Soil liquefaction and induced damage to structures: a case study from the 2012 Emilia earthquake

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ABSTRACT: A database of masonry buildings located in a number of municipalities struck by the 2012 Emilia earthquake has been analyzed for this work. Post seismic survey was carried out by the Italian Department of Civil Protection soon after the earthquake. The database included information on building characteristics, level and extent of damage to structural and non-structural components. Additionally, data on ground conditions and the results of in-situ tests (CPT) were collected. The comparative analysis of observed damage has shown evidences of the impact of soil liquefaction on structures. It led to the formation of unusual crack patterns on the structure compared to the typical inertial damage. The correlation between structural damage and soil liquefaction was then investigated with reference to an exemplificative case of study in the hamlet of San Carlo (Sant'Agostino municipality). A simplified procedure for estimating liquefaction-induced building settlement was applied, obtaining an estimated settlement compatible with the observed damage.

1 INTRODUCTION

Cyclic liquefaction is a physical state achieved by a loose saturated sandy soil when shear strength approaches zero due to the increase of excess pore water pressure triggered by a seismic event. Predisposing ground conditions are necessary for liquefaction to be induced, that make this phenomenon strongly site-dependent. In particular, loose saturated sandy deposits characterized by low fine content (up to 25%) and relatively low depths (≤15 m) can be considered to be potentially liquefiable. Liquefaction leads to the occurrence of fractures in the soils, expulsion to the surface of water and sand with possible formation of "sand boils", settlement of the ground surface, settlement and tilting of buildings, and loss of the bearing capacity of the foundations. In the world, considerable damage has been caused to structures as a consequence of liquefaction events, also with the collapse of numerous buildings (Tokimatsu et al. 1996; Yoshida et al. 2001). In Italy, liquefaction phenomena were observed during various earthquakes, among these some significant events occurred historically in Emilia-Romagna (Ferrara 1570, Argenta 1624, Cesenatico 1875, Rimini 1916). Also during the 2009 L'Aquila earthquake some evidences of liquefaction were observed (De Martini et al. 2012), but they occurred far from towns and did not produce damage to structures. Conversely, during the 2012 Emilia seismic sequence, liquefaction affected built areas causing significant damages (Crespellani et al. 2012). The liquefaction phenomena were particularly relevant in two towns in the province of Ferrara: San Carlo, a hamlet of Sant'Agostino municipality, and Mirabello, where liquefaction caused bumpy roads, failures to the gas network and unusable buildings. The main evidences observed at the ground surface were the formation of sand boils, ground bulges and cracks, settlements, upheaval of sidewalks. These effects were mainly observed along abandoned river canals (Facciorusso et al. 2012). The degree of damage to buildings was found to be variable: some buildings underwent rigid translation, and small rotation sometimes. Moreover, detachments of structurally-weak annexes from the main buildings (such as garages or deposits) and widespread damage to flooring, partitions and resistant vertical and horizontal structures were observed. After these events, a preliminary analysis of the structural damage induced by liquefaction was carried out and the vulnerability of a sample of 101 residential masonry buildings was assessed (Di Ludovico et al., submitted). Then, the correlation between structural damage and soil liquefaction has been investigated with reference to an exemplificative case of study in the hamlet of San Carlo. As a matter of fact, only liquefaction damage was observed on the selected shallow-founded building.

In this work, the liquefaction-induced building settlement has been estimated as the sum of three different components: shear-induced, volumetric-induced, ejecta-induced ground deformations (Bray and Macedo 2017). The volumetric component was computed by the dissipation of the excess pore water pressure predicted by means of a 1D dynamic analysis in effective stress (Chiaradonna et al. 2018a). The shear and ejecta-induced components were estimated applying the simplified procedure proposed by Bray and Macedo (2017). Finally, the overall settlement has been compared with the observed damage at the site.

2 DAMAGE INDUCED BY LIQUEFACTION

The liquefaction phenomenon caused the loss of bearing capacity of the soil foundation. The consequence of this phenomenon is the occurrence of differential or absolute settlements that cause a variable damage to buildings, up to make them inaccessible, in some cases. In particular, where the phenomenon affected the entire foundation, it was possible to observe absolute settlements of more than 30 cm, which led the building to undergo rotation mechanisms (Fig. 1a). In other cases, widespread differential settlements caused the opening of diagonal cracks on both vertical structures (Fig. 1b) and on the horizontal ones, with widespread damage to external paving (Fig. 1c) or inside the buildings (Fig. 1d, e). Finally, in some buildings, damage induced by liquefaction was observed in conjunction with inertial damage (Fig. 1f, g). It is possible that the liquefaction may have been triggered after an initial phase of strong shaking, thus inducing a combined damage.

