The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
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Site response analysis in effective stress of a coastal area in the North-Western Adriatic region (Italy)

A. Merli
DICEA, Università Politecnica delle Marche, Ancona, Italy

F. Dezi
DESD, University of San Marino, San Marino, San Marino Republic

G. Tropeano
DICAAR, University of Cagliari, Cagliari, Italy

A. Chiaradonna & A. d'Onofrio
DICEA, University of Napoli Federico II, Naples, Italy

ABSTRACT: The North-Western Adriatic coast is characterized by a continuous shallow marine sandy deposit, constituted by two stratigraphic units with a different fine content and with the water table close to the ground surface; therefore, this area is historically vulnerable to liquefaction phenomena. In this work, the results of a comprehensive site and laboratory surveys are presented aimed at obtaining a reliable geotechnical model of a test site along the North-Western Adriatic coast. Seismic response analyses are then carried out through the one-dimensional nonlinear code SCOSSA, which can simulate excess pore water pressure build-up, redistribution and dissipation, using as input a set of recorded accelerograms compatible with the national building code. The analyses results highlight the importance of carrying out an accurate characterization of the site and of the selection criterion of the input motions in performing advanced dynamic analyses to detect the liquefaction potential and for a reliable design of important structures and infrastructures in this area.

1 INTRODUCTION

The North-Western Adriatic coast is characterized by a shallow continuous marine sandy deposit, constituted by two stratigraphic units with a different fine content and with the water table close to the ground surface. The area under study was classified from the Italian Government as Zone 2 with a medium-high seismic hazard (O.P.C.M. 3519/2006) and is historically prone to liquefaction phenomena. The historical-scientific testimonies after the past earthquakes give evidence of several liquefaction phenomena occurred along the Romagna coast between Cervia and Cattolica (Serpieri 1889; Galli 2000). Moreover, the area is one of the most densely populated in Italy, especially in summertime when it becomes overpopulated, and it is a strategic area for the high concentration of tourist attractions, historical monuments and infrastructures.

In order to protect costal area activities, a comprehensive study on liquefaction soil susceptibility was carried out on a reference site along the North-Western Adriatic coast. An extensive geophysical and geotechnical campaign, consisting in laboratory and in-situ tests, was conducted in that site with the aim of providing a detailed characterization of subsoil, the evaluation of soil stratigraphy, shear wave velocity distribution and the dynamic characteristics of the shallow sandy deposits (Merli et al. 2017). Based on the obtained experimental data, 1D site response analyses are conducted using a set of recorded acceleration time histories, representative of a seismic action prescribed by the National Building Code (NTC 2018) for a return period of 712 years related to the limit state of life safeguard SLV (probability of exceedance of 10% in 75 years).

The analyses were performed in effective stress conditions, considering generation and dissipation of excess pore water pressure induced by seismic actions, through the 1D computer code SCOSSA (Tropeano et al. 2016; 2019). The generation of the excess pore water pressure is carried out by means of a simplified pore water pressure model, following a stress-based approach (Chiaradonna et al. 2018). The model represents a useful tool for engineering practice, since it requires only a few parameters that are clearly defined and easy to calibrate on laboratory data; i.e., cyclic triaxial or simple shear tests results. The dissipation of the excess pore pressure is also considered, since the code implements the one-dimensional consolidation theory (Terzaghi, 1943).

In the final section, the results of the analyses are shown in terms of accelerations, strains and pore pressure profiles and preliminary conclusions about the liquefaction potential of the sand deposits are provided.

