SOIL STRUCTURE INTERACTION EFFECTS OF A BENCHMARK BUILDING ON A POTENTIAL-LIQUEFIABLE SOIL

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Abstract

The assessment of soil liquefaction has become a relevant issue in earthquake engineering especially after historical events when induced damage, disruption of function and considerable replacement expenses for structures were observed. 3-D numerical simulations were herein performed in order to model the effects of liquefaction on a benchmark structure founded on shallow foundations. The soil is performed with non-linear hysteretic materials, advanced plasticity models and appropriate flow rules to reproduce the observed strong dilation tendency and resulting increase in cyclic shear stiffness and strength. OpenSeesPL was applied to investigate the complex non-linear analyses of soil-structure interaction with liquefaction and thus to assess the three-dimensional structural performance (in term of drifts and floor displacements).

Keywords: Shallow foundation; Numerical simulations; OpenSees; Liquefaction; Non-linearity

1. Background

Dramatic consequences of liquefaction have been proved during historical earthquakes, such as Niigata (Japan, 1964), Dagupan City (Philippines, 1990), Chi-Chi (Taiwan, 1999), Tohoku (Japan, 2011), Kocaeli (Turkey, 1999) and Christchurch (New Zealand, 2011). In particular, the most dangerous effects connected to such phenomenon have resulted mainly in correspondence with structural configurations on shallow foundations. The main effects consist of structural settlements, lateral spreading or even bearing capacity reduction with consequences such as damage, disruption of function and considerable replacement expenses. In literature there are many contributions ([1], [8], [23], [29] and [35]) that develop countermeasures and mitigation strategies. In this regard, numerical simulations are of fundamental importance in order to reproduce realistically the complex mechanism of Soil Structure Interaction (SSI).

On the one hand, the seismic response of shallow-founded structures depends on the stress field around the foundation [12] and was historically modelled with a wide range of accepted procedures, such as [22], [39] and [40]. These contributions estimated the liquefaction-induced settlements with empirical procedures based on one-dimensional (1D) free-field conditions neglecting the effects of the presence of the structure, [27]. Even if these approaches can be extremely detailed, they may underestimate the shear-induced soil deformations in the soil beneath shallow foundations. The principal limit of these 1D empirical procedures is that they can only capture the settlements as results of the cumulative effect of volumetric strains. Nevertheless, liquefaction-induced displacement mechanisms result from soil-structure interaction (SSI) effects. Recent studies ([4] and [5]) demonstrated that the seismically induced deformations are controlled by volumetric deformations resulting from partial drainage. Soil liquefaction-induced settlements cannot be fully estimated using the historical simplified 1D-procedures, since these methods cannot capture the shear mechanisms involved in building settlements. In addition, [19] demonstrated that 1D site response analyses are used to capture free-field soil behaviour but they generally underestimate settlements due to a simplified assessment of soil volumetric compressibility.

On the other hand, two-dimensional (2D) numerical simulations are generally advantageous since they simplify the problem to plain strain conditions. However, these assumptions may undervalue excess pore pressures and thus the building settlements, leading to conservative estimations of the detrimental liquefaction-induced effects in the soil and the consequent damage to structural components. In this regard, [27] performed comparative analyses between various approaches to compare the accuracy in terms of soil response (e.g. time history of settlement and horizontal acceleration). In addition, the assessment of induced building settlements due to liquefaction modelled with 2D numerical simulations was reproduced by [2], who specified the need of further research and detailed assessment of 3D numerical modelling of liquefaction effects.

In this background, still many researchers investigated liquefaction without considering the effects on the structure, for example [9], [14], [20], [30], [31], [32], [34], [36], [37] and [38]. Although there are such contributions, the complex mechanism of liquefaction may be fully described only by considering fundamental outcomes that predict the structural behaviour to liquefaction-induced effects, such as building period elongation, settlements, drifts and tilts. This is possible with three-dimensional (3D) fully coupled non-linear numerical models that perform SSI as shown by few contributions ([6], [7], [17], [18], [24], [25] and [33]). This exiguity may be due to the difficulty to model liquefaction non-linear effects [3], that demands robust numerical modelling approaches.

