SOIL STRUCTURE INTERACTION ASSESSMENT WITH ADVANCED NUMERICAL SIMULATIONS

D. Forcellini[1], S. Gobbi[1]

1 University of San Marino
Via Salita alla Rocca, 44, 47890, San Marino
davforc@omniway.sm

Abstract. *Soil structure interaction (SSI) plays a significant role during seismic excitations for structures. Therefore many researchers have assessed its importance in emphasizing earthquake response both in buildings and bridge arena. The present study aims at considering a 3D numerical simulation of a soil-structure system that applies nonlinear hysteretic materials with advanced plasticity models. This approach enables to reproduce soil hysteretic elasto-plastic shear response (including permanent deformations) and thus damping foundation impedances. In particular, the paper applies the open-source computational interface OpenSeesPL, implemented within the FE code OpenSees. This framework is capable of performing non linear dynamic analysis and apply user-defined materials to model the soil. It is also powerful in modeling the interface and boundary conditions that are of extreme importance in SSI problems. The aim is to reproduce the seismic response by a parametric study based on mutual behavior of soil and structural deformability in order to assess safety and cost reduction when SSI is considered in design procedures. Therefore, this study can be considered one of the relatively few attempts to assess seismic performances aiming at contributing to new easy-to-use design procedures for engineers all over the world.*

1   BACKGROUND

Soil structure interaction (SSI) takes into account the effects of the ground on the seismic response of a structural system. In particular, free field response can consistently under evaluate effects due to soil structure dynamic interaction. Even if many codes suggest to neglect SSI (for example [1] and [2]) there are some researches where SSI is shown to be non-conservative for safety and cost reduction. In such cases, it is fundamental to take into account SSI in design procedures in order to predict its effects as detailed as possible [3-14].

Unfortunately modelling SSI is a changeling problem for numerical simulations and a few contributions [15-17] have provided insights. Many of them apply SSI simply by introducing springs, dashpots and artificial masses in the interface between the structure and the soil. This could be non-sufficiently detailed in order to model the problem complexity. In this regards, free field response can differ consistently from the soil – structure response because it is straightly connected with the mutual dynamic characteristics (natural frequencies) and thus with structural mass and stiffness, soil shear velocity and layer depth [4]. In particular [5] shows that SSI depends on several dimensionless parameters, such stiffness ratio, slenderness ratio and mass ratio.

Taking into account these relevant contributions, the present study aims overcoming all previous simplifications considering a 3D soil-structure system that applies nonlinear hysteretic materials with plasticity models. This approach enables to reproduce soil hysteretic elasto-plastic shear response (including permanent deformations), damping foundation impedances and realistic boundary conditions at the base of the soils and in correspondence with the interface between the soil and the structure. In particular, the paper applies the open-source computational interface OpenSeesPL, implemented within the FE code OpenSees.

The proposed numerical simulations aim at reproducing the literature background in order to calibrate the model and thus study more detailed insight into soil structure interaction problems in order to obtain numeric results able to provide design and management decision making assessment.

2   COMPUTATIONAL PLATFORM

Numerical simulations proposed in this study aim at reproducing the seismic response of a system structure and soil using the open-source computational interface OpenSeesPL, implemented within the FE code OpenSees [18]. It consists of a framework for saturated soil response as a two-phase material following the *u-p* (where *u* is displacement of the soil skeleton and *p* is pore pressure) formulation.

In the study, the mechanical behavior of the soil has been modeled as a nonlinear hysteretic material, using a Von Mises multi-surface kinematic plasticity approach together with an associate flow rule. This constitutive formulation is able to capture both monotonic and hysteretic elasto-plastic cyclic response of those soils whose shear behavior is assumed insensitive to confining stress. According to this formulation, plasticity is exhibited only in the deviatoric stress-strain response, while volumetric response is linear-elastic. In particular, the study has been divided in two increasing detailed steps.

The first step consists of reproducing one degree of freedom (dof) structural systems with increasing fundamental periods. In particular, two parametric studies have been performed. The height of the structure has been changed in order to consider different number of floor composing the structure. Then, the importance of mass ratio has been investigated. Therefore, representative soil mass (and thus the foundation volume) has been varied and several anal-

yses have been performed considering the same structural configuration. The aim of this first step is to calibrate OpenSees materials and potentialities in reproducing literature results.

The second step consist of considering structural performance when SSI effects are applied. In particular, several structural configurations have been considered in order to assess the influence of stiffness ratio on equivalent system. Displacement have been taken into account as the main parameters in order to assess the system performance. The following sections detail the two steps.

