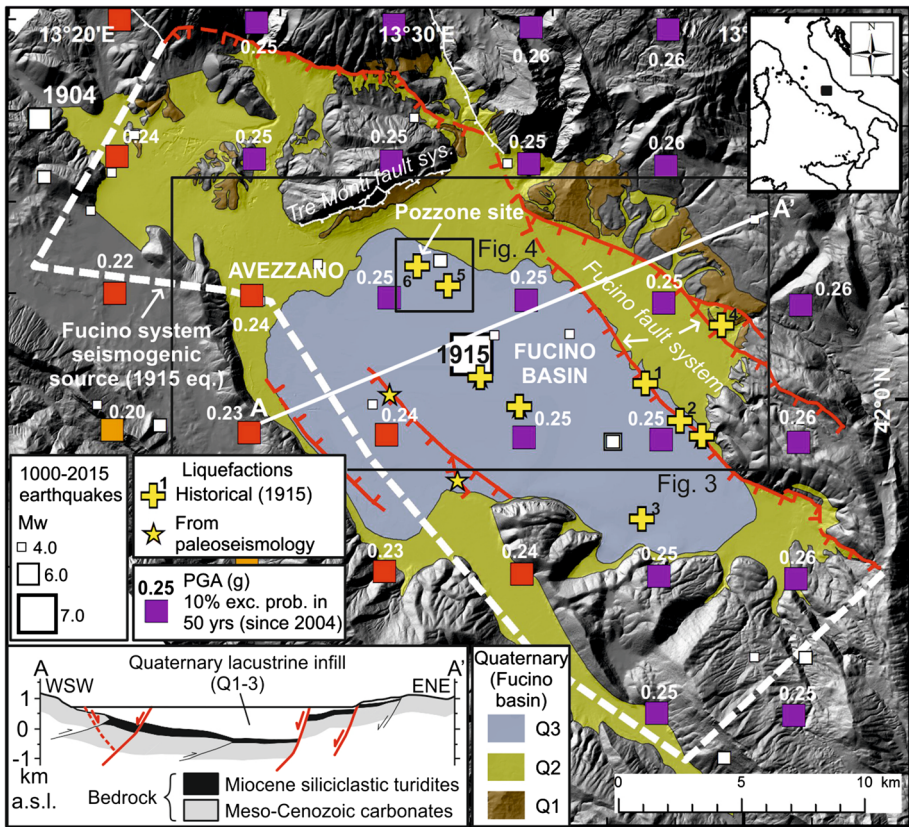

Fig. 1 Map of the Fucino basin in central Italy, with locations of liquefaction occurrences (*crosses* = 1915 M 7.0 earthquake from Oddone 1915 and Galli 2000; *stars* = paleoseismological investigations from Galadini et al. 1997; *numbers* refer to sites cited in the text). Quaternary continental deposits of the Fucino lacustrine basin are divided in Q1 (Early-Middle Pleistocene), Q2 (Late Pleistocene) and Q3 (upper part of Late Pleistocene—Holocene). The geologic section is slightly modified from Cavinato et al. (2002). The Fucino normal fault system is shown in *red*; other active (Late Quaternary) normal faults are shown in *white*. The seismogenic source of the Fucino fault system is from Pace et al. (2011). Historical earthquakes are from the 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)

different from the shallow-origin processes (<15–20 m depths) that are commonly responsible for causing liquefaction. This additional uncertainty increases the difficulty in assessing the liquefaction hazard in the Fucino area.

In this work, we investigate the Pozzone test site to evaluate its liquefaction potential. The goals of this work are twofold: (1) to confirm the liquefaction origin of the phenomena observed after the 1915 earthquake; and (2) to evaluate the liquefaction potential of lacustrine environments dominated by fine-grained sedimentation. These results have implications for seismic microzonation (SM) mapping, particularly for basic SM (e.g., Level 1 SM, according to SM Working Group 2015), which is typically based on geologic mapping and pre-existing sub-surface data instead of specific geotechnical analyses.

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 is the Fucino normal fault system, which strikes NW–SE and dips to the SW; the second is the Tre Monti fault system, which strikes WSW–ENE and dips to the SSE. Although the SSE-dipping Tre Monti system played an important role during the early evolution of the basin, the master fault is the SW-dipping Fucino fault system (Galadini and Messina 1994). Seismic reflection data reveal a half-graben sedimentary infill in the hanging wall of the Fucino fault, with Quaternary sediments recording a maximum thickness of approximately 1000 m (Cavinato et al. 2002). Quaternary continental deposits unconformably overlie Mesozoic to Middle Miocene carbonate bedrock, which outcrops in the mountains surrounding the basin. A series of Late Miocene siliciclastic turbidites are also mostly buried by these Quaternary sediments (Fig. 1).

Numerous studies detailing the age, stratigraphy, and lithology of these Quaternary continental deposits have been published over 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 in the Fucino area have been defined by the Geological Map of Italy (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 outcrop on the northern and northeastern sides of the basin (identified as Q1 in Fig. 1). These deposits are faulted and uplifted in the footwall of the main normal faults; their age ranges from Early to Middle Pleistocene (defined as the "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). The age of this succession 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; its stratigraphy is dominated by fine-grained lacustrine sediments (silt and clay), with increasing

proportions of sand layers in the areas closest to the margins (Q3 in Fig. 1). This area was previously occupied by a lake that was completely drained by the end of the nineteenth century. The age of the first few metres in this succession is Late Pleistocene (upper part) to Holocene (Giraudi 1988).

2.2 Historical seismicity and seismic hazard

The seismic history of the Fucino area is characterized by the occurrence of two strong earthquakes 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, with an estimated M_w of 5.6. The second shock occurred on 13 January 1915 and was much larger. The epicentre of this event was located within the Fucino basin, and its instrumental magnitude was $M_s = 7.0$ (Margottini and Screpanti 1999). Four localities, including Avezzano, the largest town in the Fucino area, were completely destroyed (Intensity XI MCS; Locati et al. 2016) and experienced approximately 30,000 fatalities. The earthquake produced several coseismic surface effects, including surface faulting, landslides, liquefaction, ground failure, and a series of hydrogeological anomalies (Oddone 1915; Galadini et al. 1999). Evidence of surface faulting was documented by Oddone (1915) as well as by several paleoseismologic investigations performed during the 1980s and 1990s, which demonstrated that the 1915 earthquake ruptured the SW-dipping Fucino normal fault and its prolongation along the Magnola SSW-dipping fault to create a total surface rupture length of ∼38 km. Paleoseismologists have also recognized the occurrence of 8 additional events of similar size ($M \sim 7.0$) between ∼19 kyrs ago and 1915, with average recurrence times ranging from 1400 to 2600 years (Serva et al. 1986; Michetti et al. 1996; Galadini and Galli 1999; Galli et al. 2008, 2012).

The probabilistic seismic hazard of this area, calculated on the basis of historical earthquakes, is among the highest in Italy (Fig. 1; Working Group MPS 2004). The bedrock peak ground acceleration (*PGA*) that is expected to be exceeded with 10% probability in 50 years in the Fucino area ranges between 0.24 and 0.26 g. These values do not account for the possibility of additional amplifications caused by 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, liquefaction features related to the 1915 and other pre-historical earthquakes were recognized thanks to: (1) the direct observation of coseismic surface effects immediately after the 1915 earthquake (denoted as crosses in Fig. 1) documented by Oddone (1915; see also Galli 2000) and (2) the results of paleoseismologic investigations (denoted as stars in Fig. 1; Galadini et al. 1997).

1. A variety of evidence for liquefaction was observed shortly 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) and the differential settlement of a building associated with loose sediment at the ground surface (site 5). However, the interpretation of other surface effects, such as those observed at the Pozzone site, is less straightforward (site 6). Near Pozzone, there are several small natural lakes where Oddone (1915) documented ground fracturing, the disappearance of a small island

within the largest of the Pozzone lakes, variations of the water level within these lakes, and long-lasting turbidity. Nisio et al. (2007) interpreted the Pozzone lakes to represent water-filled, deep piping sinkholes, which originated by processes that are controlled by overpressured fluids flowing up from the deep carbonate bedrock (>100–200 m depth). Therefore, this earthquake may have reactivated a mechanism that is significantly different from traditional liquefaction, which typically originates at shallow depths (<15–20 m).

