Liquefaction assessment of gravelly soils using geophysical surveys: the case study of Sulmona (Italy)

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Introduction

The occurrence of liquefaction, intended as the reduction of stiffness and shear strength in loose water-saturated cohesionless soils associated with major earthquakes, is well documented all over the world both for sandy and gravelly soils (e.g., Rollins et al. 2021). Despite of this, geologists, and engineers, who try to develop effective techniques to predict the susceptibility of soils to this phenomenon, focused their attention mostly on sandy soils, e.g., Idriss & Boulanger (2008), Boulanger & Idriss (2014).

A relationship between susceptibility to liquefaction and grain size was firstly proposed by Tsuchida & Hayashi (1971), plotting the grain-size distribution of soils at Japanese liquefaction sites, and tracing the grain-size boundaries of the most liquefiable and potentially liquefiable soils. These grain-size boundaries are still widely used and are included in national building codes (e.g., Italy, NTC, 2018). However, these liquefaction susceptibility boundaries do not include gravelly soils that have been observed to liquefy in well documented cases, analyzed by Rollins et al. (2021) and reported in Fig. 1a.

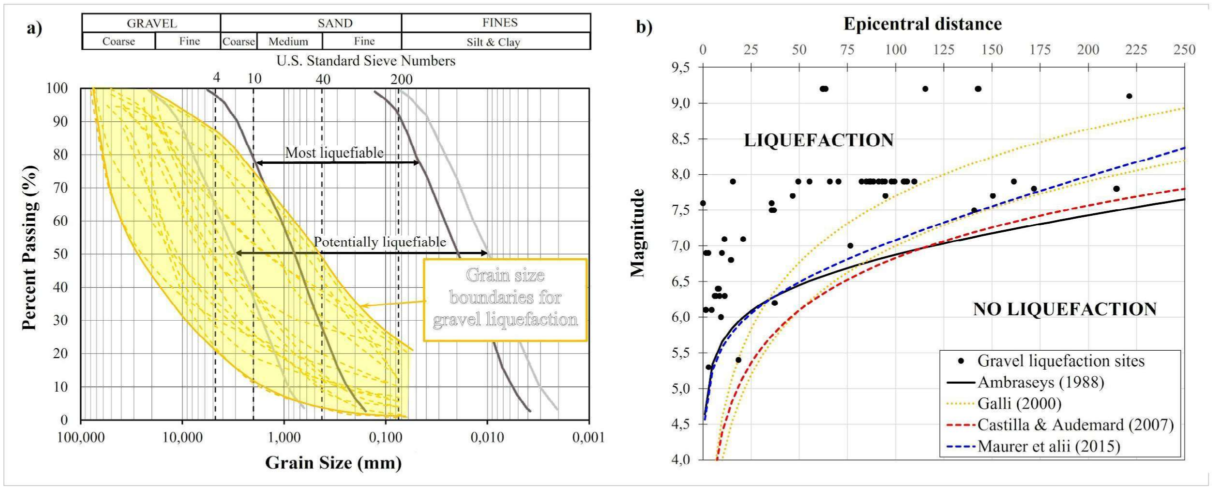

Fig. 1 – a) Gradation curves of liquefied gravelly soils (dashed yellow lines) in comparison with the grain size ranges proposed by Tsuchida & Hayashi (1971) and b) Chart of magnitude vs. epicentral distance to gravel liquefaction sites and available reference correlations (Salvatore et al., 2022).

Furthermore, Salvatore et al. (2022) compared the liquefaction susceptibility of sands and gravels in terms of magnitude vs. epicentral distance (Fig. 1b), using the gravel liquefaction case histories (black dots in Fig. 1b) and liquefaction curves available for sands (Ambraseys, 1988; Galli, 2000; Castilla & Audemard, 2007; Maurer et al., 2015). As shown in Fig. 1b, the triggering boundary for the gravel liquefaction can be assumed similar to the boundary curves already available for sands, highlighting that gravel liquefaction is not only associated with strong seismic events.