Figure 1. Damage induced by liquefaction.

3 CORRELATION BETWEEN DAMAGE – SETTLEMENTS

A preliminary assessment of the observed damage was carried out through the AeDES forms (Baggio et al. 2007), a tool for the evaluation of earthquake-induced damage. A section of the form that provides the information used in this study is shown in Figure 2.

Structural component / Pre-existing damage \ Level - extension		DAMAGE									
		D4-D5 Very heavy			D2-D3 Medium-severe			D1 Slight			Null
		> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	
		A	B	C	D	E	F	G	H	I	L
1	Vertical structures	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
2	Floors	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
3	Stairs	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
4	Roof	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
5	Infills-partitions	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
6	Pre-existing damage	☐	☐	☐	☐	☐	☐	☐	☐	☐	○

Figure 2. Section 4 of AeDES form.

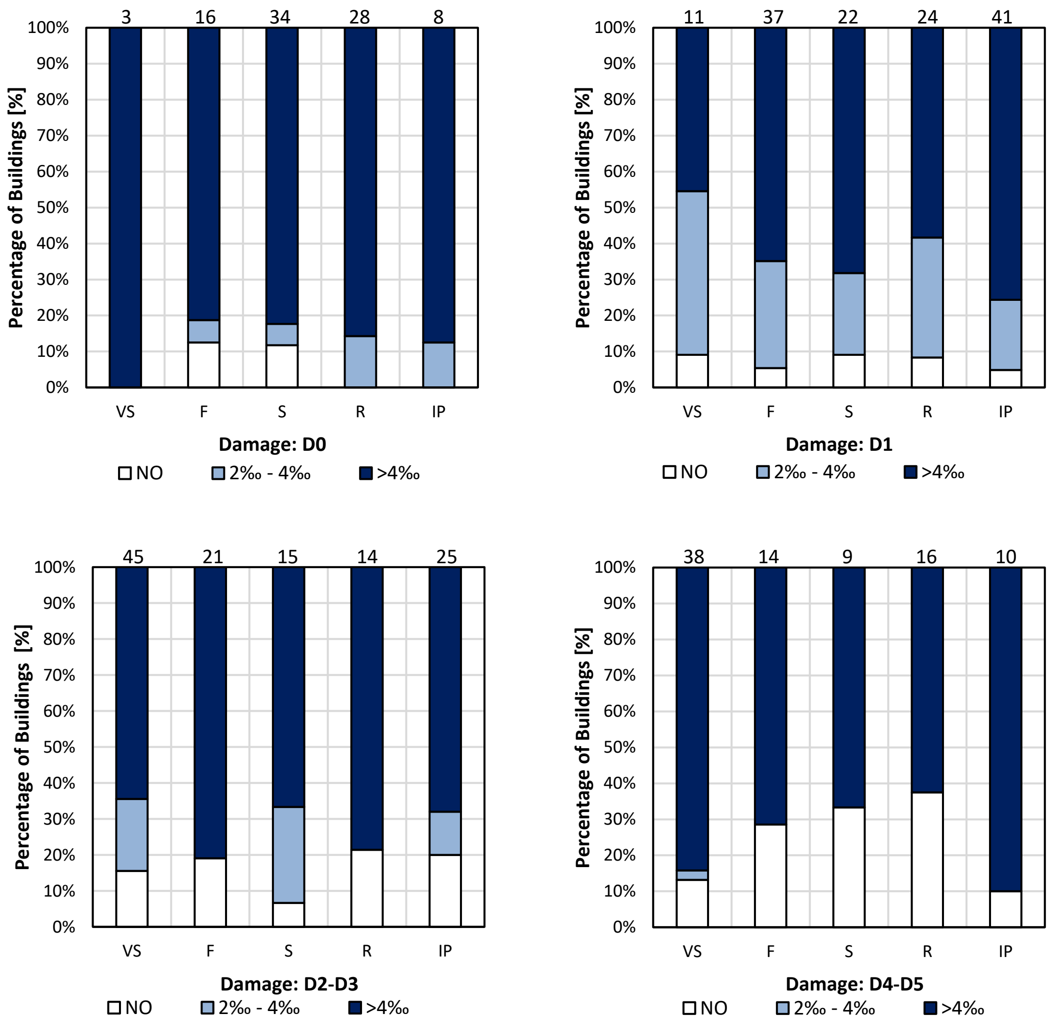

Figure 3. Percentage of buildings in function of levels damage defined to AeDES form.