3   CALIBRATION

The first step consists of performing a 3D mesh (Figure 1) aimed at performing tridimensional soil structure interaction analyses, by applying OpenSees PL [19]. Originally the interface has been calibrated for pile analysis. Here it has been modified in order to consider the presence of the system structure – foundation. The study considers two typical concrete shear type structures that can be studied as one single degree of freedom (DOF) models following procedure [20]. In particular dynamic characteristics structural mass (m), stiffness (k) and natural frequency (ω_0) have been calculated and shown in Table 1. The foundation has been considered as a swallow foundation (0.50 m depth) with a rigid element.

The soil has been considered one-layer homogenous cohesive material with a 30 m depth (see table 2). The adopted 3D (20m × 20m x 30m) FE mesh is composed of 2496 brickUP linear isoparametric 8 node elements with 2873 nodes (Figure 1). The model base boundary is set at a depth of 30 m from ground surface. Pore pressure generation effects have been neglected. Opensees is able to simulate real wave propagation adopting realistic boundaries, by assuming that at any special location, symmetry conditions can be adopted and thus, periodic boundaries [21] have been considered. Displacement degrees of freedom of the left and right boundary nodes were tied together both longitudinally and vertically using the penalty method. In this regards, base and lateral boundaries were modelled to be impervious, as to represent a small section of a presumably infinite (or at least very large) soil domain by allowing the seismic energy to be removed from the site itself. For more details, see previous studies [22-25]. Connections between the structure and the soil are built up with Equaldof elements that imposes the displacements to be the same between the structure and the soil nodes [18, 19]. The clay layer has been modelled with the implemented material named Pressure independent Multiyield [19]. It consists of a nonlinear hysteretic material, using a Von Mises multi-surface kinematic plasticity approach together with an associate flow rule. Its constitutive formulation is able to capture both monotonic and hysteretic elasto-plastic cyclic response of those soils whose shear behavior is assumed insensitive to confining stress. According to this formulation, plasticity is exhibited only in the deviatoric stress-strain response, while the volumetric response is linear-elastic. The study has been divided into several steps.

First of all, SSI has been neglected by considering shear velocity values up to 3000 m/s, in order to simulate fixed based conditions and reproducing the fundamental structural periods. In this regards, a eigenvalue analysis has been performed and the fundamental frequencies (3 Hz and 6 Hz) have been confirmed.

Then, soil stiffness has been varied in order to take into account SSI effects. In particular shear wave velocity (Vs) has been varied in order to simulate different soil conditions. Table 2 shows soil characteristics in correspondence of Vs=250 m/s. Following the literature [5, 6], soil-foundation-structure equivalent system dynamic characteristics have been calculated in terms of equivalent system mass (m_e), stiffness (k_e) and natural frequency (ω_e). Figure 2

shows the 3D mesh deformation for Vs equal to 250 m/s and in correspondence with the equivalent system fundamental period.

Therefore, mass ratio value ($\bar{m}$), defined as the ratio between the relative structural mass and the soil mass, has been considered constant and equal to 0.5 for the two structural configurations. Results in terms of stiffness ratio ($\bar{s}$) and ratio of natural frequencies (between the equivalent system and the structure) are represented in Figure 3. Results for both structures show a good agreement with the theoretical approach [5], confirming Opensees potentialities and model assumptions in performing soil structure interaction 3D numerical problems. In particular, results in correspondence with stiff structure (f_0= 6Hz) is shown to be more consistent with the theory (figure 3).

Finally, in order to evaluate the importance of mass ratio, a parametric study has been performed by considering several values ($\bar{m}$=0.5, $\bar{m}$=1.0, $\bar{m}$=3.0). All analyses have been performed considering the stiffest structural configuration (f_0=6 Hz). Figure 4 shows the effects of increasing $\bar{m}$ values (and thus increasing the structural mass in comparison with the soil volume) on the relationship between dynamics characteristics and structural ratio. These results are still consistent with the theory [5].

Structural Parameters	f=6 Hz	f=3 Hz
m [t]	400	400
k [N/m]	$5.60 \cdot 10^8$	$1.40 \cdot 10^8$
h [m]	3.00	4.75
ω_0 [rad/s]	37.40	18.85
T_0 [s]	0.168	0.330

Table 1. structural parameters.