Methods

The liquefaction assessment of gravelly soils through the geotechnical laboratory characterization has always been a challenge because of the difficulties in taking undisturbed or partly disturbed samples and the high costs. Consequently, classical in situ tests such as Standard Penetration Test (SPT), developed for clean sandy soils, were adapted to gravelly soils. Although the use of the SPT-based approach correctly estimates the liquefaction potential in loose gravel with low penetration resistance, after the application of a correction factor (e.g., Kokusho & Yoshida, 1997), the results may be inaccurate when the penetration resistance increases, therefore new penetration tests with larger diameter tips have been developed to overcome these problems. In particular, the dynamic cone penetration test (DPT), that consists of a 74 mm cone driven continuously by a 120 kg hammer dropped from one meter, using a drilling rig or a simple SPT tripod system (Chinese Design Code, 2001), has been introduced and used firstly by Cao et al. (2013) and later by Rollins et al. (2022) to develop a procedure for the liquefaction assessment in gravelly soils.

Furthermore, Cao et al. (2011) also developed a liquefaction triggering curve VS-based for gravelly deposits, using the MW 7.9 Wenchuan dataset, and similarly to the DPT chart, Rollins et al. (2022) realized probabilistic liquefaction triggering curves based on *VS* data from a worldwide gravel liquefaction case history database (137 sites related to 17 earthquakes in seven countries within different geological environments and magnitudes).

Liquefaction assessment at the Santa Rufina test site

The VS – based method was applied to the Santa Rufina (Sulmona, Central Italy) test site, where nine SPTs, two DPTs and a down-hole (DH) were performed. To better constrain the analysis, 13 disturbed soil samples were also collected (Salvatore et al., 2022). The Sulmona basin (Fig. 2) is an intermountain tectonic depression caused by the Quaternary activity of a normal fault system affecting the western slope of Mt. Morrone (Miccadei et al., 1998; Galli et al., 2015). Based on an empirical relationship, the seismogenic potential attributed to this source has been estimated to be M_W 6.5-6.7 (e.g., Pizzi et al., 2002), with a recurrence time of 2.4 ± 0.2 ka (Galli et al., 2015). According to Miccadei et al. (1998) the Sulmona basin is mainly filled by lacustrine deposits and subordinately alluvial and slope deposits dating back to the Lower Pleistocene, although the entire sequence of the Quaternary filling has never been observed in either an outcrop or in a borehole to define its thickness.