2 GEOLOGICAL AND GEOTECHNICAL CHARACTERIZATION

2.1 *Geological main features and overall geotechnical characterization of the coastal deposits*

The reference site is located on the Riminese North coastal area, here named RNN (Figure 1a), along the North-Western Adriatic coast. From a geological point of view, Holocene sea level fluctuations, together with the action of redistribution operated by currents, increased the marine sedimentary deposit until the current configuration (Merli et al. 2016). The coastal deposits constituting the typical sand wedge are characterized by areal continuity and homogeneity. These deposits are generally divided in two main units: a more superficial sandy unit, here named A, constituted by well sorted medium dense to dense sands occasionally interbedded with thin silty layers, deposited mainly in high-energy beach environments and a second underlying silty sandy unit, here named B, richer in silts and looser, due to an incomplete rearrangement of marine and alluvial sediments operated by sea currents, as typical of backshore and lagoon environments with less depositional energy. Finally, a purely alluvial clayey layer, here named C, can be individualized at the bottom of the coastal deposits (Figure 2) (Merli et al. 2017). The geotechnical characterization is based on an extensive database of in situ and laboratory tests, taken from the local government and new investigations in representative test fields. Typical cone tip resistance profiles, obtained from Cone Penetrometer Tests (CPT) are reported in the cross section showed in Figure 1b and in Figure 2a, showing the different arrangement of the three units, while Table 1 summarizes the main geotechnical characteristics of the representative sandy units. The grain size distributions of the

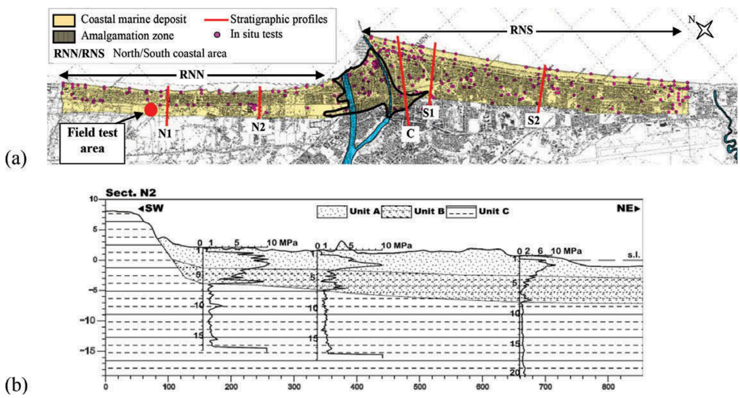

Figure 1. Schematic geological map (a) and cross section N2 (b).

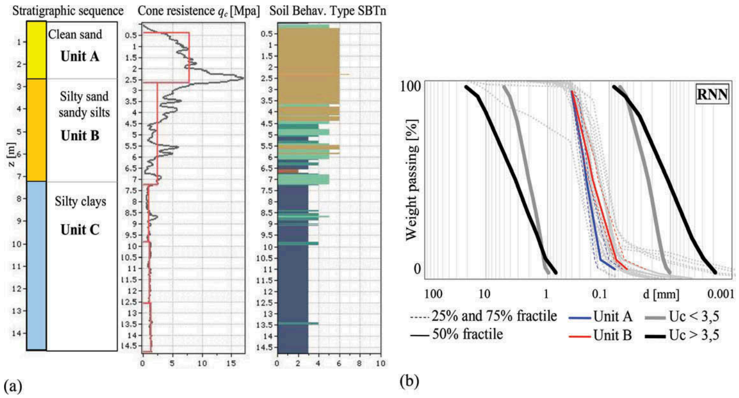

Figure 2. Typical stratigraphic sequence, CPT profile and interpretation in terms of Soil Behaviour Type Index, I_c (a), particle size distribution and statistical curves for unit A and B in the North Riminese sandy coastal area (RNN) superimposed to the liquefaction susceptibility range of Tsuchida (1970) (b).

Table 1. Main parameters of the sandy Units A and B

soil	thickness [m]	q_c [MPa]	FC [%]
Unit A	2.5÷3.5	5.0	2÷7
Unit B	3.0÷4.0	1.5÷5.0	8÷16

q_c – Cone resistance; *FC* – Content in fine (particles size ≤ 0.075 mm)

Table 2. Hydraulic conductivity (horizontal k_h and vertical k_v) of sandy coastal deposits.

soil	k_h [m/s]	k_v [m/s]
Unit A	1.20E−4	5.42E−5
Unit B	9.35E-5	–

two main geotechnical units (A and B) of the sand wedge are showed in Figure 2b superimposed to the liquefaction susceptibility range of Tsuchida (1970).