In this paper, the analyses are performed with OpenSeesPL [26] from the Pacific Earthquake Engineering Research (PEER) Center that can simulate realistic modelling of structures and soils, assess challenging non-linear SSI problems and take advantage of the latest developments in databases, models and computing [19]. The present paper presents several elements of novelty. The 3D model overcomes the previous studies by considering the transmission of soil deformations along the height of the building, by modelling the structure in detail and by assessing the 3-D behaviour of both the soil and the structure. The models may realistically assess the volumetric deformations of the soil in a spatial domain with particular attention to the rotations (and the consequent overturning moments) along the principal axes of the structure (longitudinal, transversal and vertical) and torsional effects, responsible for the rocking components and reductions of the bearing capacity. When the foundation settles inside the soil, it is fundamental to accurately assess which part of the soil below the foundation liquefies losing its bearing capacity. Therefore, a detailed description of such 3D variability of the shear capacity of the foundation is fundamental to assess the stability of the entire system (soil + structure) and ultimately to consider the structural effects of the liquefaction-induced mechanisms. The principal idea herein is to perform a benchmark building on a homogenous layer of a potential-liquefiable soil to assess liquefaction damages.

2. Benchmark structure and foundation

The following sections (2 and 3) describe the 3D finite element model that was implemented by performing OpenSees PL [26]. In particular, the structural response to liquefaction depends on multiple parameters, such as the contact pressure that the structure applies on the foundations, as shown in [19]. Fig. 1 and 2 show the considered benchmark structure, based on a rigid shallow foundation. A 20m-thick and uniform soil layer was performed and the development of pore pressure along its depth was calculated and discussed. The soil fundamental period can be estimated with the linear formulation [21] to be around 0.55 s. The structure was chosen to be stiffer than the soil, with the fundamental period in the typical range of residential buildings (floor height: 3.40 m, total heights: 6.80 m, with H/B values of: 0.92). The structural schemes consist of 4x3 columns (4 in longitudinal direction (8 m spaced) and 6 in the transversal direction (10 m spaced)) with a shear-type behavior and plan and vertical regularity. The dynamic characteristics are obtained by applying the seismic masses at each floor. The vibrational periods and correspondent mass participation ratios (in brackets) are shown in Tab. 1. The structure was assumed to be linear elastic and modelled with elastic-beam column elements (Tab. 2).

The shallow foundation (thickness: 0.5 m) was considered rigid by linking all the nodes at the base of the columns together and to the soil domain (by applying equaldof, [28]). Horizontal rigid beam-column links were set normal to the column longitudinal axis in order to simulate the interface between the column and the foundations. Pressure Independent Multiyield ([26] and [28]) was used to model the foundation, by simulating an equivalent concrete material (Tab. 3). Tab. 3 shows the parameters adopted for the surrounding infill layer soil (named soil W), modelled with Pressure Independent Multiyield material.