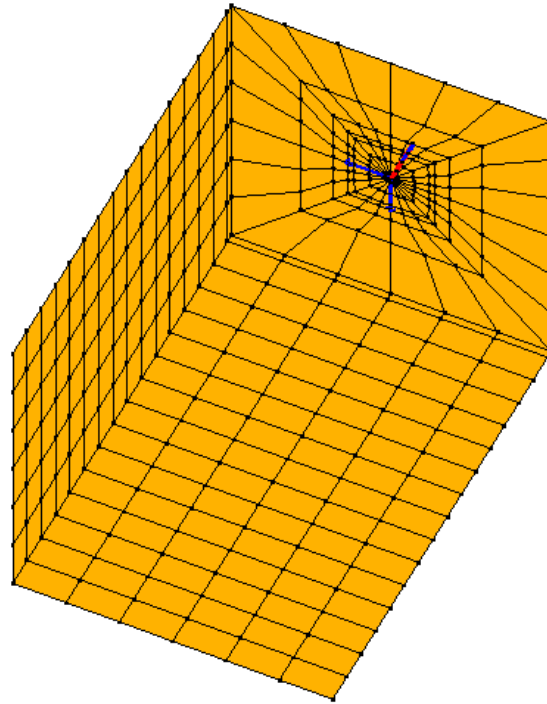| density [t/m^3]	G [kPa]	B [kPa]	ν	C [kPa]	Peak shear strain
1.80	$1.125 \cdot 10^5$	$5.25 \cdot 10^5$	0.4	75.0	3%

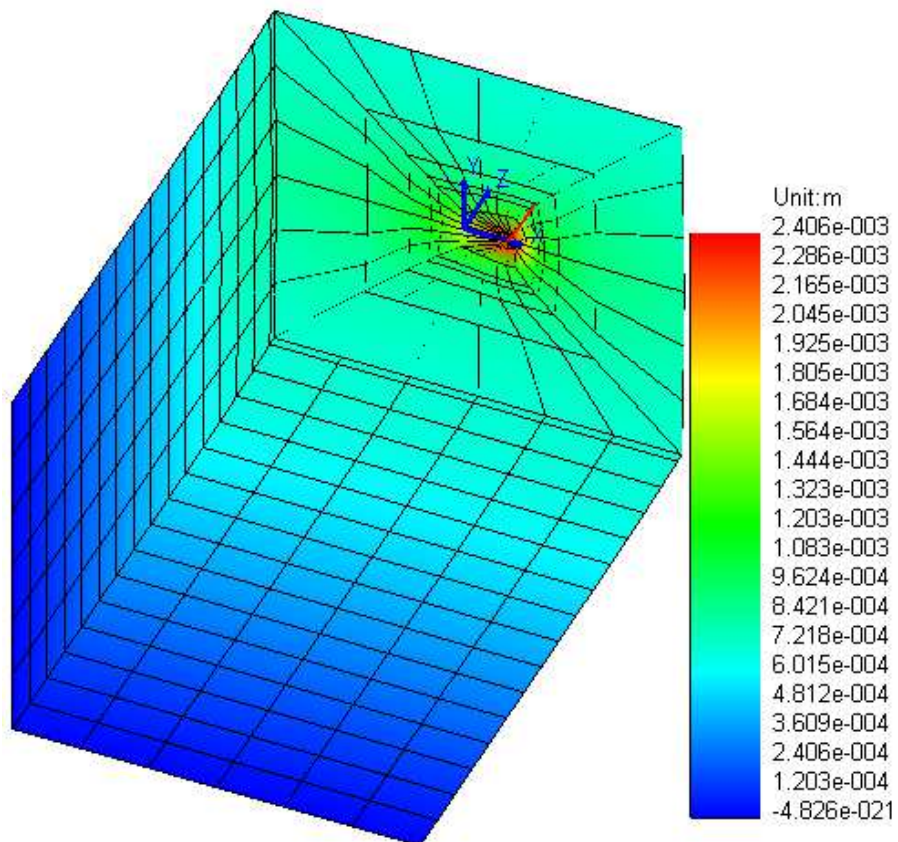Table 2. soil parameters [VS=250 m/s].

Figure 1. 3D mesh

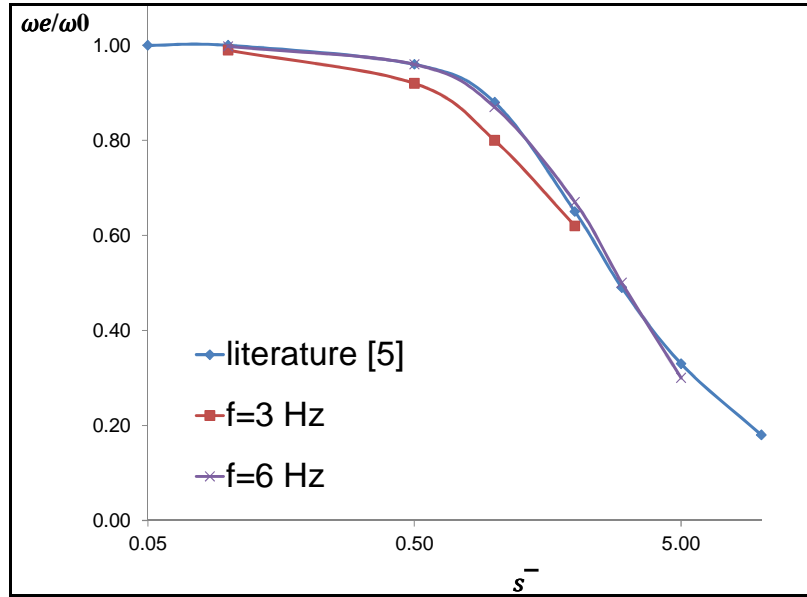Figure 2. 3D deformed mesh for Vs=250 m/s (scale 1: 1000).