The definition of the level of damage is of particular relevance. It is based on the European Macroseismic scale EMS-98. The EMS-98 scale provides six possible damage levels to the building as a whole (D0-null damage, D1-light damage, D2-medium damage, D3-severe damage, D4-very serious damage or partial collapse, D5-collapse of most of the building), according to the level and the extent of the damage of structural and non-structural elements of the building. The maximum damage observed for each structural component was thus correlated with intervals of failure provided by the Region (Regione Emilia-Romagna, 2012), that allowed to identify three intervals of differential settlements in order to define an operational level for the evaluation of the economic contribution for reconstruction: i) absence of failure; ii) differential settlement between 2‰ and 4‰ of the wall length; iii) greater than 4‰.

Fig. 3 allows to observe the percentage of buildings falling within a range of settlement as it shares on structural and non-structural components at the same level of AeDES damage. The figure shows that a direct trend between damage levels to structural and no structural components and differential settlements is not easily detectable; this confirms that the damage may be due to inertial forces before liquefaction occurred. Furthermore, even when liquefaction occurs it could also imply a rigid rotation of the building only, without affecting the damage to building components.

4 ESTIMATION OF THE LIQUEFACTION-INDUCED SETTLEMENT OF A REFERENCE SHALLOW-FOUNDED BUILDING

A shallow-founded rectangular masonry building (Fig. 4b) in the hamlet of San Carlo (Sant'Agostino municipality) (Fig. 4a) was selected for the estimation of liquefaction-induced settlement, since it is a representative case of the liquefaction-induced damage. As a matter of fact, the cracks pattern observed along the south side of the building highlights a rotation mechanism, which can be ascribed exclusively to liquefaction effects (Fig. 4c).

An estimate of the liquefaction-induced building settlement was computed as a sum of three different components: shear-induced, volumetric-induced and ejecta-induced ground deformations, as reported by Bray & Macedo (2017). According to these researchers, building settlements is governed primarily by shear-induced mechanisms as a result of soil-structure-interaction (SSI)-induced ratcheting and bearing capacity-type ground deformations.

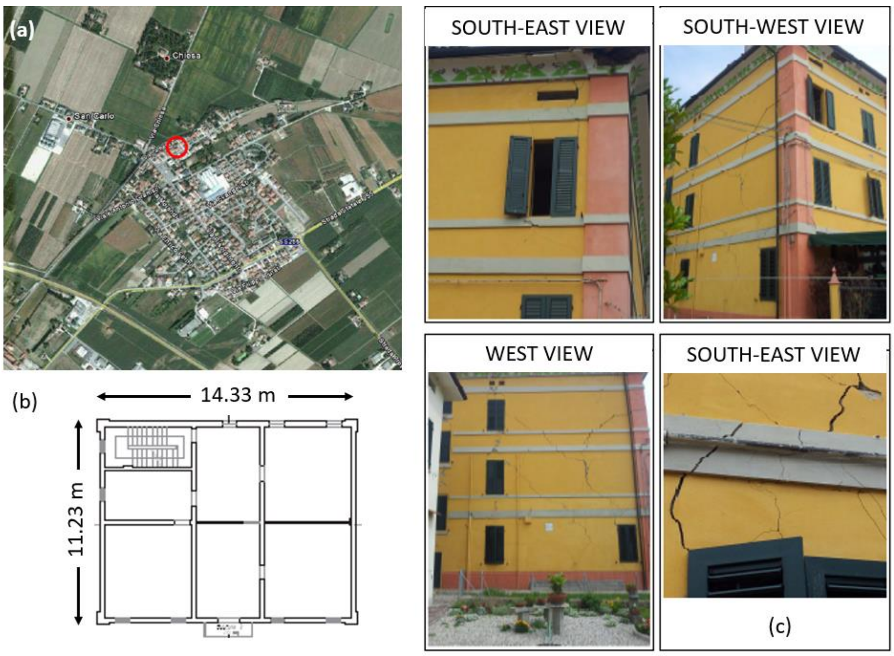

Figure 4. Location of the site (a), plan view of the selected shallow-founded building (b) and observed damage pattern (c).

The volumetric-induced component is due to sedimentation and post-liquefaction reconsolidation mechanism and it can also produce significant building settlement. Finally, sediment ejecta mechanism physically transports soil that was supporting the foundation to the ground surface and it is often the dominant factor when a significant amount occurs (Macedo & Bray, 2018).