2. Liquefaction-related sedimentary and structural features, such as sand dykes, sand sills, or the breaking of shallow layers into blocks separated by fissures filled by liquefied material were recognized in paleoseismological trenches (stars in Fig. 1; Galadini and Galli 1999).

2.4 Susceptibility to liquefaction based on pre-existing shallow subsurface data

To obtain a first-order evaluation of the susceptibility to liquefaction using only pre-existing data, without performing any additional specific investigations, we collected a large number of stratigraphic logs from boreholes as well as a series of geotechnical and geophysical data throughout the entire Fucino area. This approach is commonly used in basic SM studies (Level 1 SM according to SM Working Group 2015), which rely on using geologic maps and pre-existing subsurface data to draw homogeneous microzones. Overall, the following data were gathered for this study: (a) 427 stratigraphic logs from boreholes that have been drilled for hydrogeological exploration and exploitation since the 1950s (water wells in Fig. 2); (b) 3 geophysical investigations (mostly Vertical Electric
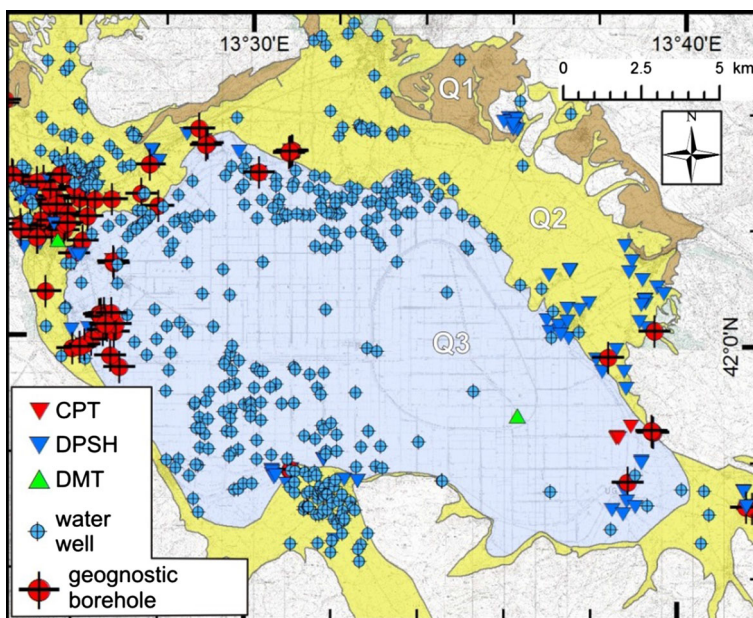

Fig. 2 Pre-existing data collected to estimate first-order susceptibility to liquefaction. *CPT* Cone Penetration Test; *DPSH* Dynamic Probing Super Heavy; *DMT* Flat Dilatometer Test. Geognostic boreholes often have in-hole SPT. Q1, Q2 and Q3 are the same as in Fig. 1

Soundings) performed for hydrogeological studies between the 1950s and the 1980s; 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). These latter data include a series of 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
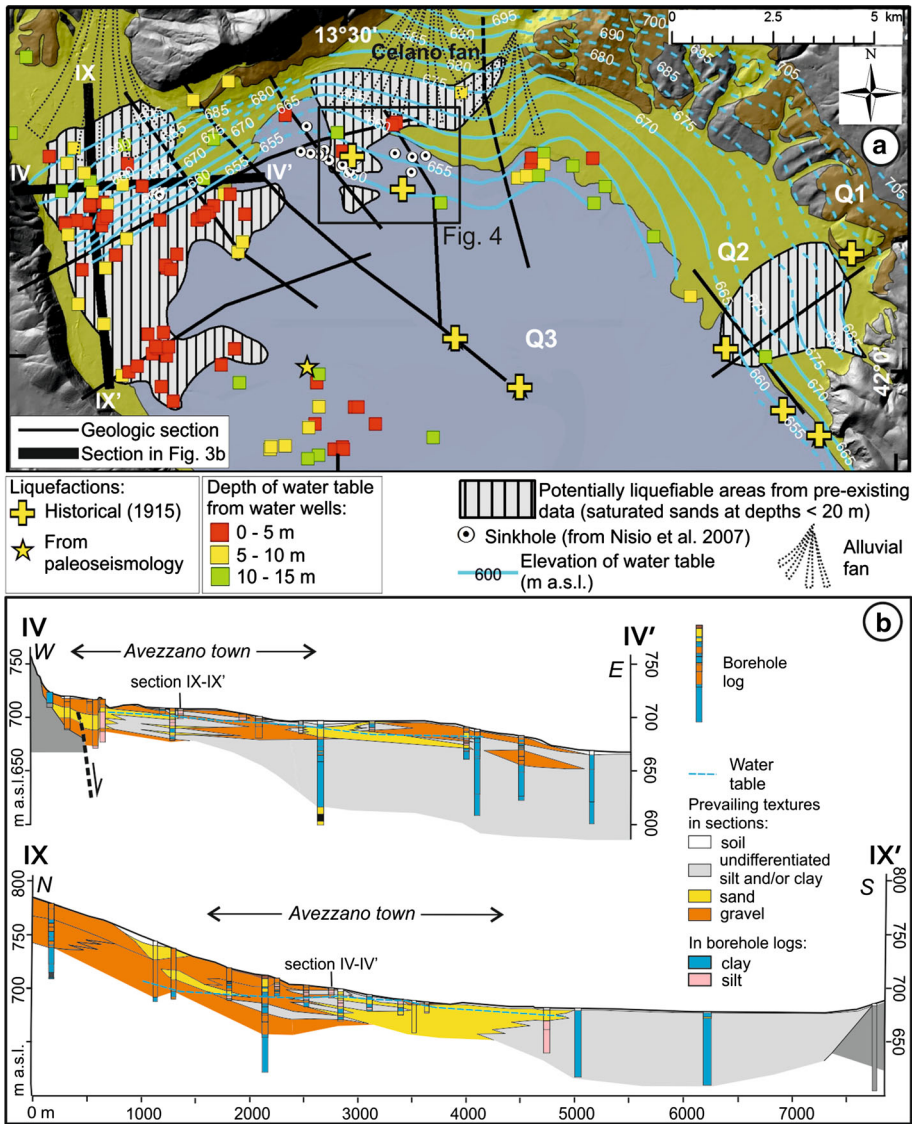

Fig. 3 a Map of the northern Fucino area with areas potentially susceptible to liquefaction based on pre-existing geological data (i.e., areas with water-saturated sand bodies within the first 20 m of depth); the elevation of the water table is from Petitta et al. (2005); Q1, Q2 and Q3 are the same as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

Fig. 4 **a** Map of the Pozzone site (location in Figs. 1, 3), and locations of 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 simply
as "clay". The detailed stratigraphy of 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 illustrated in Fig. 5

the water table was determined by using both 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 produced for an ongoing seismic microzonation project
within the Avezzano Municipality), a number of detailed geological sections were con-
structed to define the geometry and lateral continuity of sedimentary bodies susceptible to
liquefaction. In particular, we focused mostly on the northern side of the Fucino basin,
where data are more abundant (Fig. 3). These reconstructed 2D geometries allow us to
identify areas characterized by water-saturated sand bodies within the first 20 m of depth
that are therefore potentially susceptible to liquefaction.