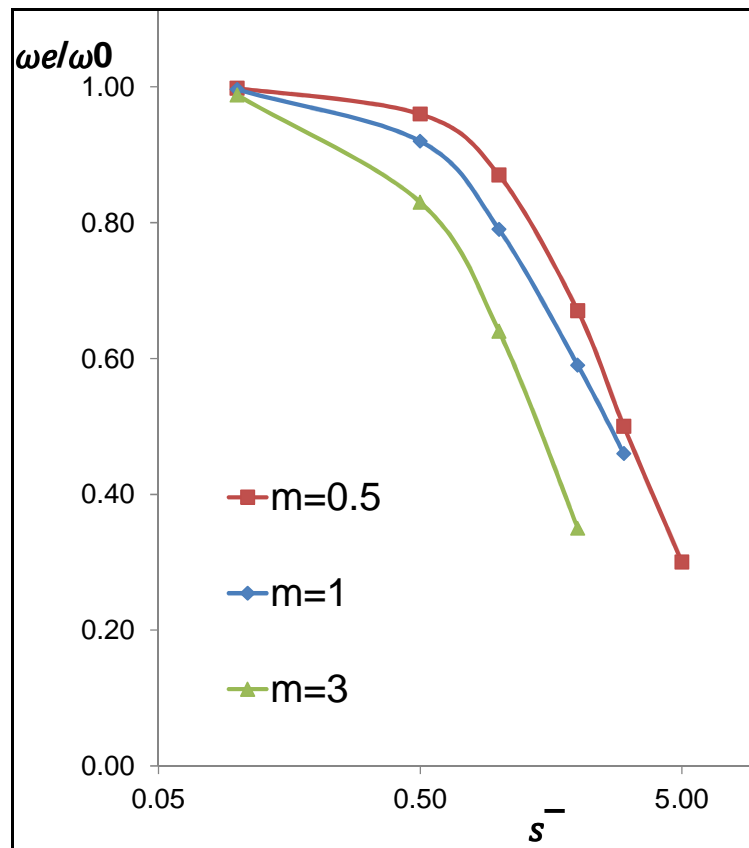Figure 3. $\overline{m}$=0.5 results. Literature [5] and numerical results.

Figure 4. $\overline{m}$=0.5; $\overline{m}$=1; $\overline{m}$=3 numerical results.

4   SSI ASSESSMENT

This section aims at investigating soil structure dynamic interaction significant role during seismic excitations. The study aims at assessing equivalent system seismic performance by referring to displacements. In particular, traditional approaches are based on introduction of linear (translational and rotational) springs and dashpot as to reproduce the stiffness and damping characteristics of the compliant soil-foundation system [5, 6]. On the contrary, the presented approach considers a 3D soil-structure system that applies nonlinear hysteretic materials with advanced plasticity models, without separating the different contributions with artificial elements. In particular, sinusoidal excitations were defined along the base in the longitudinal direction (*x*-axis), with 0.2 g of amplitude and 1 Hz frequency, considering three structural configurations (f_0=3 Hz, f_0=6 Hz and f_0=10 Hz). All the analyses here have been performed considering the same mass ratio ($\overline{m}$=3).

Displacements have been considering at different height of the equivalent system, as shown in Figure 5 that clarifies all the components:

- U_{FF}: free field displacement, calculated without the structure.
- U_s: soil displacement evaluated at the top of the soil layer and caused by the presence of the structure.
- U_{ST}: structural displacement (the sum of the effects of rotation and longitudinal displacement)
- U_{TOP}: top structural displacement: $U_{TOP} = U_{FF} + U_S + U_{ST}$.
- U_{BASE}: displacement relative to free field: $U_{BASE} = U_{FF} + U_S$.

In particular, for each performed case, U_{TOP} and U_{BASE} time histories have been taken into consideration while U_{ST} has been calculated with their difference.