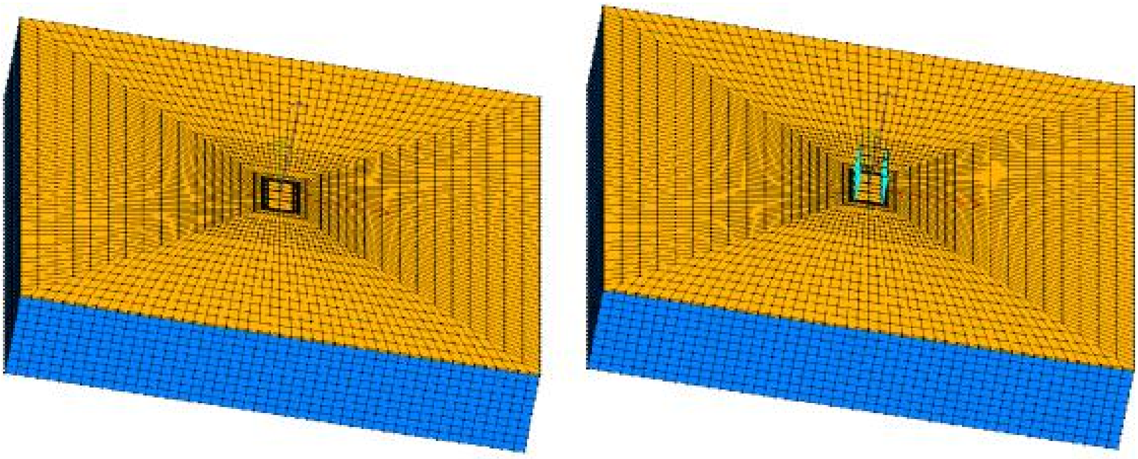


Fig 1 – 3D meshes

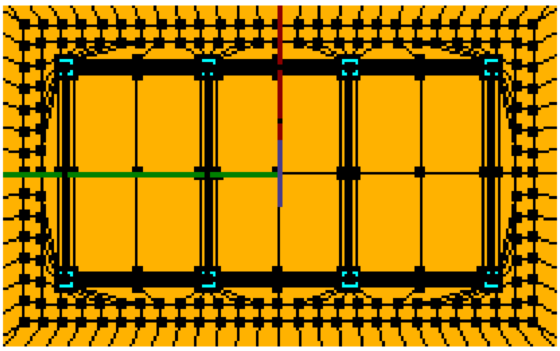


Fig 2 – Plan of foundation

Table 1 – Structural characteristics

Structural characteristics	
n floor	2
H [m]	6.80
H/B	0.92
Bearing Pressure [kPa]	135
T1x [s]	0.341 (91.77%)
T1y [s]	0.331 (86.67%)

Table 2 – Structural material parameters

Parameter	Value
Young Modulus (kN/m^2)	$3.5 \cdot 10^7$
Shear modulus (kN/m^2)	$1.73 \cdot 10^7$
Column cross section Area (m^2)	0.12
Column inertial moment (m^4)	$9 \cdot 10^{-4}$

Table 3 – Material parameters

	Foundation	Soil W
Mass density (kN/m^3)	24	17
Reference Shear modul (kPa)	$1.25 \cdot 10^7$	$5.50 \cdot 10^4$
Reference Bulk modul (kPa)	$1.67 \cdot 10^7$	$1.50 \cdot 10^5$

3. Soil 3D mesh

The 3D model of the soil consists of a 118.4 x 124.4 m (20 m thick) mesh (Fig. 1 and Fig. 2) with 31860 nodes and 35868 non-linear Bbar brick elements [23], calibrated with a convergence study. Tab. 4 shows the details regarding the increasing number of nodes and elements for the applied mesh. The definition of mesh dimensions followed the approach already adopted in [10], [11] and [12] and based on literature indications by [3], [16] and [19]. The dimension of the elements was increased from the structure to the lateral boundaries that were modelled to behave in pure shear and located far away from the structure. The PressureDependMultiyield02 [26] material has been adopted and the parameters (Tab. 5) have been taken from the calibration study by [41]. In order to assess that the mesh simulates free-field conditions in correspondence with lateral boundaries, accelerations at the surface (0.00 m depth) were compared with those calculated in correspondence with Free Field conditions and they were found to be identical, confirming the effective performance of the mesh. The base boundaries (20 m depth) were considered rigid and the water level was at the surface (0 m depth).

Numerical simulations of highly non-linear liquefaction analyses require robust and reliable tools because of difficult convergence that was herein solved by dividing the analyses into four sub-steps, as in [12]. The first step of the analyses was to assess pore pressure generation to reproduce liquefaction outcomes. Such findings were verified in order to demonstrate that the 3D model can perform proper behaviors (see section 4). The second step consisted of performing highly non-linear dynamic analyses. The input motion was selected from the Italian Accelerometric Archive [15] and it consists of the east-west (E-W) acceleration (epicentral distance: 9.3 km), during the 1979 Val Nerina (Italy) earthquake (Fig. 3). This input is defined on a presumed rigid bedrock (classified with soil A* by the Italian code) and was applied at the base of the model along the longitudinal direction (x-axis).

Table 4 – Convergence study: meshes

	Number of nodes	Number of elements
Mesh 1	8096	9228
Mesh 2	31860	35868
Mesh 3	52452	56898