Interestingly, most of the historical or pre-historical liquefaction sites lie outside of
these potentially liquefiable areas. This suggests that either (a) the features and phenomena
attributed to liquefaction must be reinterpreted, or, more likely, that (b) the pre-existing
data are not sufficient to evaluate the liquefaction potential of this area. Hereinafter, this
study focuses 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 on the northern side of the Fucino lacustrine basin, in a flat area
that was occupied by water prior to the drainage of the lake. This region features outcrops
of Holocene lacustrine sediments of the Q3 unit (Fig. 4) and is located ∼1 km south of the
toe of a large alluvial fan (Celano alluvial fan; Q2 in Fig. 3). This fan supplied the Fucino
basin with coarse-grained material during the cold climatic conditions of the Late Pleis-
tocene. The Holocene lacustrine sediments (Q3) cover a 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). To date, data from several synthetic strati-
graphic logs of water wells drilled during the 1950s are available (denoted as EF water
wells in Fig. 4b, which reach a maximum depth of 90 m). A detailed stratigraphic log from
a continuous-coring geognostic borehole is available on the northern side of the area (the
UdA Paludi borehole in Fig. 4). The stratigraphic descriptions of these available EF water
wells are generally coarse; for example, silt is not distinguished from clay and pelitic
sediments are generically categorized as simply "clay". Comparing the stratigraphy of the
EF wells with that defined in this work (S1 Pozzone geognostic borehole, Fig. 5)
demonstrates that using only information obtained from these old wells is insufficient for
conducting an adequate liquefaction hazard study. Only discontinuous areas within this
region record sand bodies within a depth of 20 m (Fig. 4a); below a depth of ∼20 m there
are extensive bodies of sands and gravels, but they do not significantly influence the
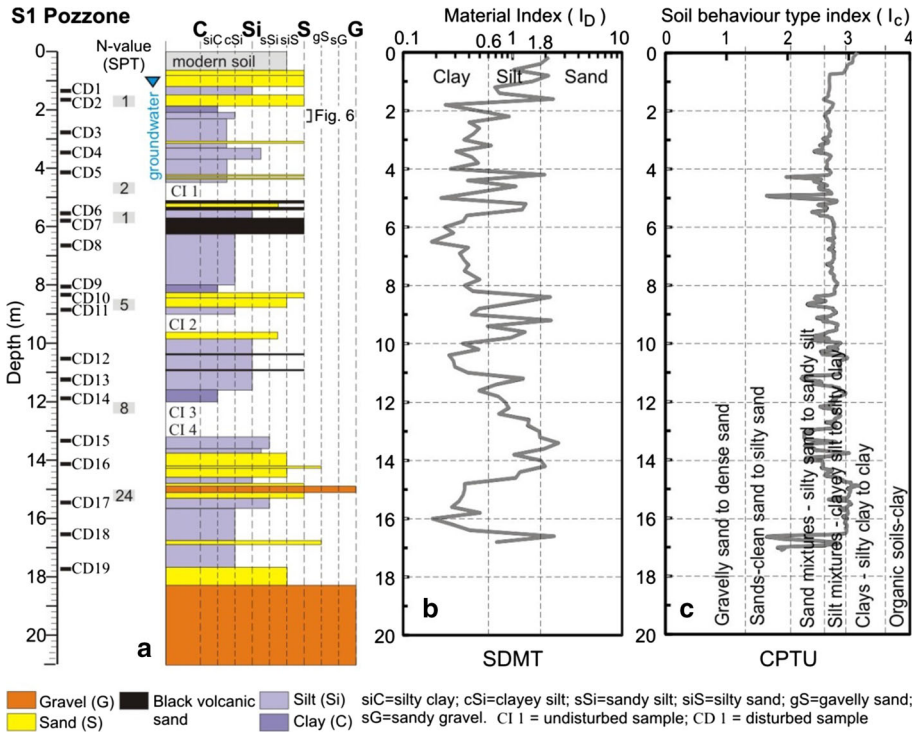liquefaction hazard of this region.
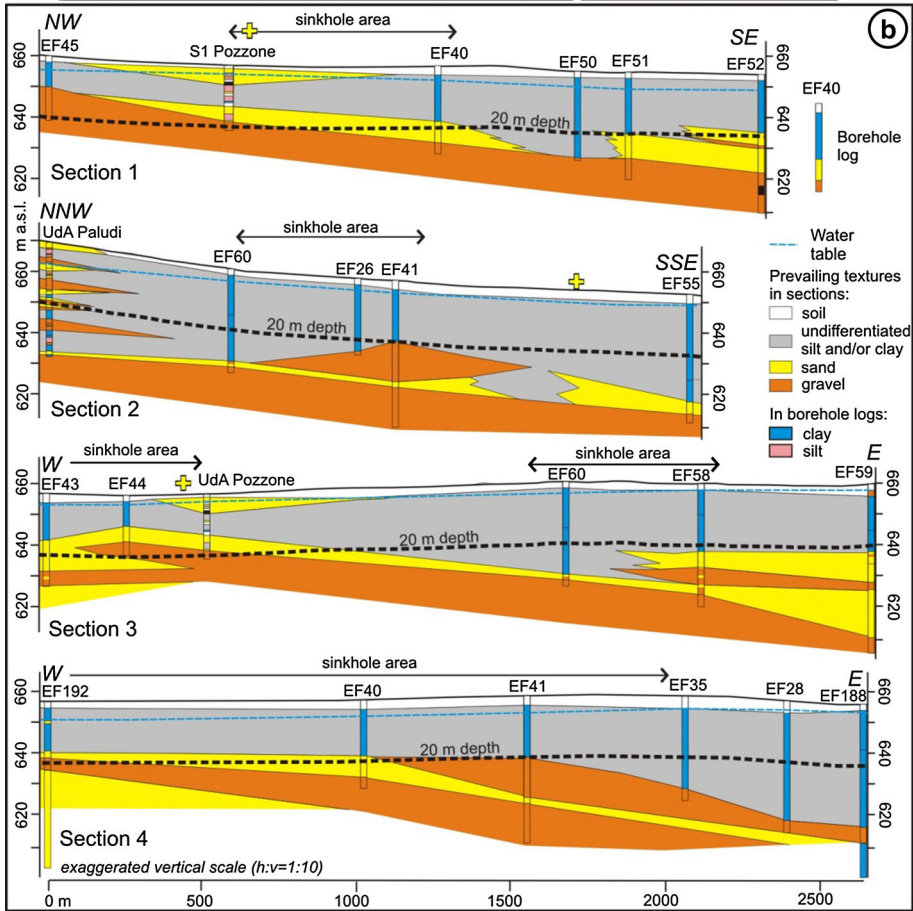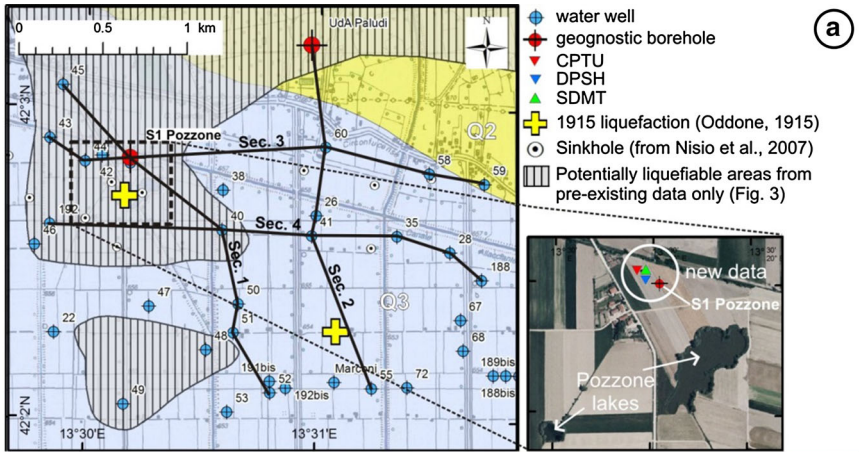
Fig. 5 **a** Stratigraphy of the continuous-coring S1 Pozzone borehole determined from field logging; note that SPT tests were performed in a parallel hole; lithological characterization of the Pozzone site from SDMT (**b**) and CPTu (**c**) tests, located close to the S1 borehole; location is shown in Fig. 4a

To define a detailed stratigraphy of the Pozzone site, we drilled a 21-m-deep, continuous-coring borehole (S1 Pozzone in Fig. 4; location in Fig. 4a). The stratigraphy is illustrated in Fig. 5. At a depth of 18.5 m, the top of a body of dense gravel can be observed; this horizon correlates with the top of the gravels observed in the EF water wells (Fig. 4b). From the surface to a depth of 18.5 m, the stratigraphy comprises 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 contain silt or clayey silt, with rare silty clay. The coarser strata are 1.3–3.6 m thick and consist of decimetric layers of sand, silty sand and sandy silt. Between depths of ~5 and 6.2 m we observe 3 layers of medium- to coarse-grained black volcanic sands with large biotite crystals that have been recognized in several places within the Fucino basin, yielding ages ranging from 27 to 19 kyrs before the present (B.P.) (upper part of Late Pleistocene; Galadini and Galli 1999; Giraudi 1999).