Figure 6 - Figure 8 show the response of equivalent soil-structure system in terms of structural (U_{ST}), top displacements (U_{TOP}) and base displacements (U_{BASE}) respectively, scaled with the maximum displacement reached. SSI effects are shown to increase all the displacements until a particular value of stiffness ratio ($\overline{s}$), where the displacements reach their maximum values. In particular, structural displacement (U_{ST}) is affected by foundation rotations and translations. In this regards, the performed simulations have the advance to overtake the traditional approaches [5, 6] based on introduction of linear (translational and rotational) springs and dashpot reproducing directly stiffness and damping characteristics of the compliant soil-foundation system. Figure 8 shows 3D deformed mesh for f_0=3 Hz, $\overline{s}$=2 case.
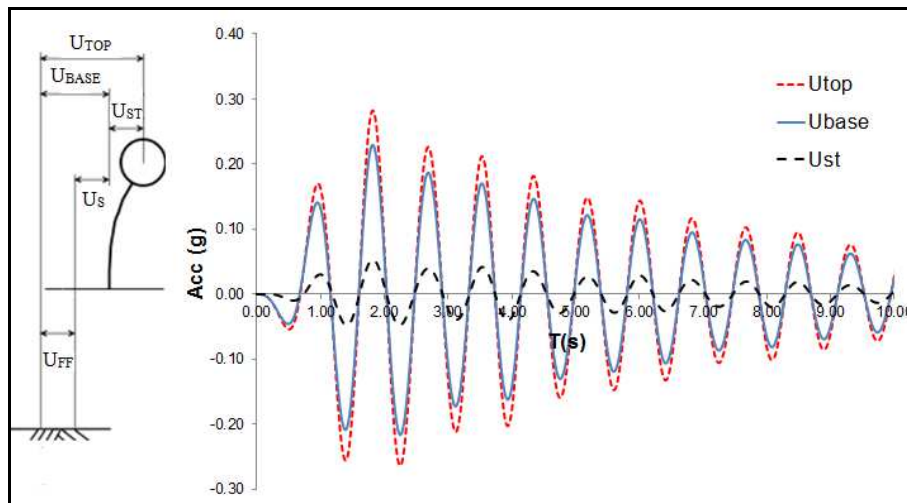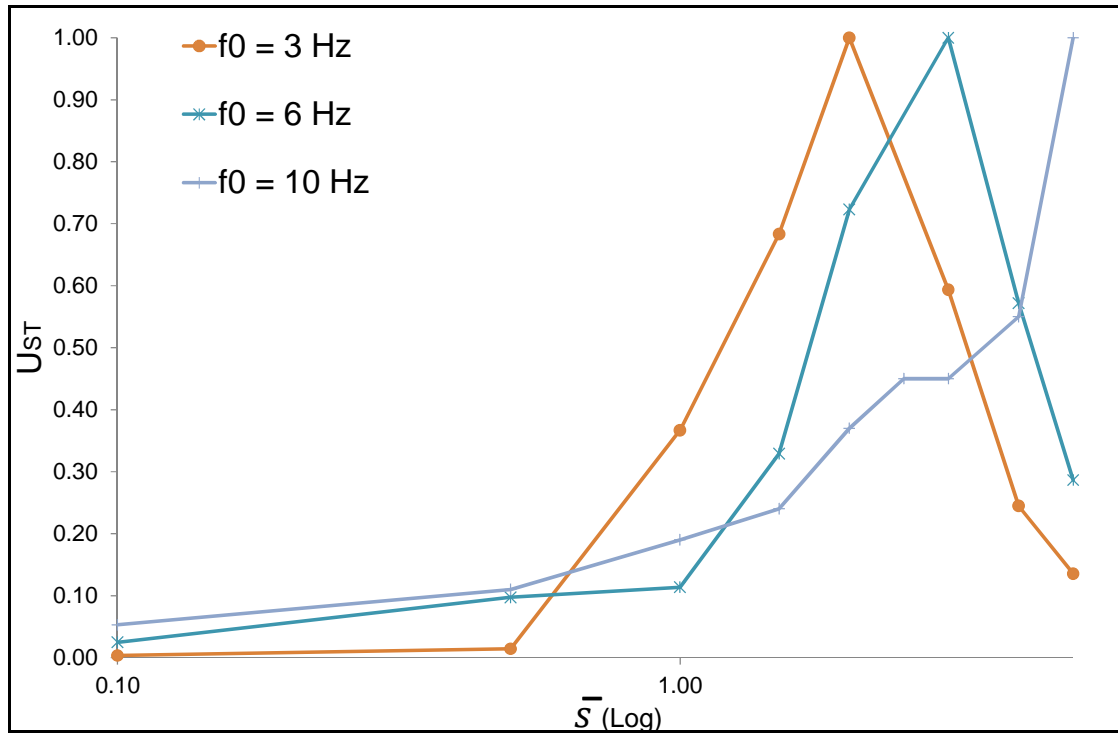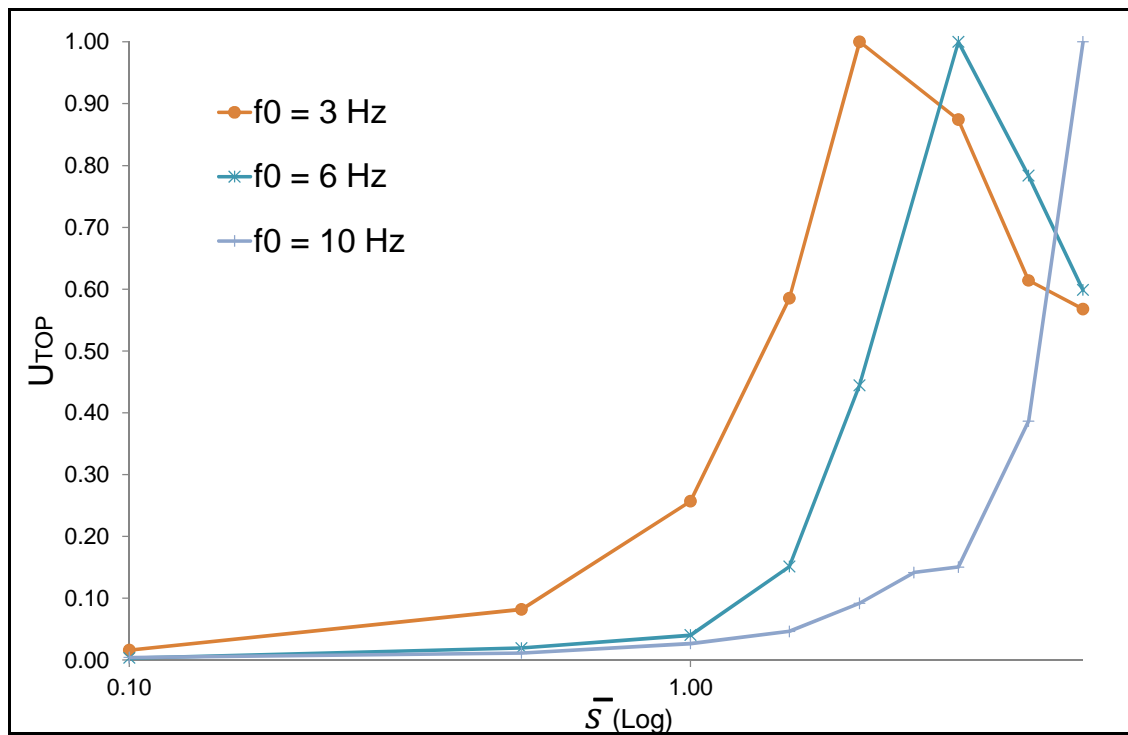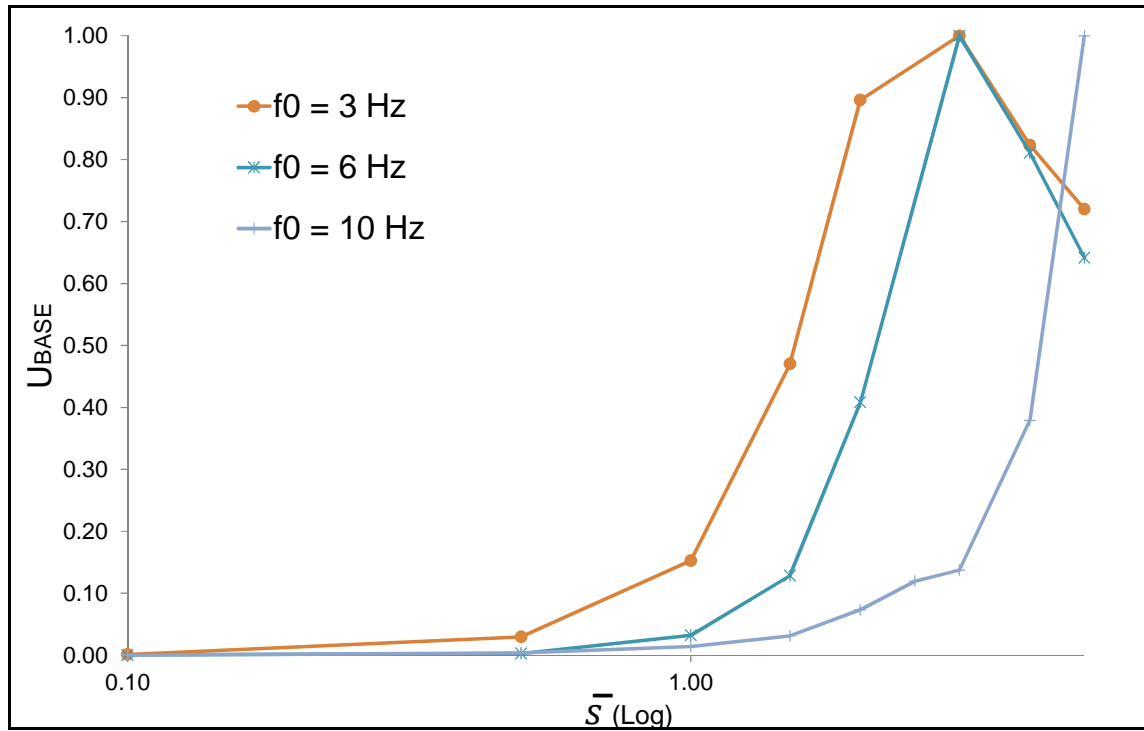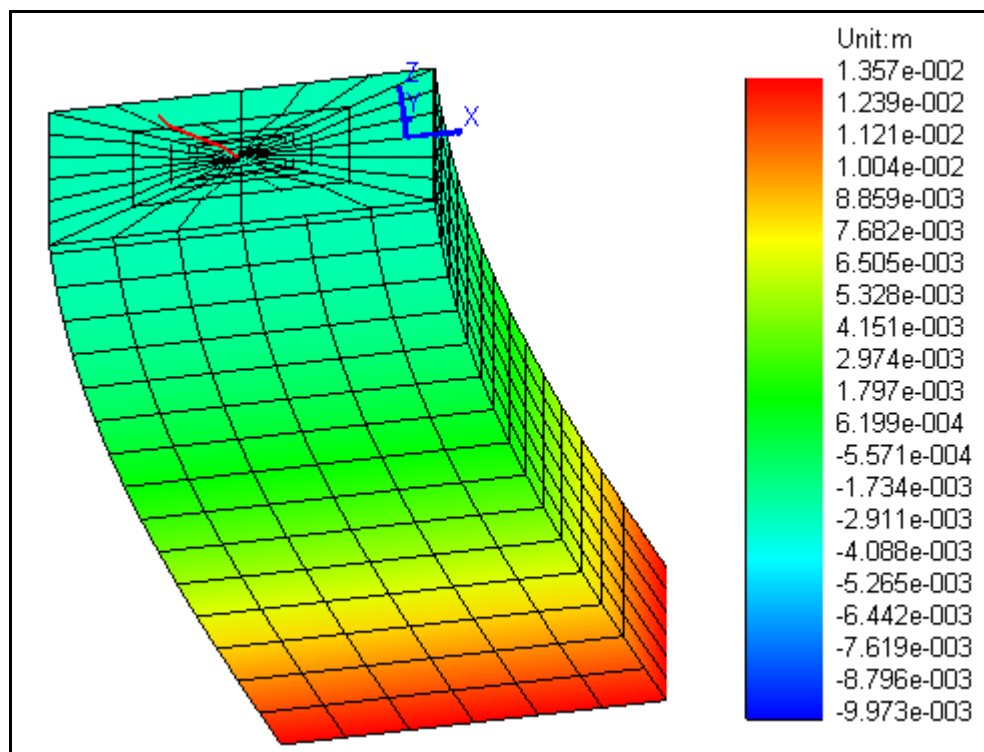