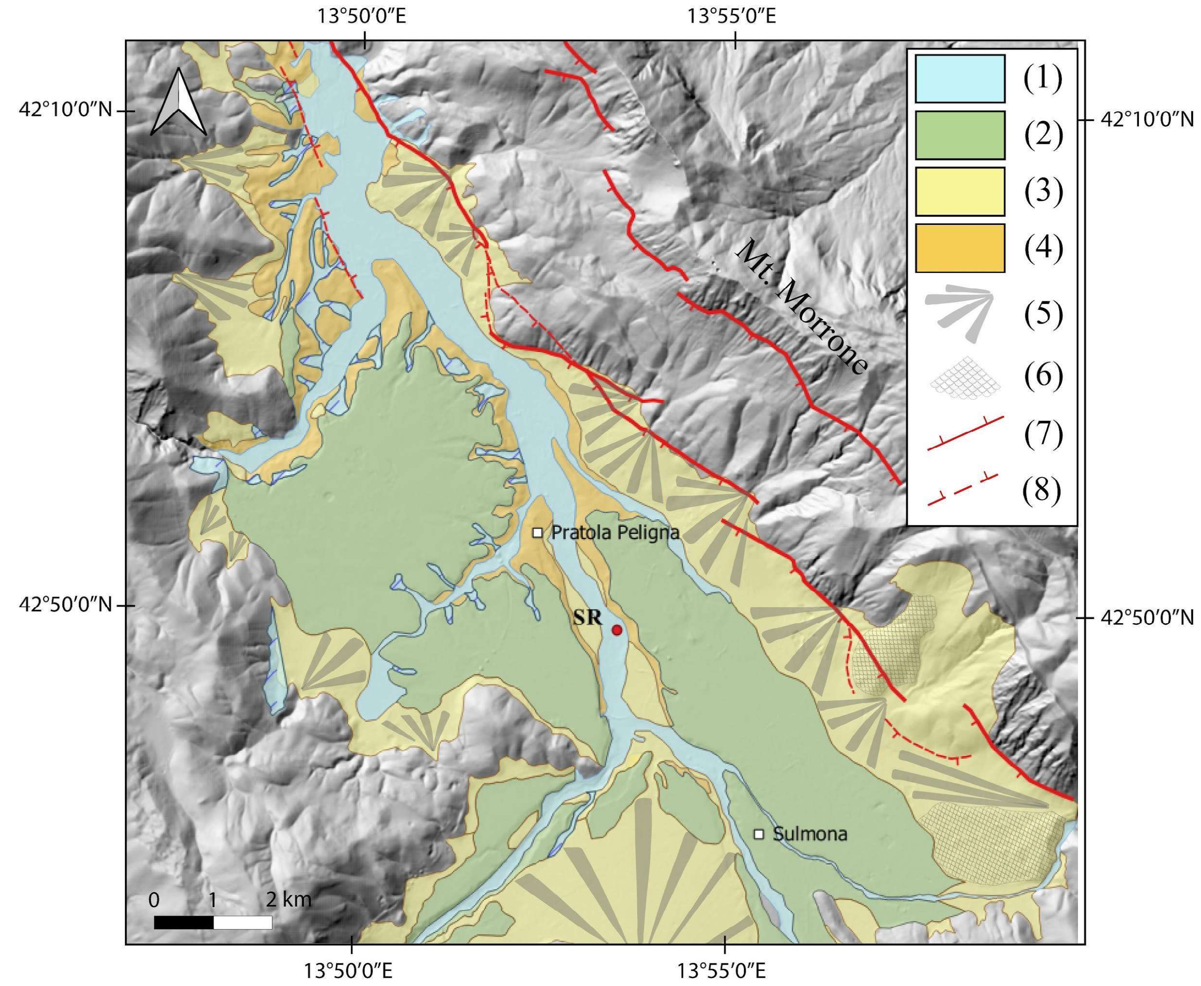

Fig. 2 – Geological map of the Sulmona Quaternary basin, after Galli et al. (2015), draped on DTM (Regione Abruzzo) (1) Upper Pleistocene - Holocene alluvial deposit; (2) Middle - Upper Pleistocene alluvial and colluvial deposit; (3) Upper Pleistocene fluvial-alluvial, slope fan and landslide deposit; (4) Lower-early Upper Pleistocene lacustrine deposit; (5) alluvial fan; (6) landslide; (7) active normal fault, inferred (8) (Salvatore et al., 2022).

The borehole stratigraphic log of Santa Rufina test site highlighted the variability in sediments within the first few meters of the Holocene alluvial plain, showing, under the present topsoil, an alternance of sandy-gravelly and silty (plastic) thin layers until 7 m depth. The groundwater table (GWT) was intercepted at a depth of 1 m below the ground surface (Salvatore et al., 2022). Fig. 3 summarizes the simplified borehole log obtained using the USCS classification (Unified Soil Classification System) together with the fine content (FC) profile provided by the laboratory testing.

To evaluate the CSR7.5 profile according to the “simplified procedure”, the peak ground acceleration at the ground surface ($a_{max} = 0.296g$) has been determined starting from (1) the value at outcropping rock conditions equal to 0.255 g, as proposed by Valentini et al. (2019) in the Sulmona area for a return period of 475 years based on a fault based PSHA study, and (2) the stratigraphic amplification factor Ss = 1.16 for the B subsoil class of the Italian building code (NTC, 2018). To evaluate the liquefaction safety factor (FSliq) and therefore the liquefaction potential index (LPI) through the cyclic resistance ratio $CRR_{7.5}$ (Fig. 3) we used the corrected V_S values (V_{S1}) according to Cao et al. (2011) and Rollins et al. (2022).