At a depth of 2.13 m, we observe evidence of paleo-liquefaction (Fig. 6). Between the depths of 2.13 and 2.33 m, there is a layer of grey silt featuring reddish bands formed by oxidation or general pedogenic processes. This layer is likely related to a period of low water level within the Fucino basin, and has been dated between 12.1 and 10.8 kyrs B.P. (Giraudi 1999). During this period, the marginal basin was likely exposed to subaerial conditions and erosion. Atop the reddish layer is a mushroom-shaped body of loose sand formed by an upper lens that is 1- to 2-cm thick, convex upwards, and connected downwards by a curved dike. This mushroom-shaped body can be interpreted as the remnant of a
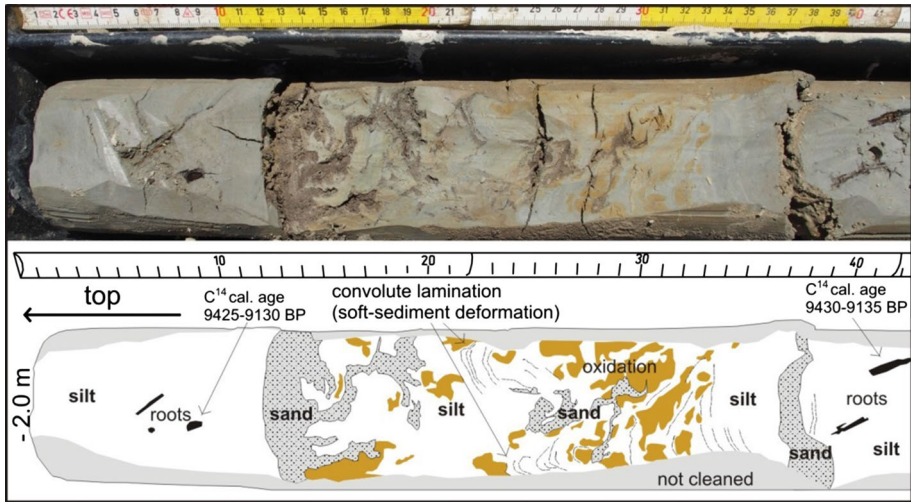
Fig. 6 Details of the core sampled in the Pozzone borehole between depths of 2.0 and 2.42 m, showing a mushroom-shaped body of loose sand (in the 2.12–2.20 m interval) interpreted as the remnant of a small sand blow formed by a paleo-liquefaction event. The *reddish layer* represents the top layer at the time of paleo-liquefaction, which has since become deformed by soft-sediment structures. Note that the dated roots (with ages from AMS C^{14} dating) are only apparently dispersed fragments. Careful examination of the internal parts of the core suggests that they are continuous, nearly vertical (i.e., life position) roots

small sand blow, and the top of the reddish layer can be interpreted as the ground surface at the time of a liquefaction event (thus representing an event horizon in the paleoseismo-logical literature). It is worth noting that the entire reddish layer is deformed by soft-sediment deformation, consistent with the occurrence of an earthquake-induced liquefac-tion event.

The sediments lying both above and below this paleo-liquefaction event are penetrated by a series of nearly vertical roots that have been dated at 9.43–9.13 kyrs old (AMS C^{14} dating, calibrated ages B.P.). Therefore, this liquefaction event is younger than 12.1–10.8 kyrs ago (the age of the reddish layer) and is older than the 9.43–9.13 kyr-old roots. During their extensive paleoseismologic investigations in this region, Galadini and Galli ([1999](#)) found evidence of two prehistoric earthquakes occurring between 12.7 and 7.5 kyrs B.P. The Pozzone paleo-liquefaction event may therefore correspond to the older of these two earthquakes.

3.2 Geotechnical and geophysical investigations for liquefaction potential assessment

We performed a series of geotechnical and geophysical investigations to model the subsoil and thus 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, the results of which are not discussed here), 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, the results of which are not discussed here), and laboratory analyses (sieve analyses and Atterberg limits) on 21 disturbed samples. In the SDMT test, two shear wave sources were used in a

symmetrical configuration (i.e., hammer blows striking an anvil on two opposite sides) to produce two SH seismic wave trains with opposite polarities (SDMT1 sx and SDMT1 dx). Data from DPSH and noise measurements, and further details about SDMT and CPTu can be found in Amoroso et al. (2015a, b).

Figure 5 summarizes the borehole log data, along with recorded SPT N-values (determined based on the blows needed to drive the sampler a distance of 0.3 m), and soil type classifications obtained from SDMT and CPTu investigations, which are based on their material index I_D and their soil behaviour type index I_c, respectively. In situ lithologies mostly correspond to the geological stratigraphic section, considering that I_D and I_c are not grain size distribution indexes but instead reflect 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 occurring at depths of 4.20–5.40 m, 8.40–10.60 m, and 12.60–14.20 m, according to I_D (Marchetti 1980; Marchetti et al. 2001) and I_c (Robertson 1990, 2010) classifications.

Actual soil grain size distributions were determined using laboratory tests. The results of sieve analyses and Atterberg limits of disturbed samples are listed in Table 1, which lists their 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 containing a high fine fraction ($FC \geq 19.31\%$).

Based on the definition of liquefaction susceptibility established by Idriss and Boulanger (2008), these silty clays and clayey silts appear to exhibit behaviours falling within the transition between "sand-like" and "clay-like" materials across a fairly narrow average range of $PI \approx 3–6\%$. Consequently, these Pozzone fine-grained soils may exhibit "intermediate" behaviour, which can be more accurately constrained by performing cyclic triaxial or simple shear tests.

Table 1 Results of geotechnical laboratory tests (sieve analyses and Atterberg limits) on disturbed samples retrieved from the S1 Pozzone borehole (CD samples shown 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	–	–	–

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

The water table was detected at a depth of 1.7 m, based on the pore pressure u_2 obtained from the piezocone and C-readings (see Marchetti et al. 2001), which are additional DMT measurements acquired only in sandy layers. In contrast, the water table depth measured in the borehole was 1.2 m below the ground surface. This variability can be justified by seasonal fluctuations of the water table and the fact that the in situ tests and borehole were executed at different points in time.

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, as obtained from DMT, have also been proposed (e.g., Monaco et al. 2005). Previous research has demonstrated that K_D is sensitive to factors such as stress history, ageing, cementation, and structure, all of which greatly increase the resistance to liquefaction for a given relative density (Monaco and Schmertmann 2007; Monaco and
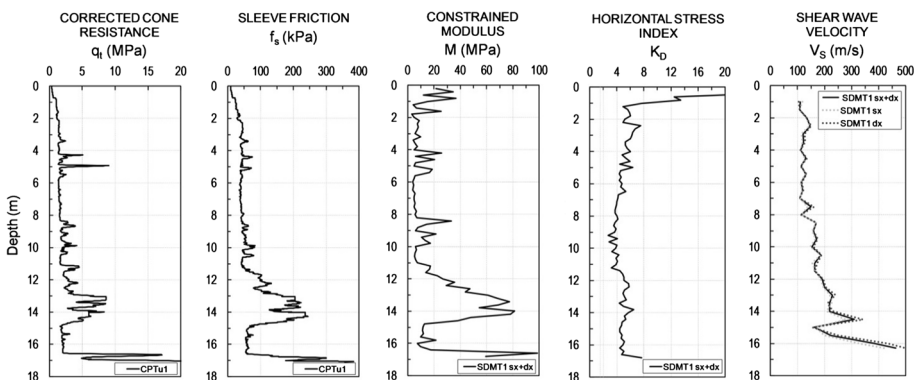

Fig. 7 CPTu and SDMT results at the Pozzone site

Marchetti 2007). However, these methods are currently supported by only a relatively limited database of liquefaction case histories.