Figure 5. displacements scheme and acceleration.

Figure 6. Structural displacement - stiffness ratio ($\overline{\overline{m}}$=3)

Figure 7 Top displacement - stiffness ratio ($\overline{\overline{m}}$=3)

Figure 8 Base displacement - stiffness ratio ($\overline{\overline{m}}$=3)

Figure 9. 3D mesh deformations (scale 1:100, f=3 Hz, $\overline{\overline{s}}$=2 case).

5 CONCLUSIONS

The paper shows a numerical study aimed at investigating soil structure dynamic interaction significant role during seismic excitations. It can be considered a first study able to overcome traditional simplifications adopting a 3D soil-structure system that applies nonlinear hysteretic materials with advanced plasticity models. In particular, the paper applies the open-source computational interface OpenSeesPL, implemented within the FE code OpenSees performing parametric studies based on mutual behavior of soil and structure dynamic characteristics.

Calibration procedures show good agreement with theoretical approaches confirming Opensees potentialities and model assumptions in performing soil structure interaction 3D numerical problems. In particular, two parametric studies have been performed in order to assess the role of structural dynamic characteristics and mass ratio. The paper shows also an assessment study that investigates SSI significant role during seismic excitations assessing seismic performance in terms of displacements. The aim is the safety assessment and cost reduction in design procedures with particular attention to those cases where SSI can become non-conservative.

The study reproduces several one degree of freedom (dof) structural systems with different dynamic characteristics. Further analysis will aim at reproducing more complex systems, such as buildings and bridges.