The first and the last component of ground deformation were evaluated according to the simplified procedure proposed by Bray & Macedo (2017), while the volumetric-induced component was computed straightforward from the seismically induced pore water pressure build-up.

4.1 *Estimation of the volumetric-induced settlement*

The volumetric component was computed by the dissipation of the excess pore water pressure predicted by means of a 1D dynamic analysis in effective stress (Chiaradonna et al. 2018a).
The analysis was performed in free-field (i.e. neglecting the presence of the building at the surface) and in effective stress, taking into account the generation of excess pore water pressure induced by seismic actions, through the 1D computer code SCOSSA (Chiaradonna et al. 2016; 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. 2018b). 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 or in-situ test data.
The soil model is based on the results of SCPTUs until 30 m depth and on the geological knowledge of the area. An alternation of liquefiable (sandy and silty soils with $I_c<2.6$) and non-liquefiable (clayey soils with $I_c>2.6$) soils can be identified in the soil column reported in Figures 5a,b. The shear wave velocity profile was defined from the interpretation of the results of the SCPTU, shown in Figure 5c. The water table was located around 4.6 meter depth.
The non-linear soil properties were modelled assuming shear modulus reduction and damping curves of the soil deposits at Scortichino (Chiaradonna et al. 2018c) for the non-liquefiable deposit and at Pieve di Cento (Flora et al. 2019) for the liquefiable layer, where resonant column tests were performed (Fig. 5d). Both sites have the same geological background of San Carlo and are relatively close to the considered reference site (about 20 km far from Scortichino and 4 km far from Pieve di Cento). The selection was based on similarities on the grain size distribution of the considered soils. The parameters of the pore water pressure model were also assigned to the silt and sand layers (Fig. 5e,f), using the calibration procedure based on cone tip resistance, as described in Chiaradonna et al. (2017).

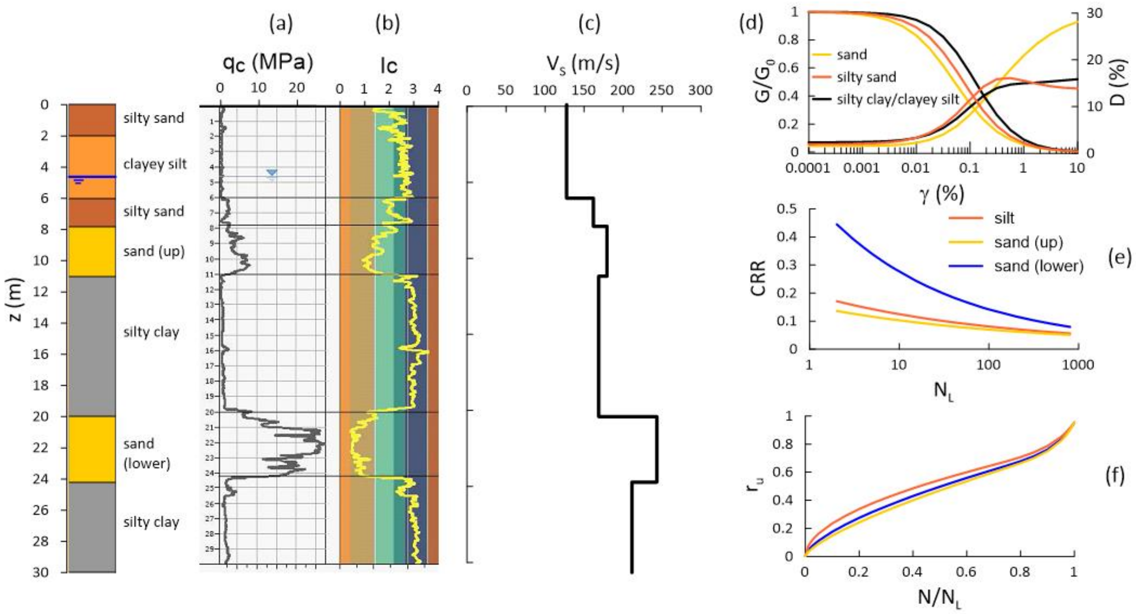

Figure 5. Vertical profile of cone tip resistance (a), soil behaviour type (b), shear wave velocity profile (c), shear modulus reduction and damping ratio curves (d), cyclic resistance (e) and excess pore water pressure ratio curves adopted in the model.