The use of "redundant" correlations, based on using a series of different in situ techniques or parameters, is commonly recommended to more reliably estimate the cyclic liquefaction resistance *CRR*. For example, Robertson and Wride (1998) recommended estimating *CRR* by using more than one method for medium- to high-risk projects, and using just CPT (which is preferable to SPT) only for low-risk, small-scale projects. Data from the 1996–1998 NCEER Workshops (Youd et al. 2001) indicated that, when possible, two or more tests should be used. Idriss and Boulanger (2004) further warned that using a number of in situ tests should be standard practice and that the allure of relying on a single approach (e.g., CPT-only) should be avoided.

At the Pozzone site, we performed liquefaction analyses using the "simplified procedure" introduced by Seed and Idriss (1971), which is based on comparing the seismic demand on a soil layer generated by an earthquake (i.e., the cyclic stress ratio *CSR*) to the capacity of the soil to resist liquefaction (i.e., the cyclic resistance ratio *CRR*) for a magnitude 7.5-earthquake event. The ratio between *CRR* and *CSR* represents the liquefaction safety factor F_L. Additionally, we calculated the liquefaction potential index I_L using the procedure of Iwasaki et al. (1982) to estimate the liquefaction susceptibility of the entire soil profile.

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

One of the goals of this work is the back analysis the phenomena associated with the 13 January 1915 earthquake; therefore, the seismic input was assessed by a deterministic approach that takes into account the seismogenic source of the 1915 earthquake (Fig. 1). In particular, four different ground motion prediction equations were used (GMPEs; 1 = Bindi et al. 2011; 2 = Akkar et al. 2014a, b; 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"). GMPEs 1–3 use the Joiner-Boore distance (R_{jb}, which is defined as the shortest distance from the site to the surface projection of the rupture), which is equal to 0, as the Pozzone site is located within the surface projection of the 1915 rupture (Fig. 1). GMPE 4 uses the R_{rup} distance (which is the shortest distance from the site to the rupture surface), which is calculated as 3.8 km by assuming an average dip of 50° for the seismogenic source. The mean of the PGA values obtained by the four GMPEs is 0.5 g.

The magnitude scaling factor *MSF* is calculated for a moment magnitude of $M_w = 7.0$, which corresponds to the instrumental magnitude of the 13 January 1915 earthquake determined by Rovida et al. (2016).

We then derived the cyclic resistance ratio *CRR* from the CPTu and SDMT results. For CPTu data, we use the approach of Idriss and Boulanger (2008), which introduces the normalized cone tip resistance q_{c1N} for "sand-like" soils, and the s_u ratio, which is 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 the absence of cyclic triaxial or simple shear test results, the limit between "sand-like" and "clay-like" behaviour is assumed to correspond with a soil behaviour type index I_c of 2.6. The Pozzone soil deposits are thus considered to be sand-like at values of $I_c \leq 2.6$, and clay-like at values of $I_c > 2.6$. In contrast, DMT and V_S liquefaction assessment methods can be applied only to sand-like soils. We therefore used

a series of DMT-based correlations to derive *CRR* from the horizontal stress index K_D, including those proposed by Monaco et al. (2005), Tsai et al. (2009) and Robertson (2012). We also estimated *CRR* from the overburden stress-corrected shear wave velocity V_{S1}, based on the methods of Andrus and Stokoe (2000) and Kayen et al. (2013), using values of fine content FC obtained from sieve analyses or estimated from CPTu. In both the CRR-K_D and CRR-V_{S1} methods, the Pozzone deposits are considered to be sand-like when the DMT material index is $I_D \geq 1.2$.

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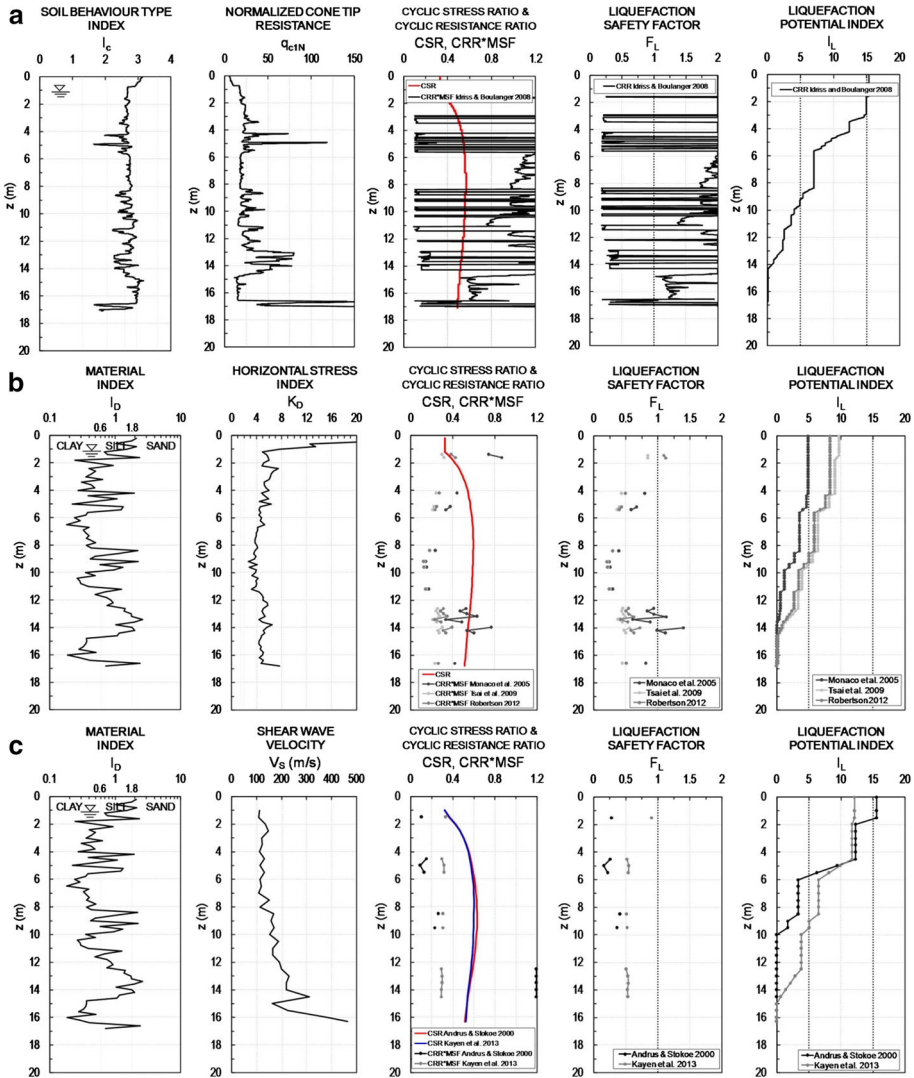

Fig. 8 Results of liquefaction analyses based on CPTu (**a**), DMT (**b**) and Vs (**c**) at the Pozzone site, with seismic input defined by a deterministic approach for the 13 January 1915 earthquake ($M_w = 7.0$, $PGA = 0.5$ g)

The results of liquefaction analyses are illustrated in Fig. 8. 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 to evaluate CRR (q_{c1N}, K_D or V_{S1}), the value of CSR compared to that of 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 liquefaction assessment method. In fact, for a M_w of 7.0, the calculated MSF values are $MSF = 1.14$ for CPTu and DMT sand-like soils (Idriss and Boulanger 2008), $MSF = 1.02$ for CPTu clay-like soils (Idriss and Boulanger 2008), $MSF = 1.19$ for V_S sand-like soils (Andrus and Stokoe 2000), and $MSF = 1.10$ for V_S sand-like soils (Kayen et al. 2013).

A comparison of the results obtained at the Pozzone site indicates that the results of the methods based on the CPTu, DMT and V_S datasets all broadly agree. In general, the silty sand and sandy silt layers located at depths of 4.20–5.40 m, 8.40–10.60 m and 12.60–14.20 m are potentially liquefiable, although their CPTu, DMT and V_S measurements produce variable values of I_L. The liquefaction potential index I_L varies from a minimum of 4.9 (Monaco et al. 2005), representing low liquefaction potential according to Iwasaki et al. (1982), to a maximum of about 15 (CPTu-based, Idriss and Boulanger 2008; V_S-based, Andrus and Stokoe 2000), representing high-to-very high liquefaction potential.

Furthermore, although the CPTu-based method (Idriss and Boulanger 2008) produces the highest estimated values of I_L at the Pozzone site, these I_L values do not depend on the contributions of "clay-like" soils to the liquefaction assessment. In fact, the calculations yield the same I_L values when only considering the contributions of "sand-like" soils.