The particle size distribution reveals a high susceptibility to liquefaction (Tsuchida, 1970), as consequence of the particle size, the low to moderate content in fine and the degree of sorting of the sand (Figure 2b).

The hydraulic conductivity of coastal sandy deposits was estimated through: (*i*) indirect extensive analyses of the particle size distributions and CPT tests and (*ii*) direct tests (laboratory and in-situ test such as pumping tests, slug tests, Lefranc and tracer tests) in the field test area. Table 2 lists the hydraulic conductivity obtained by in-situ tests in the field test area.

2.2 *Dynamic and cyclic soils features*

An extensive geophysical survey was carried out consisting in *Refraction Microtremor* (ReMi), *Multichannel Analysis of Surface Waves* (MASW), *Extended Spatial Auto-Correlation* (ESAC), *Horizontal-to-Vertical Spectral Ratio* (HVSR) and *Seismic Dilatometer Marchetti* (SDMT) tests.

By combining the information gained from superficial geophysical surveys with the borehole surveys, a representative stratigraphic sequence and a profile of shear wave velocity *Vs*, was obtained up to the seismic bedrock depth (Figure 3a). Essentially, silty clays and gravels result in an interlayered sequence under the shallowest marine sands (units A and B). The water table was detected at around 1 m depth.

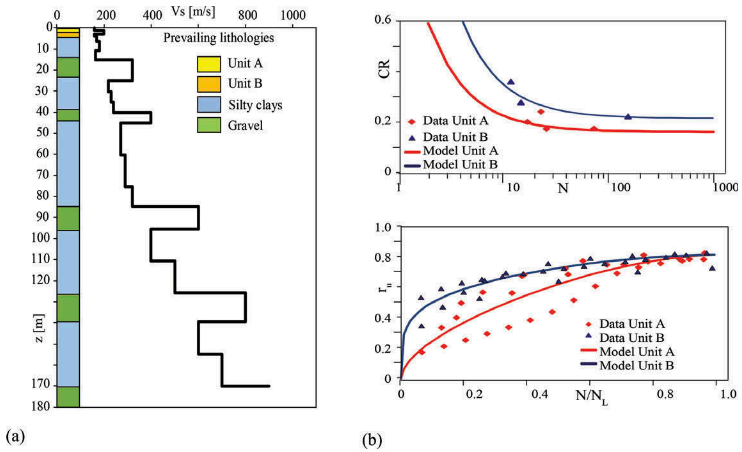

Figure 3. Shear wave velocity profile and related stratigraphy used for seismic response (a). Fitting CTX data to calibration of PWP model for effective stress analysis (b).

Table 2. Normalized shear modulus reduction and damping ratio curves adopted in the model

Soil	$G/G_0 - \gamma$	$D - \gamma$
Unit A	SDMT 1−3 m	Seed et al. 1986 Sand – Average
Unit B	SDMT 4−6 m	Seed et al. 1986 Sand – Lower Bound
Unit C	SDMT 13 m	Sun et al. 1988 – Average
Gravel	Rollins et al. 1998	Rollins et al. 1998

The non-linear and dissipative behavior of soils was modelled in terms of modulus reduction, G/G_0, and damping ratio, D (%), curves. For low-medium range strains, G/G_0 curves were obtained through SDMT tests (Marchetti et al. 2008). In Figure 4a, those experimental curves are reported and compared with some literature reference curves (for Unit A and Unit B, curves proposed by Seed et al. 1986 while for Unit C that proposed by Sun et al. 1988) and G/G_0 curves obtained through resonant column (RC) tests performed in a different area along the coast in the same lithotypes. In Figure 4b, damping ratio curves obtained by RC tests are also shown and compared with the selected literature curves. The normalized shear modulus reduction and damping ratio curves used in the site response analyses are summarized in Table 2. For the gravelly and deeper layers have been respectively used literature curves (G/G_0 and D) of Rollins et al. (1998) and EPRI 1993 for generic soils as a function of depth.