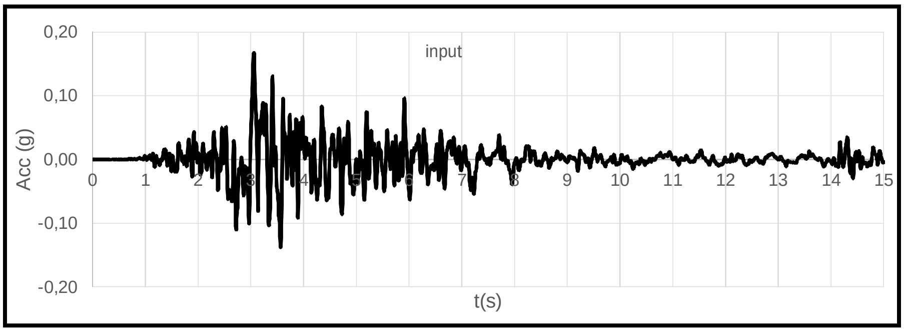
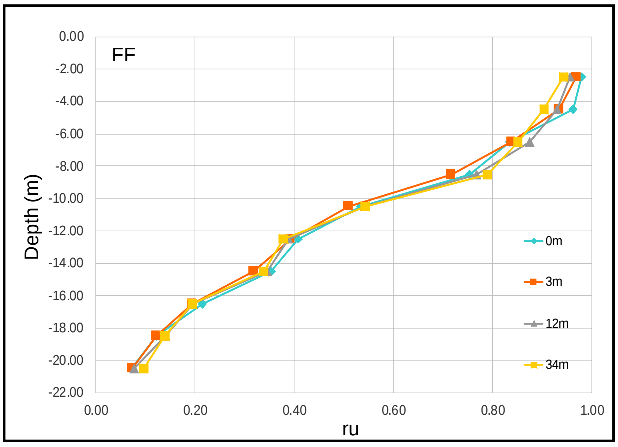


Fig 3 – Input motion: Cassia east-west (E-W) component

4. Pore pressure analyses

The first step of the analyses consisted of computing the pore pressure ratio (ru) value as the ratio between the total pore pressure and the total overburden pressure. Different verticals (Fig. 4) at various depths for the system (S) and for free-field (FF) conditions were considered: point O (at the mesh center), A (3m distance), B (12 m distance) and C (34 m distance). Fig. 5 shows the effects of the location on ru values and how the presence of the structure affects the vertical stresses below the foundation. In correspondence with FF conditions, ru values have similar trends for all the considered positions. This means that the FF conditions are respected along the models and that the mesh performed properly. When the structure is considered, its presence affects the vertical pressures in the superficial layers and the corresponding ru values reduce. It is worth noticing that when points are sufficiently distant from the center (for example point C, 34 m), ru values are not influenced by the structure and FF conditions are respected.

Fig 4 – Locations (plan view)



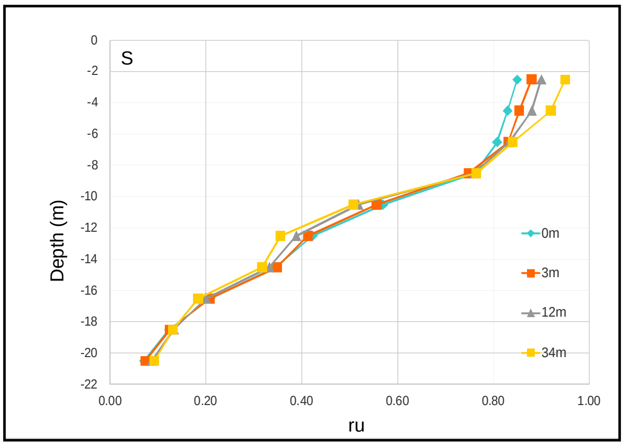


Fig 5 – Effects of the locations on ru-values

Table 5 – Soil material parameters

Parameter	Value
Mass density (kN/m^3)	19.58
Reference Shear modul (kPa)	4.17·105
Reference Bulk modul (kPa)	5.55·105
Shear Wave velocity (m/s)	145
Friction Angle (°)	30
Permeability (m/s)	10-8
Peak angle (°)	23
c1	0.07
d1	0.4
d2	2
l1	10
l2	0.01
l3	1

5. SSI results

This paragraph discusses liquefaction effects on the structural performance, particularly due to the deviatoric deformations that are the principal responsible of the settlements and the rotations of the building. The performed 3D FEM model was fundamental to assess realistic responses of the complex system soil-foundation-structure. Significant parameters are here described, such as displacements at various floors and total inter-story drifts. Firstly, effects of soil deformability were studied to account the known phenomenon of period elongation [21]. In this regard, transfer functions (TF) under fixed base conditions were computed and compared with the structural peak values (Fig. 6) to demonstrate that the fixed base model performed properly. Secondly, period elongation due to the interaction between the soil and the structures was also considered (Fig. 6), showing amplifications due to soil deformability. Such phenomenon is driven by the mutual characteristics of the structures and the input motion, as previously discussed in [11] and [19].