The three DMT-based liquefaction methods produce different estimates of I_L, depending on the different CRR-K_D formulations used. For example, I_L values predicted by Tsai et al. (2009) usually fit I_L values predicted by CPTu better than those of Robertson (2012) and Monaco et al. (2005). Additionally, the results of the Monaco et al. (2005) method yield the lowest observed values ($I_L = 4.9$). Nevertheless, in general, it may be beneficial to use all three CRR-K_D correlations, because to date a more consistent CRR-K_D liquefaction curve based on an enlarged case history database and which considers the influence of fine content (currently not taken into account by CRR-K_D correlations that are only valid for clean uncemented sand) is not available.

Furthermore, different CRR-V_{S1} methods yield different values of I_L. In particular, the method proposed by Andrus and Stokoe (2000) yields more conservative results than does that of Kayen et al. (2013); these results suggest that only shallow sand layers will liquefy.

4 Discussion

Performing detailed analyses of the Pozzone site is useful for interpreting phenomena observed after the 1915 earthquake (Oddone 1915). They are also useful for generally constraining the susceptibility to liquefaction of the Fucino lacustrine deposits, which are mostly fine-grained; these results also have implications for future SM mapping studies.

- The stratigraphic evidence of paleo-liquefaction at a depth of 2.1–2.3 m as well as the results of geotechnical analyses indicate that this site is liquefiable under conditions similar to those of the 1915 earthquake. Therefore, the 1915 coseismic phenomena can be interpreted as reflecting liquefaction and do not require other deep-origin mechanisms (e.g., deep piping sinkholes, Nisio et al. 2007). The Pozzone lakes and other sinkholes in the region described by Nisio et al. (2007) are likely the result of cumulative settlements occurring over several seismic cycles.

- The concentration of sinkholes near Pozzone, and their approximate E–W alignments (Fig. 3), can be related to the buried frontal lobe of the alluvial fan that fed the lacustrine basin from the north (Celano alluvial fan, Q2 in Fig. 3) during periods of large sediment supply. This enhanced the progradation of the fan within the basin, which increased the ratio of coarse- (sand) to fine-grained sediments and consequently increased their susceptibility to liquefaction (i.e., the four strata of coarser sediments recognized in the Pozzone borehole).
- These results demonstrate that, in geologic environments dominated by fine-grained sedimentation (e.g., lacustrine basins), only accurate stratigraphic reconstructions are effectively useful for identifying sites susceptible to liquefaction. These stratigraphic reconstructions must be particularly precise along marginal areas, where high-energy sedimentary systems may have supplied coarser sediments into the lake (e.g., sand strata in the frontal lobes of alluvial fans). The ratio of coarse to fine sediments cannot easily be predicted from surface or very shallow subsurface data, as it may have changed over time (i.e., with depth) due to a combination of climatic and tectonic conditions. Therefore, only the combination of deep drilling, continuous coring, and accurate in situ testing, may significantly help estimate liquefaction potential in these regions.
- Despite the average high content of fine-grained soils within the stratigraphic section, all liquefaction analyses classify this site as being susceptible to liquefaction due to the cumulative contributions of sandy silt-to-silty sand interlayers. There is broad agreement between the results of the CPTu, DMT and V_S "simplified approaches", despite some differences in their calculated values of the liquefaction potential index. The results presented here do not indicate the superiority of a single method or correlation. Instead, it appears evident that, within the Pozzone site and other areas with similar stratigraphic features (i.e., continental lacustrine environments; proximity to an alluvial fan) it is only possible to obtain reliable estimates of cyclic liquefaction resistance by using a series of different in situ techniques or parameters. In fact, the use of redundant tests helps to reduce the uncertainties of empirical correlations at complex sites, such as those characterized by interbedded layers with variable grain sizes and high fine contents.
- The results of this work have implications for basic SM mapping (e.g., Level 1 SM; SM Working Group 2015). Basic SM mapping is mostly based on detailed geologic maps and pre-existing subsurface data. Usually, specific geognostic, geotechnical, or geophysical investigations are not carried out for this work. Areas potentially susceptible to liquefaction are defined based on historical data (i.e., evidence of liquefaction observed during past earthquakes) and empirical evaluations constrained by available pre-existing data (e.g., ages and types of deposits, prevailing grain size, with particular attention paid to clean sands, and depth of the water table). Therefore, without the use of careful stratigraphic reconstructions, this approach may be inadequate for mapping areas potentially susceptible to liquefaction in lacustrine sedimentary environments similar to the Fucino basin.

5 Conclusions

By combining accurate stratigraphic reconstructions and geotechnical analyses with in situ tests of the Pozzone site, we are able to define the susceptibility to liquefaction of a lacustrine sequence dominated by fine-grained sediments in the Fucino lacustrine basin of central Italy.

- The upper 18.5 m of the section comprise mostly silty deposits with four main strata (1.3-to-3.6 m thick) containing decimetric interlayers of sand, silty sand and sandy silt. We interpret these strata as the distal part of an alluvial fan, which fed the lacustrine basin with coarser sediments during periods when climatic and tectonic factors favoured the progradation of the fan within the basin.
- In situ geotechnical analyses reveal cumulative contributions of coarser-grained strata, suggesting that for seismic input similar to the 13 January 1915 earthquake ($M_w = 7.0$, $PGA = 0.5$ g) the liquefaction potential ranges from low to very high in this area, depending on the method/correlation used to estimate the liquefaction susceptibility.
- These data suggest that a number of coseismic phenomena with ambiguous interpretations (e.g., ground deformation, water-level variations, turbidity in natural lakes) observed after the 1915 Fucino earthquake can thus be interpreted as being liquefaction-related.
- Soft-sediment deformations and small layers of loose sand observed in cores drilled at a depth of 2.1–2.3 m are interpreted as remnants of a paleo-liquefaction event occurring during a large earthquake between 12.1–10.8 and 9.43–9.13 kyrs B.P. These results corroborate the hypothesis that this site suffered repeated liquefaction events during earthquakes prior to the 1915 earthquake.
- Geotechnical data produced by the CPTu, DMT and V_S methods agree broadly in determining the liquefaction susceptibility of silty sand and sandy silt layers. The results of these analyses and the predominance of fine-grained sediments at this site suggest that the use of "redundant" correlations, based on different in situ techniques/parameters, is highly recommended for reliably estimating the cyclic liquefaction resistance.
- Laboratory tests may be used to attribute intermediate behaviours (from sand-like to clay-like) to the Pozzone fine-grained soils. Performing cyclic triaxial or simple shear tests on these low-plasticity silty clays and clayey silts can significantly improve the accuracy of liquefaction assessments, which cannot be attained by using only existing in situ simplified methods. Therefore, future cyclic triaxial tests on undisturbed samples from the Pozzone site as well as further investigations into lacustrine sedimentary environments affected by historical and paleo-liquefaction events are necessary to improve our current knowledge of the liquefaction behaviour of fine-grained soils to therefore better define the seismic hazards of the area.
- In the absence of accurate stratigraphic reconstructions, basic SM mapping (i.e., Level 1 SM) in a lacustrine environment dominated by fine-grained sedimentation may underestimate the presence of liquefiable areas if only simple empirical evaluations are used.