The parameters of the pore water pressure model (PWP) for the liquefiable layers, Unit A and Unit B, were estimated by cyclic triaxial test (CTX) data. Figure 3b reports the experimental data, in terms of cyclic resistance curve and excess pore pressure ratio with the normalized number of cycles, compared with the modelled curves used in the computations. The parameters of the pore water pressure model were defined through a regression analysis of the experimental data, following the suggestions reported by Chiaradonna et al. (2018). The model is based on the damage parameter concept and implemented into non-linear seismic response analyses operating in the time domain through the code SCOSSA (Tropeano et al. 2019). Finally, a consolidation coefficient was estimated based on the measured hydraulic conductivity.

2.3 *Input selection*

The considered site is located in a medium-high seismicity area, characterized by periodical events of very strong to severe macroseismic intensity, due to prevailing compressive seismic

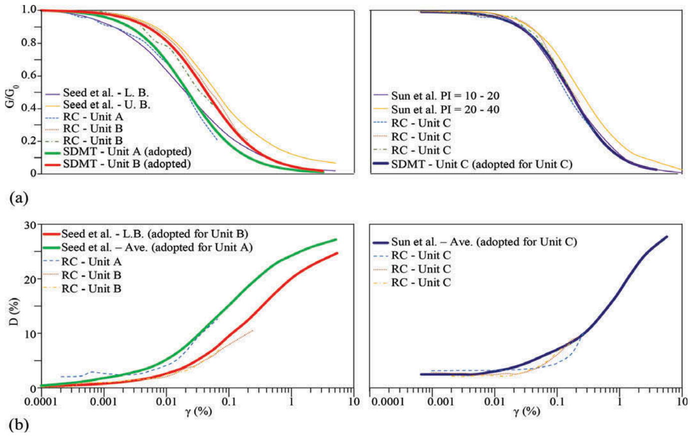

Figure 4. Modulus reduction G/G_0 (a) and damping ratio curves (b) for soils Unit A, B, C adopted in the analyses (a), obtained by comparing experimental data (from RC and SDMT) and literature curves.

Table 3. Main features of the acceleration records adopted in the analyses

Event	Earthquake	Date	M_w	E_{epi} [km]	SF	*Drms*	$D_{5\text{-}95}$ [s]	Fault Mechanism
000055xa	Friuli	06/05/1976	6.5	23	0.594	0.0172	4.35	thrust
000149xa	Friuli (afters.)	15/09/1976	6.0	12	1.554	0.029	6.83	thrust
000198xa	Montenegro	15/04/1979	6.9	21	1.172	0.049	12.22	thrust
004675xa	South Iceland	17/06/2000	6.5	13	1.610	0.023	4.48	strike slip
007142ya	Bingol	01/05/2003	6.3	14	0.713	0.014	6.79	strike slip
IN0386ya	Christchurch	13/06/2011	6.0	5.1	0.375	0.027	9.16	reverse
MMO-HGN	Central Italy	30/10/2016	6.5	19.2	1.124	0.020	12.8	normal
Mean:			**6.4**	**15.3**	**1.020**	**0.025**	**8.09**	

E_{epi} = epicentral distance
M_w = moment magnitude
Drms = average root-mean-square deviation of the observed spectrum from the target design spectrum
$D_{5\text{-}95}$ = significant duration
SF = scale factor