Fig. 7 shows the differential foundation settlement (tilt) normalized by the width (along the longitudinal direction: 7.4 m). It is worth to notice that there is a significant concentration of tilt (almost 1.50%) at around 3-4 s (peak of the input motion). The presence of tilts below the foundation is responsible of the transmission of significant overturning moments to the structure, affecting the structural performance in terms of story displacements and inter story drifts. Overturning moment and the settlement versus rotation in correspondence with the foundations were calculated and shown in Fig. 8. Applying the proposed 3D non-linear model allowed to include the effects of structural non-linearities, such as P-delta. The values of the settlements and the rotations of the foundations are driven by liquefaction phenomenon that can potentially induce damage in the building. In order to investigate the structural performance, longitudinal drifts (due to foundation rocking, consequent rotations and to the column flexural distortion [19]) were calculated as the ratio between the relative longitudinal displacement and the height of the floor from the foundation level. Thanks to the detailed structural model, it was possible to calculate the response in correspondence with the floors and the maximum value of the top level drifts was -1.404 %. Fig. 10 shows the envelope of the maximum displacements calculated for each floor (Tab. 6).

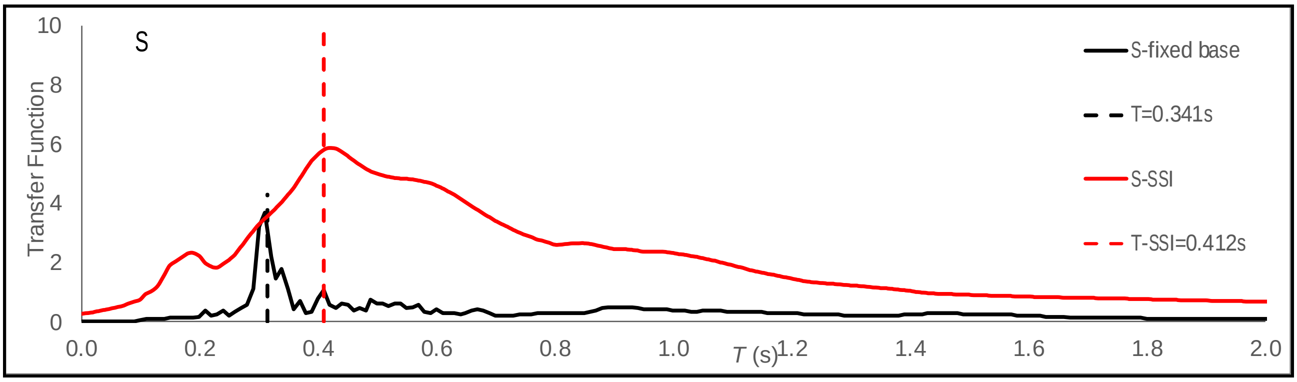


Fig 6 – Transfer functions (period elongation)