References

AGI, Burghignoli A, Cavalera L, Chieppa V, Jamiolkowski M, Mancuso C, Marchetti S, Pane V, Paoliani P, Silvestri F, Vinale F, Vittori E (1991) Geotechnical characterization of Fucino clay. In: Proceedings of X ECSMFE, Firenze, vol 1, pp 27–40

Akkar S, Sandikkaya MA, Bommer JJ (2014a) Empirical ground-motion models for point- and extended-source crustal earthquake scenarios in Europe and the Middle East. Bull Earthq Eng 12(1):359–387. doi:10.1007/s10518-013-9461-4

Akkar S, Sandikkaya MA, Bommer JJ (2014b) Erratum to: Empirical ground-motion models for point- and extended-source crustal earthquake scenarios in Europe and the Middle East. Bull Earthq Eng 12(1):389–390. doi:10.1007/s10518-013-9508-6

Amoroso S, Boncio P, Famiani D, Hailemikael S, Manuel MR, Milana G, Monaco P, Vassallo M, Vessia G (2015a) Preliminary Liquefaction Studies for Seismic Microzonation of Avezzano, Italy. In: 3rd International conference on the flat dilatometer, 14–16 June 2015, Rome, Italy, pp 285–292. ISBN: 979-12-200-0116-8. http://www.marchetti-dmt.it/conference/dmt15/papers%20DMT%202015%20(pdf)/77.pdf#page=1

Amoroso S, Boncio P, Famiani D, Hailemikael S, Manuel MS, Milana G, Monaco P, Vassallo M, Vessia G (2015b) Liquefaction assessment by in situ testing in the Fucino plain (central Italy). Miscellanea INGV, Abstracts Volume 6th International INQUA Paleoseismology, Active Tectonics Archaeoseismology, 19–24 April 2015, Pescina, Fucino Basin, Italy, vol 27, pp 21–24. ISSN: 2039-6651. http://www.ingv.it/editoria/miscellanea/2015/miscellanea27/

Andrew DCA, Martin GR (2000) Criteria for liquefaction of silty soils. In: Proceedings of the 12th world conference on earthquake engineering, Auckland, NZ. Paper 0312

Andrus RD, Stokoe KH (2000) Liquefaction resistance of soils from shear-wave velocity. J Geotech Geoenviron Eng ASCE 126(11):1015–1025

Bindi D, Pacor F, Luzi L, Puglia R, Massa M, Ameri G, Paolucci R (2011) Ground motion prediction equations derived from the Italian strong motion database. Bull Earthq Eng 9:1899–1920. doi:10.1007/s10518-011-9313-z

Boncio P, Milana G, Cara F, Di Giulio G, Di Naccio D, Famiani D, Galadini F, Rosatelli G, Vassallo M (2015) Local seismichazard from detailed geologic investigations: the Avezzano town in the epicentral area of the M7, 1915 earthquake (Fucino basin, centralItaly). In: 6th International INQUA meeting on paleoseismology, active tectonics and archaeoseismology, 19–24 April 2015, Pescina, Fucino Basin, Italy, Miscellanea INGV 27

Boore DM, Stewart JP, Seyhan E, Atkinson GM (2014) NGA-West 2 equations for predicting PGA, PGV, and 5%-damped PSA for shallow crustal earthquakes. Earthq Spectra 30(3):1057–1085. doi:10.1193/070113EQS184M

Bosi C, Galadini F, Messina P (1995) Stratigrafia plio-pleistocenica della conca del Fucino. Il Quat 8(1):83–94

Bray J, Sancio RB (2006) Assessment of the liquefaction susceptibility of fine-grained soils. J Geotech Geoenviron Eng 132(9):1165–1177

Bray JD, Sancio RB, Durgunoglu T, Onalp A, Youd TL, Stewart JP, Seed RB, Cetin OK, Bol E, Baturay MB, Christensen C, Karadayilar T (2004) Subsurface characterization at ground failure sites in Adapazari, Turkey. J Geotech Geoenviron Eng 130:673–685

Bray J, Cubrinovski M, Zupan J, Taylor M (2014) Liquefaction effects on buildings in the central business district of Christchurch. Earthq Spectra 30(1):85–109

Cara F, Di Giulio G, Cavinato GP, Famiani D, Milana G (2011) Seismic characterization and monitoring of Fucino Basin (Central Italy). Bull Earthq Eng 9:1961–1985. doi:10.1007/s10518-011-9282-2

Cauzzi C, Faccioli E, Vanini M, Bianchini A (2015) Updated predictive equations for broadband (0.01–10 s) horizontal response spectra and peak ground motions, based on a global dataset of digital acceleration records. Bull Earthq Eng 13(6):1587–1612. doi:10.1007/s10518-014-9685-y

Cavinato GP, Carusi C, Dell'Asta M, Miccadei E, Piacentini T (2002) Sedimentary and tectonic evolution of Plio-Pleistocene alluvial and lacustrine deposits of Fucino Basin (central Italy). Sed Geol 148:29–59

Centamore E, Crescenti U, Dramis F (2006) Note illustrative della Carta Geologica d'Italia alla scala 1:50.000, Foglio 368 "Avezzano", APAT – Servizio Geologico d'Italia e Regione Abruzzo – Servizio Difesa del Suolo, S.EL.CA., Firenze

Cetin KO, Seed RB, Der Kiureghian A, Tokimatsu K, Harder LF, Kayen RE, Moss RES (2004) Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential. J Geotech Geoenviron Eng ASCE 130(12):1314–1340

Famiani D, Boncio P, Cara F, Cogliano R, Giulio GD, Fodarella A, Milana G, Pucillo S, Riccio, G, Vassallo M (2015) Local seismic response in a large intra-mountain basin as observed from earthquakes and microtremor recordings: the Avezzano Area (Central Italy). In: Lollino G et al. (eds) Engineering geology for society and territory, vol 5. doi: 10.1007/978-3-319-09048-1_220. ISBN 978-3-319-09047-4, ISBN (eBook) 978-3-319-09048-1

Fortunato C, Martino S, Prestininzi A, Romeo RW, Fantini A, Sanandrea P (2012) New release of the Italian catalogue of earthquake-induced ground failures (CEDIT). Ital J Eng Geol Environ 5:55. doi:10.4408/IJEGE.2012-02.O-05

Foti S, Lancellotta R, Marchetti D, Monaco P, Totani G (2006) Interpretation of SDMT tests in a transversely isotropic medium. In: Failmezger RA, Anderson JB (eds) Flat dilatometer testing, proceedings of 2nd international conference on the flat dilatometer, Washington, D.C., USA, April 2–5, pp 275–280

Galadini F, Galli P (1999) The Holocene paleoearthquakes on the 1915 Avezzano earthquake faults (central Italy): implications for active tectonics in the central Apennines. Tectonophysics 308:143–170

Galadini F, Messina P (1994) Plio-Quaternary tectonics of the Fucino basin and surrounding areas (central Italy). G Geol 56:73–99

Galadini F, Galli P, Giraudi C (1997) Geological investigation of italian earthquakes: new paleoseismological data from the Fucino plain (central Italy). J Geodyn 24:87–103

Galadini F, Galli P, Giraudi C (1999) Gli effetti geologici del terremoto del 1915. In: Castenetto S, Galadini F (eds): "13 gennaio 1915, il terremoto nella Marsica". Servizio Sismico Nazionale e C.N.R. Istituto di Ricerca sulla Tettonica Recente, Roma, pp 283–299

Galli P (2000) New empirical relationships between magnitude and distance for liquefaction. Tectonophysics 324:169–187

Galli P, Galadini F, Pantosti D (2008) Twenty years of paleoseismology in Italy. Earth Sci Rev. doi:10.1016/j.earseirev.2008.01.001

Galli P, Messina P, Giaccio B, Peronace E, Quadrio B (2012) Early Pleistocene to late Holocene activity of the Magnola fault (Fucino fault system, central Italy). Bollettino di Geofisica Teorica ed Applicata 53(4):435–458

Giraudi C (1988) Evoluzione geologica della piana del Fucino (Abruzzo) negli ultimi 30.000 anni. Il. Quaternario 1(2):131–159

Giraudi C (1999) Evoluzione geologica tardo pleistocenica ed olocenica della Piana del Fucino e dei versanti adiacenti: analisi di nuovi dati stratigrafici e radiometrici e ricostruzione delle variazioni ambientali. In: Castenetto S, Galadini F (eds) 13 gennaio 1915, il terremoto nella Marsica. Servizio Sismico Nazionale e C.N.R. Istituto di Ricerca sulla Tettonica Recente, Roma, pp 183–197

Idriss IM, Boulanger RW (2004) Semi-empirical procedures for evaluating liquefaction potential during earthquakes. In: Proceedings of 11th international conference on soil dynamics and earthquake engineering and 33d international conference on earthquake geotechnical engineering, Berkeley, pp 32–56

Idriss IM, Boulanger RW (2006) Semi-empirical procedures for evaluating liquefaction potential during earthquakes. J Soil Dyn Earthq Eng 26:115–130