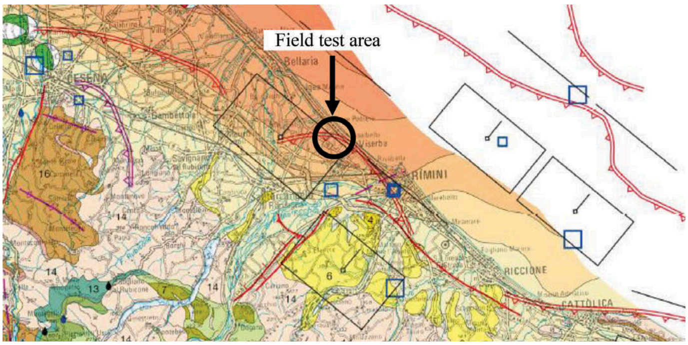

Figure 5. Sketch of the Seismotectonic Map of the Emilia Romagna Region (Martelli et al. 2017) showing the active seismic structures and the epicentral distance of historical earthquakes.

activity, where several individual and composite seismogenetic sources are close to the test site and along to the Adriatic coast. By considering a return period of 712 years, the rock outcropping PGA (0.212 g) and the target response spectrum are suitably selected considering

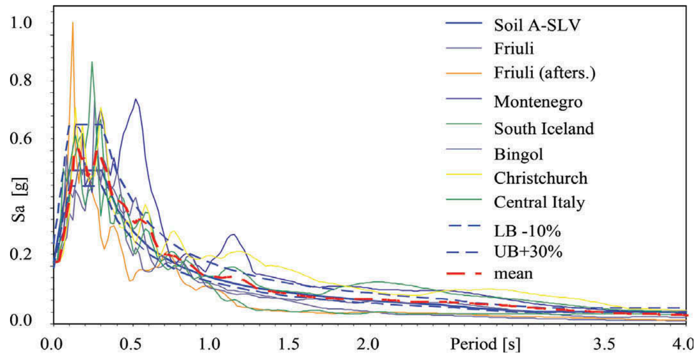

Figure 6. Acceleration response spectra of the selected input motions superimposed to the target spectrum.

information from the Italian probabilistic seismic hazard map (O.P.C.M., 28 Aprile 2006, n. 3519, All. 1b). Seven recorded accelerograms (Table 3) were selected coupling spectrum compatibility with magnitude-distance range from disaggregation and information obtained from the new seismotectonic map of the Emilia Romagna (Martelli et al. 2017) (Figure 5). The elastic pseudo-acceleration response spectra of the selected earthquakes with the design spectra are reported in Figure 6.

3 SITE RESPONSE ANALYSIS IN EFFECTIVE STRESS

The results of effective stress analyses are shown in Figure 7 in terms of vertical profiles of the peak values of acceleration, shear strain and excess pore pressure ratio.

The acceleration profile at the free field does not show significant amplification, due to the high deformations developed between 12 and 15 m depth, across the interface between stiff gravels and soft clays. This localized deformation phenomenon, even if to a less evident extent, can also be highlighted in correspondence of the deeper layers of gravel. Due to the lower accelerations and the cyclic resistance offered by the sands, the maximum value of excess pore pressure ratio is locally limited to 0.7. This ratio does not reach the limit value of $r_u = 0.95 \div 1.0$ generally considered for the liquefaction triggering of sands. However, it can be a critical value in presence of pre-existing stress states with significant deviatoric component as in the case of soils underlying buildings and/or infrastructures (e.g., roads, bridges, railways, harbors, etc.). Finally, results show that the selected seismic input motions do not provide an unequivocal evaluation of the liquefaction phenomenon potential (a change in the selection parameters or the use of accelerograms with certain characteristics can affect the estimation of the liquefaction potential).

By way of example Figure 8 reports the MMO-HGN time histories of shear stress and excess pore pressure ratio at 2.25 and 5.88 m depth, i.e., in the unit A and B, respectively. The MM0-HGN and 000198xa accelerograms are those among the set that lead to higher overpressure and are characterized by the highest duration ($D_{5\text{-}95}$) and Arias Intensity. According to Foti et al. (2018) is evident that some of the characteristics of the seismic motion may affect the trigger mechanisms and the development of excess pore water pressure. It can be noted that, in both soils, the pore pressure build-up starts at the time value of 4 s (in correspondence of $\gamma_{max} = 0.04$ %) and the largest amount of the reconsolidation process starts after the most critical stage of the time history (15 s) and that it still tends to continue after the end of the seismic shaking. Especially in the lower Unit B, dissipation is less evident due to the lower vertical hydraulic conductivity of the layer and to clay deposits at the bottom of the layer.