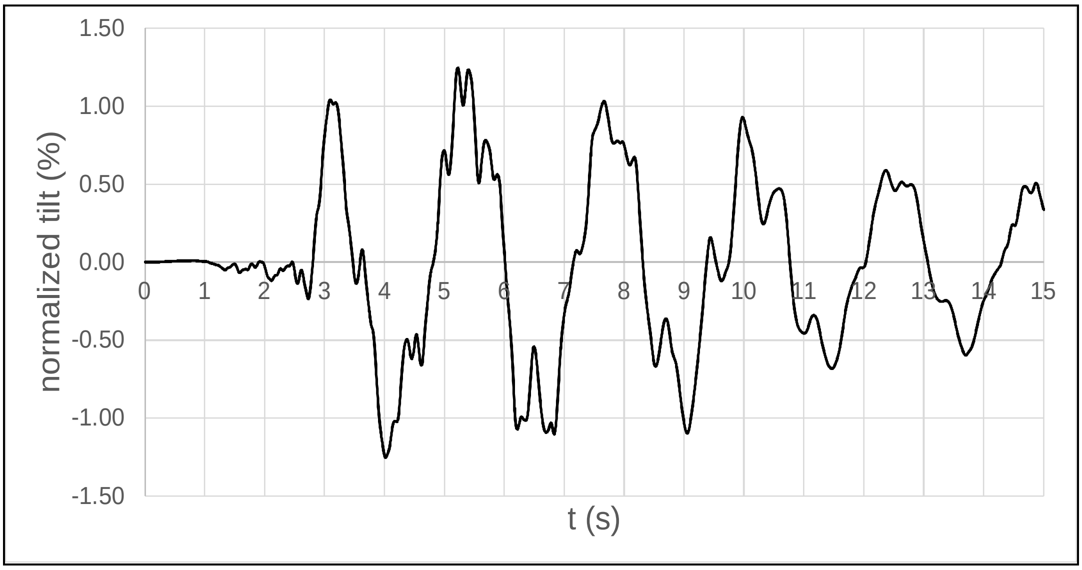


Fig 7 – Normalized tilt time histories

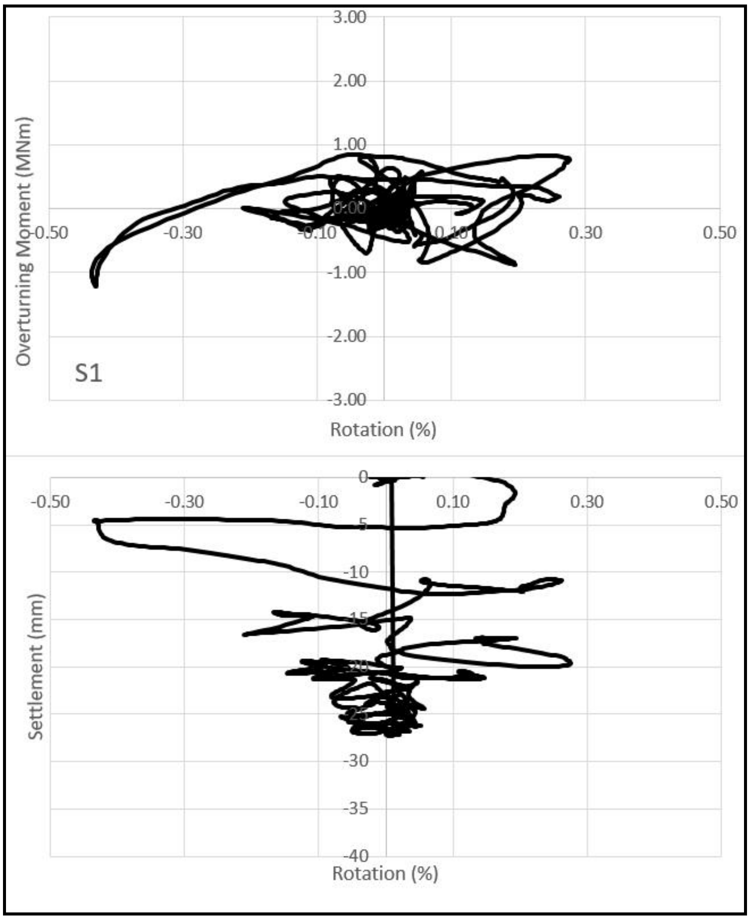


Fig 8 – Rotation Vs Settlement; Rotation Vs Overturning Moment

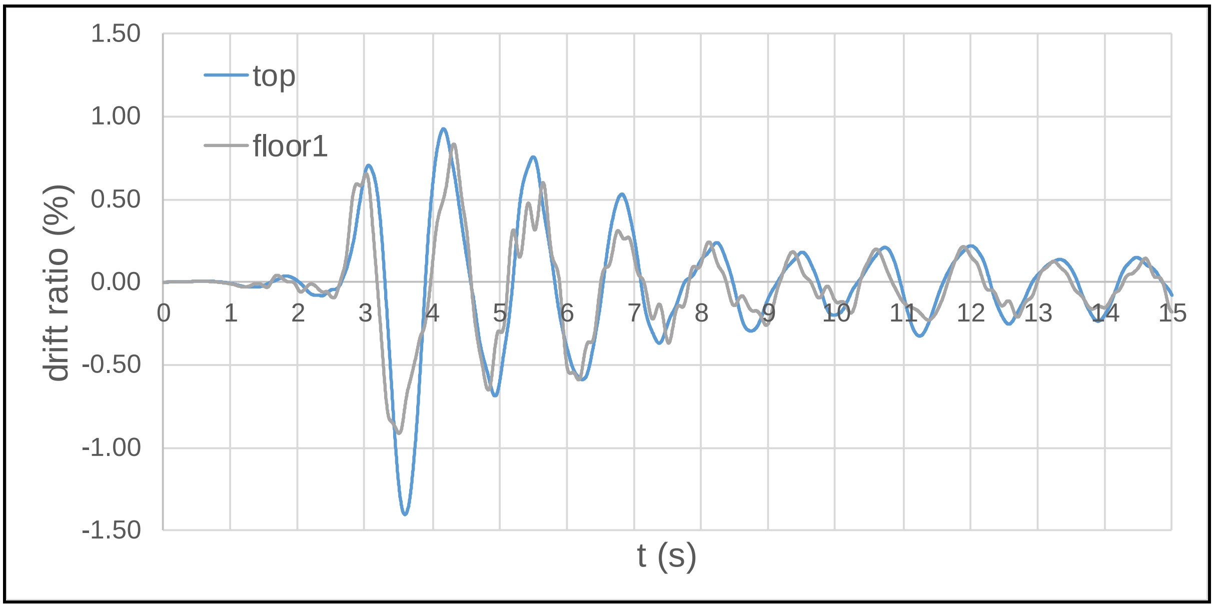


Fig 9 – Longitudinal drift time histories at various floors

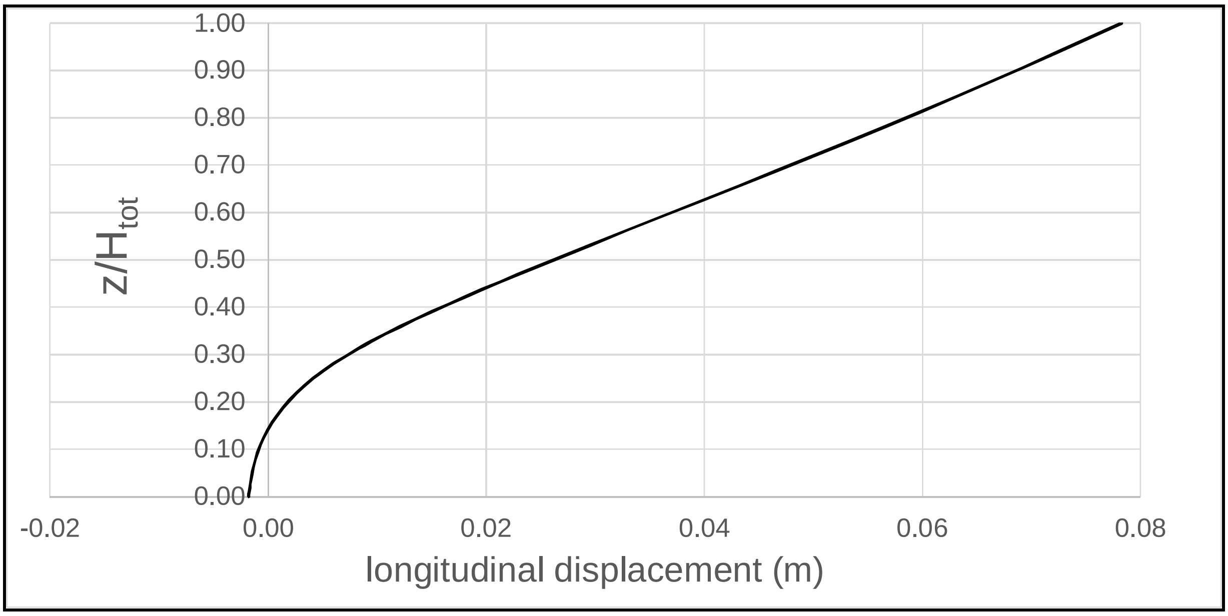


Fig 10 – Maximum Longitudinal displacement (Envelope) along the structures (relative height).

	Long. Disp. (cm)
top	9.55
floor 1	2.54
base	1.54

Tab. 6 – Maximum Longitudinal Displacements

5. Conclusions

The paper investigates liquefaction effects by analyzing a 3D soil-structure model built up with OpenSeesPL. The principal novelty consists of representing both the soil and the structure in details, overcoming the previous contributions that analyzed only the soil (free-field cases) or equivalent structures (single degree of freedom). Liquefaction effects, due to the partial drainage of the soil and to the consequent volumetric strains that occur under the foundation were herein calculated in correspondence with the soil, with the foundation and along the structure. Such response affected the non-linear behavior of the entire system and the structural performance, expressed herein in terms of displacements and drifts. Overall, the paper states the need to account SSI in order to assess the soil and the structural mutual behavior under liquefaction. It is worth to notice that the presented findings are limited to the soil, structures and loading conditions that were herein performed. It is anticipated that numerical simulations of the response of shallow-founded structures on different potential-liquefiable soil deposits and subjected to other input motions will be object of future study.

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