Since the seismic bedrock is very deep in San Carlo, the dynamic analysis was carried out applying at the base of the considered soil column the accelerogram of the convoluted record at 30 m depth of the mainshock of 20 may 2012 Emilia earthquake (Chiaradonna et al. 2018c).

The results of effective stress analyses are shown in Figure 6 in terms of vertical profiles of the peak values of acceleration, shear strain and excess pore pressure ratio. The results of the analysis show the attainment of the liquefaction condition between 8 and 11 m depth, in conjunction with high shear strain at the same depth and significant reduction of the acceleration transmitted at the surface.

At the end of the consolidation process, the generated excess pore pressure induced a post-seismic consolidation settlement equal to 3.4 cm, estimated with the simplified procedure based on CPT proposed by Chiaradonna et al. (2018a).

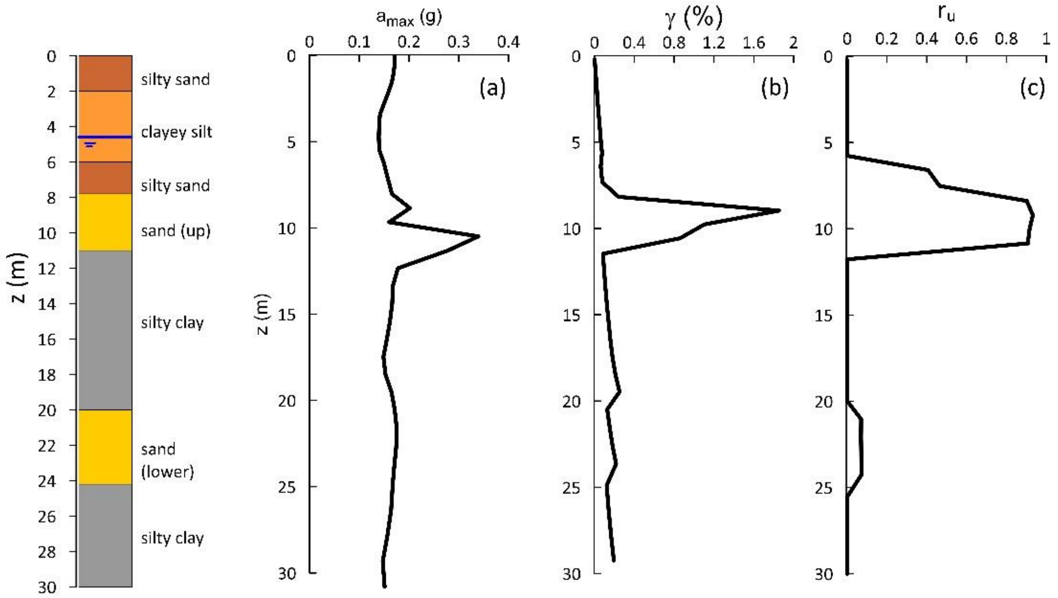

Figure 6. Results of the 1D dynamic analysis in terms of vertical profiles of maximum (a) acceleration, (b) shear strain and (d) pore pressure ratio.

4.2 *Estimation of the shear-induced and sand ejecta-induced settlements*

As reported in Bray and Macedo (2017), the shear-induced settlement occurred during the strong shaking as a result of SSI-induced ratcheting and bearing capacity-type movements. The shear-induced component was estimated applying the simplified procedure proposed by Bray and Macedo (2017) and it leads to an average value of 2 mm.

The ejecta-induced settlement was estimated equal to zero, since no significant amount of sand was observed around the building. Finally, the overall settlement is approximately estimated around 4 cm, which is compatible with the damage pattern observed on the structure.

5 CONCLUSIONS

The interpretation and analysis of a database of masonry buildings located in a number of municipalities struck by the 2012 Emilia earthquake is presented in this paper. Post seismic survey included information on building characteristics, level and extent of damage to structural and non-structural components. The analysis of the observed damage showed peculiarities of liquefaction-induced damage on structures.

Soil liquefaction led to the formation of unusual crack patterns compared to the typical inertial damage. The correlation between structural damage and soil liquefaction has been investigated with reference to an exemplificative case of study in the hamlet of San Carlo, where only liquefaction-induced damage was observed. The liquefaction-induced building settlement has been predicted as the sum of three different components: shear-induced, volumetric-induced, ejecta-induced ground deformations. Differently from the approach proposed by Bray and Macedo

(2017), the volumetric component was directly computed by the dissipation of the excess pore water pressure as predicted by a 1D dynamic analysis in effective stress. The computed total settlement is compatible with the damage observed at the site.

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