The stratigraphic peculiarity of the site, with interlayered silty clays and gravels under the marine sands (units A and B), clearly conditioned the results of the analyses. The test site, in

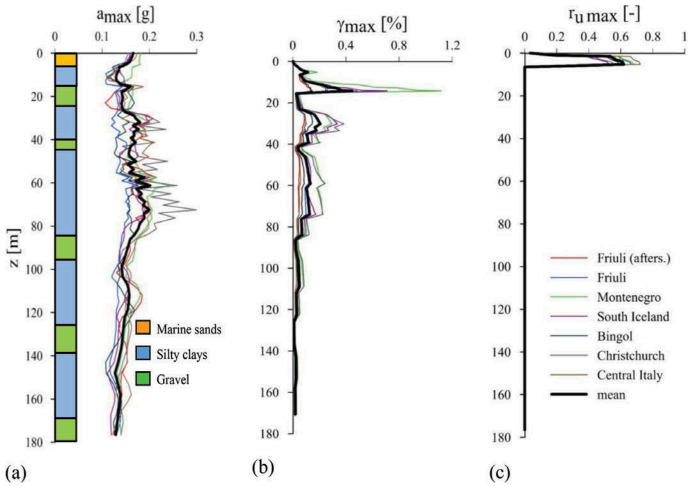

Figure 7. Vertical profiles of maximum (a) acceleration, (b) shear strain and (d) pore pressure ratio resulting from analyses.

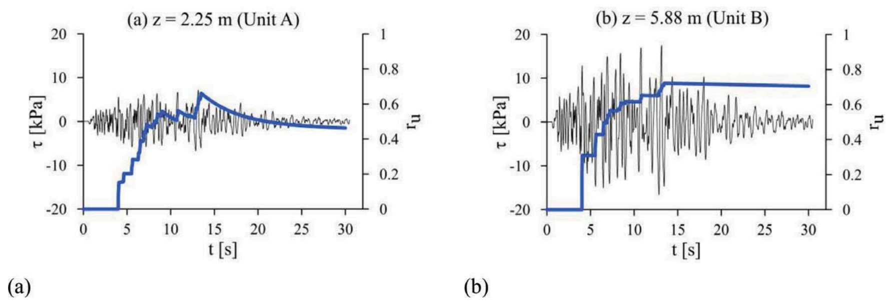

Figure 8. Example of MMO-HGN time histories of shear stress and excess pore pressure ratio of at (a) 2.25 m (Unit A) and (b) 5.88 m (Unit B) depth from ground level.

fact, is located close to the upstream of the "sand wedge", where the coastal deposits are more consolidated and "aged", while towards the shoreline become more recent and without the interbedded gravelly layers at the interface of which high strains occur.

4 CONCLUSIONS

This paper presents a liquefaction study on a test site along the North-West Adriatic seaside, which is an area of great interest from an economic, touristic and historical point of view.

An accurate geological, geophysical and geotechnical investigation allowed the construction of a reliable geotechnical model used for carried out 1D dynamic analysis in effective stress under seismic actions with a return period of 712 years, as prescribed by the current national building code. Analysis results show a moderate liquefaction potential of the sandy deposits, which can become critical in urbanized contexts (because of soil/structure interaction phenomena) and areas closed to the shoreline.

The obtained results underline also that the selection criterion for the seismic input motion should be carefully analysed and that pure spectro-compatibility criterion may not be effective for liquefaction evaluations.

As future perspective, the study will be finalized to rebuild a seismic scenario representative of the historical earthquakes, such as the 1916 and 1786 events, in order to simulate the liquefaction evidences observed in the past.

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