REFERENCES

[1] ATC-3-06. *Amended tentative provisions for the development of seismic regulations for buildings*. ATC Publication ATC 3-06, NBS Special Publication 510, NSF Publication 78-8, Applied Technology Council. US Government Printing Office: Washington, DC; 1978;

[2] Building seismic safety council, NEHRP. *Recommended provisions for the development of seismic regulations for new buildings (and other structures).*National earthquake hazards reduction programme: Washington, DC; 1985, 1988, 1991, 1994 (1997, 2000);

[3] J. E. Luco, *Linear soil-structure interaction: a review. Earthquake Ground Motionand Its Effects on structures,* 1982;

[4] J. P. Wolf, *Dynamic Soil-Structure Interaction*, Prentice-Hall, Englewood Cliffs, 1985;

[5] S. L. Kramer, *Geotechnical Earthquake Engeneering*, Prentice-Hall, International Series in Civil engineering and engineering Mechanics, William J. Hall Editor, 1996;

[6] National Institute of Standards and Technology, *Seismic soil-structure interactionfor building structure,*Report NIST GCR 12-917-21, 2012.

[7] Mylonakis G, Gazetas G. *Seismic soil-structure interaction: beneficial or detrimental?* Journal of Earthquake Engineering 2000; 4: 277−301;

[8] Veletsos AS, Nair VV. *Seismic interaction of structures on hysteretic foundations*. Journal of Structural Engineering, 101101; 109-129;

[9] Abate G, Massimino MR, Maugeri M, Muir Wood D. *Numerical modelling of a shaking table test for soil-foundation-superstructure interaction by means of a soil constitutive model implemented in a fem code*. Geotechnical and Geological Engineering Journal 2010; 28(1): 37-59;

[10] Saouma V, Miura F, Lebon G, Yagome Y. *A simplifyed 3D model for soil-structure interaction with radiation damping and freefield input*. Bulletin of Earthquake Engineering 2011;9(5):1387–1402;

[11] Barcena A, Esteva L. *Influence of dynamic soil-structure interaction on the nonlinear response and seismic reliability of multistory systems*. Earthquake Engineering and Structural Dynamics 2007; 36: 327–346;

[12] Avilés J, Pérez-Rocha LE. *Evaluation of interaction effects on the system period and the system damping due to foundation embedment and layer depth*. Soil Dynamics and Earthquake Engineering 1996; 15: 11–27;

[13] Mylonakis G, Nikolau S, Gazetas G. *Footing under seismic loading: Analysis and design issues with emphasis on bridge foundations*. Soil Dynamics and Earthquake Engineering 2006; 26: 824–853;

[14] Renzi S, Madiai C., Vannucchi G. *A simplified empirical method for assessing seismic soil-structure interaction effects on ordinary shear-type buildings.* Soil Dynamics and Earthquake Engineering 2013; 55: 100–107;

[15] Paolucci R, Shirato M, Yilmaz T. *Seismic behaviour of shallow foundations: Shaking table experiments vs numerical modelling*. Earthquake Engineering and Structural Dynamics 2008; 37: 577-595;

[16] Rayhani MT, El Naggar MH. *Physical and numerical modeling of seismic soil-structure interaction in layered soils*. Geotechnical and Geological Engineering Journal 2012;30(2):331–342;

[17] Pitilakis D, Dietz M, Wood DM, Clouteau D, Modaressi A. *Numerical simulation of dynamic soil-structure interaction in shaking table testing*. Soil Dynamics and Earthquake Engineering 2008; 28(6): 453–467;

[18] S. Mazzoni, F. McKenna, M. H. Scott, G. L. Fenves, *Open System for Earthquake* Engineering Simulation, User Command-Language Manual, Pacific Earthquake Engineering Research Center, University of California, Berkeley, 2009;

[19] Opensees PL (http://soilquake.net/openseespl/);

[20] Chopra A., *Dynamics of Structures – theory and applications to earthquake engineering*. New Jersey: Prentice Hall, Englewood Cliffs 305-336;

[21] H.K. Law, I.P. Lam, *Application of periodic boundary for large pile group,* Journal of Geotech. Geoenviron. Eng., 127-10, 889–892, 2001;

[22] A. Elgamal, J. Lu, D. Forcellini, *Mitigation of liquefaction-induced lateral deformation in a sloping stratum: three-dimensional numerical simulation*, J. Geotech. Geoenviron. Eng., **135**, 1672–1682, 2009;

[23] D. Forcellini, A.M. Tarantino, *Countermeasures assessment of liquefaction-induced lateral deformation in a slope ground system,* Journal of Engineering, Article ID 183068, 2012;

[24] D. Forcellini, F. della Bartola, and A. M. Tarantino, *Liquefaction-induced lateral deformations computational assessment during Tohoku Earthquake* ISRN Civil Engineering, Article ID 408961, 2013;

[25] D. Forcellini, A.M. Tarantino, Assessment of stone columns as a mitigation technique of liquefaction-induced effects during italian earthquakes (May 2012), Scientific World Journal, Article ID 216278, 201, 2014.