Idriss IM, Boulanger RW (2008) Soil liquefaction during earthquakes. ERI Report, Publ. No.MNO-12, Earthquake Engineering Research Institute 2008

Iwasaki T, Tokida K, Tatsuoka F, Watanabe S, Yasuda S, Sato H. (1982) Microzonation for soil liquefaction potential using simplified methods. In: Proceedings of 3rd international conference on microzonation, Seattle, vol 3, pp 1319–1330

Kayen R, Moss R, Thompson E, Seed R, Cetin K, Kiureghian A, Tanaka Y, Tokimatsu K (2013) Shear-wave velocity-based probabilistic and deterministic assessment of seismic soil liquefaction potential. J Geotech Geoenviron Eng ASCE 139(3):407–419

Locati M, Camassi R, Rovida A, Ercolani E, Bernardini F, Castelli V, Caracciolo C H, Tertulliani A, Rossi A, Azzaro R, D'Amico S, Conte S, Rocchetti E (2016) DBMI15, the 2015 version of the Italian Macroseismic Database. Istituto Nazionale di Geofisica e Vulcanologia. doi:http://doi.org/10.6092/INGV.IT-DBMI15. http://emidius.mi.ingv.it/CPTI15-DBMI15/index_en.htm

Marchetti S (1980) In situ tests by flat dilatometer. J Geotech Eng Div ASCE 106(GT3):299–321

Marchetti S, Monaco P, Totani G, Calabrese M (2001) The flat dilatometer test (DMT) in soil investigations. A Report by the ISSMGE Committee TC16. In: Failmezger RA, Anderson JB (eds) Proceedings of international conference on in situ measurement of soil properties and case Histories, Bali, 2001, official version reprinted in Flat dilatometer testing, proceedings of 2nd international conference on the flat dilatometer, Washington D.C., April 2–5, 2006, pp 7–48

Marchetti S, Monaco P, Totani G, Marchetti D (2008) In situ tests by seismic dilatometer (SDMT). In: From research to practice in geotechnical engineering, Geotechnical Special Publication No. 180, pp 292–311, ASCE

Margottini C, Screpanti A (1999) Attribuzione della magnitudo al terremoto di Avezzano del 13 gennaio 1915 e studio dell'evoluzione temporale della crisi sismica associata. In: Castenetto S, Galadini F (eds) 13 gennaio 1915, il terremoto nella Marsica. Servizio Sismico Nazionale e C.N.R, Istituto di Ricerca sulla Tettonica Recente, Roma, pp 301–318

Michetti AM, Brunamonte F, Serva L, Vittori E (1996) Trench investigations of the 1915 Fucino earthquake fault scarps (Abruzzo, Central Italy): geological evidence of large historical events. J Geophys Res 101:5921–5936

Monaco P, Marchetti S (2007) Evaluating liquefaction potential by seismic dilatometer (SDMT) accounting for aging/stress history. In: Pitilakis KD (ed) Proceedings of 4th international conference on earthquake geotechnical engineering, Thessaloniki, Paper 1626

Monaco P, Schmertmann JH (2007) Discussion of "Accounting for soil aging when assessing liquefaction potential" by Evangelia Leon, Sarah L. Gassman, and Pradeep Talwani (in J Geotech Geoenviron Eng 132(3), 363–377). J Geotech Geoenviron Eng 133(9):1177–1179

Monaco P, Marchetti S, Totani G, Calabrese M (2005) Sand liquefiability assessment by flat dilatometer test (DMT). In: Proceedings of XVI ICSMGE, Osaka, vol 4, pp 2693–2697

Nisio S, Caramanna G, Ciotoli G (2007) Sinkholes in Italy: first results on the inventory and analysis. In: Parise M, Gunn J (eds) Natural and anthropogenic hazards in karst areas: recognition, analysis and mitigation, vol 279. Geological Society, Special Publications, London, pp 23–45. doi:10.1144/SP279.4

Oddone E (1915) Gli elementi fisici del grande terremoto Marsicano-Fucense del 13 gennaio 1915. Bollettino della Società Sismologica Italiana 19:71–291

Pace B, Albarello D, Boncio P, Dolce M, Galli P, Messina P, Peruzza L, Sabetta F, Sanò T, Visini F (2011) Predicted ground motion after the L'Aquila 2009 earthquake (Italy, Mw6.3): input spectra for seismic microzoning. Bull Earthq Eng 9:199–230

Petitta M, Burri E, Del Bon A, Marchetti A (2005) Carta idrogeologica del Fucino, scala 1/50.000. Atlante tematico del Fucino, foglio 1, ARSSA Abruzzo, SELCA Firenze

Robertson PK (1990) Soil classification using the cone penetration test. Can Geotech J 27(1):151–158

Robertson PK (2010) Soil behaviour type from the CPT: an update. In: 2nd International symposium on cone penetration testing, CPT'10, Huntington Beach, CA, USA

Robertson PK (2012) The James K. Mitchell Lecture: interpretation of in situ tests—some insights. In: Proceedings of 4th international conference on geotechnical and geophysical site characterization—ISC'4, Porto de Galinhas, Brazil, vol 1, pp 3–24

Robertson PK, Wride CE (1998) Evaluating cyclic liquefaction potential using the cone penetration test. Can Geotech J 35(3):442–459

Rovida A, Locati M, Camassi R, Lolli B, Gasperini P (eds) (2016) CPTI15, the 2015 version of the Parametric Catalogue of Italian Earthquakes. Istituto Nazionale di Geofisica e Vulcanologia. doi:http://doi.org/10.6092/INGV.IT-CPTI15. http://emidius.mi.ingv.it/CPTI15-DBMI15/index_en.htm

Seed HB, Idriss IM (1971) Simplified procedure for evaluating soil liquefaction potential. J Geotech Eng Div ASCE 97(9):1249–1273

Serva L, Blumetti AM, Michetti AM (1986) Gli effetti sul terreno del terremoto del Fucino (13 Gennaio 1915); tentative di interpretazione della evoluzione tettonica recente di alcune strutture. Memorie della Società Geologica Italiana 35:893–907

SM Working Group (2015) Guidelines for Seismic Microzonation. Civil Protection Department and Conference of Regions and Autonomous Provinces of Italy. 1 Vol. English edition of: Gruppo di lavoro MS, Indirizzi e criteri per la microzonazione sismica, Conferenza delle Regioni e delle Province autonome – Dipartimento della protezione civile, Roma, 2008, 3 vol. e Dvd. Available online at http://www.protezionecivile.gov.it/httpdocs/cms/attach_extra/GuidelinesForSeismicMicrozonation.pdf

Sonmez H (2003) Modification of the liquefaction potential index and liquefaction susceptibility mapping for a liquefaction-prone area (Inegol, Turkey). Environ Geol 44(7):862–871. doi:10.1007/s00254-003-0831-0

Totani G, Monaco P, Leopardi M, Farroni A (2000) Stabilization and environmental restoration of the main central channel in the Fucino plain, Italy. In: Moore D, Hungr O (eds) Proceedings of 8th IAEG Congress, Vancouver, Canada, 21–25 Sept 1998, Balkema, Rotterdam, pp 4215–4222

Tsai P, Lee D, Kung GT, Juang CH (2009) Simplified DMT-based methods for evaluating liquefaction resistance of soils. Eng Geol 103:13–22

Wang WS (1979) Some findings in soil liquefaction. Water Conservancy and Hydroelectric Power Scientific Research Institute, Beijing

Working Group MPS (2004) Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM 3274 del 20 marzo 2003. Rapporto Conclusivo per il Dipartimento della Protezione Civile, INGV, Milano-Roma, aprile 2004, pp 65 + 5 appendici. http://zonesismiche.mi.ingv.it/

Youd TL, Idriss IM, Andrus RD, Arango I, Castro G, Christian JT, Dory R, Finn WDL, Harder LF, Hynes ME, Ishihara K, Koester JP, Liao SSC, Marcuson WF, Martin GR, Mitchell JK, Moriwaki Y, Power MS, Robertson PK, Seed RB, Stokoe KH (2001) Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. J Geotech Geoenviron Eng ASCE 127(10):817–833

Zarlenga AF (1987) I depositi continentali del bacino del Fucino (L'Aquila, Italia Centrale). Geol Romana 26:223–253