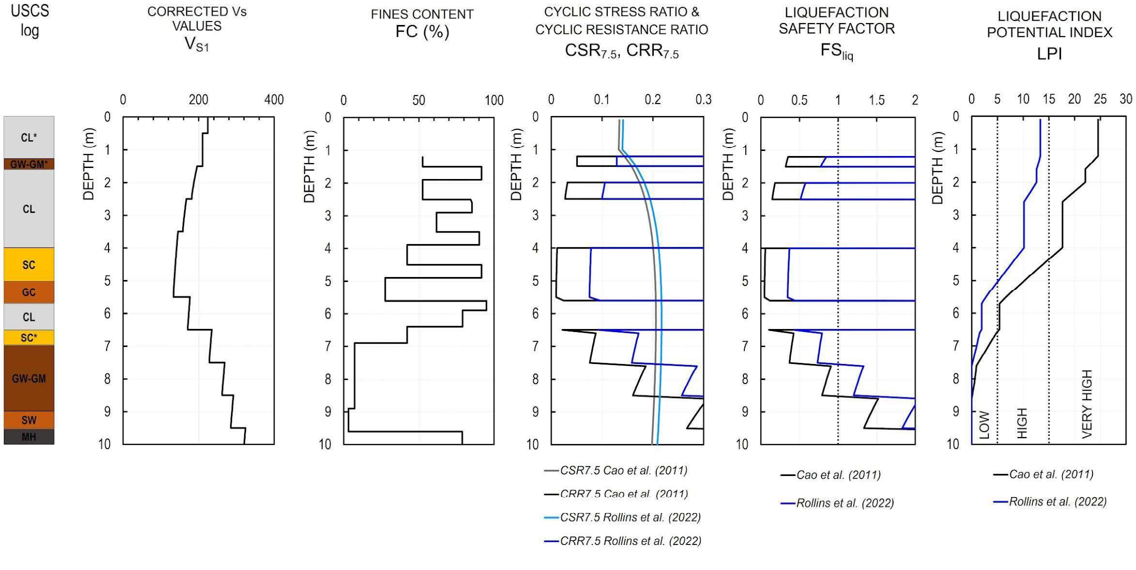

Fig. 3 –Liquefaction assessment results based on V_S methods by Cao et al. (2011) and Rollins et al. (2022) at Santa Rufina test site.

We also compared the results from V_S – based methods to those from DPT and SPT already estimated by Salvatore et al. (2022), recalculating also the LPI values according to the laboratory screening criteria (Tab. 1).

As it can be seen in Tab. 1, even if SPT-based methods gave lower LPI values compared with DPT-and V_S – based methods, they are all included in the range of "high" LPI, except for Cao et al. (2011) which gives a value in the "very high" range. When the fines content (FC) and the plasticity index (PI) are considered (case "B"), all methods showed LPI values close to zero or in the "low" range.

Table 1 – Santa Rufina test site: comparison of LPI results obtained using only in situ tests and FC measurements (case "A"), and using in situ tests, FC and PI measurements, excluding interbedded layers (case "B") (modified after Salvatore et al. 2022).

In situ test	*Method*	*LPI (case "A")*	*LPI (case "B")*
SPT	Youd et al. (2001)	5.9	0.0
	Idriss and Boulanger (2008)	7.0	0.0
	Boulanger and Idriss (2014)	8.9	0.0
DPT	Cao et al. (2013)	13.5	0.3
	Rollins et al. (2021)	12.8	0.2
VS	Cao et al. (2011)	24.5	2.5
	Rollins et al. (2022)	13.3	0.7

Conclusions

In this work we proposed an innovative and multidisciplinary approach to liquefaction assessment in gravelly soils, using a combination of in situ and laboratory geophysical and geotechnical methods.

The site of Santa Rufina (Sulmona, Central Italy) is characterized by an alluvial Upper Pleistocene – Holocene profile that consists both of sandy-silty and gravelly-sand alternating layers, with high vertical and lateral variabilities that introduce relevant uncertainties in the regional extensions (e.g., microzonation studies) of the liquefaction risk assessment at discrete vertical profiles with simplified methods.

The liquefaction assessment based only on the V_S measurements gives a "very high" LPI value using Cao et al. (2011), while the LPI value derived from the triggering curve proposed by Rollins et al. (2022) results "high", such as DPT and SPT methods tested by Salvatore et al. (2022).

Similarly, when liquefiable layers between interbedded cohesive layers (e.g., layers characterised by a "clay-like" behaviour according to well-known screening criteria) are excluded, the LPI value from Cao et al. (2011) remains greater than the LPI value from Rollins et al. (2022), which is comparable with the DPT-based methods. This aspect may be related to the different dataset used to develop the liquefaction prediction equations for DPT and V_S methods (single earthquake for the Cao formulas and worldwide case histories for the Rollins correlations).

Acknowledgements

This study was carried out in the framework of the ReLUIS-DPC 2019–2021 research project under funding of the Italian Civil Protection Department (Task 16.1 Site Response and Liquefaction). Additional funding by Regione Abruzzo is also acknowledged. Partial funding provided by grant CMMI-1663546 from the U.S. National Science Foundation. However, the opinions, conclusions and recommendations in this paper do not necessarily represent those of the sponsors.

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