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3D NUMERICAL SIMULATIONS OF A BASE-ISOLATED RESIDENTIAL BUILDING WITH SOIL STRUCTURE INTERACTION

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Abstract. *Base isolation (BI) is a well-known technique with many applications all over the world. This study aims at considering 3D numerical simulations of a soil-structure system applied to a base isolated ordinary building. In particular, the soil has been performed with nonlinear hysteretic materials and advanced plasticity models, implemented in Opensees. The proposed approach enables to drive the assessment of isolation technique with evaluation of soil non-linear response into a unique twist. In this regard, the paper aims at assessing the cases where BI becomes detrimental. In particular, the model of the structure allows to assess the structural performance, by considering accelerations and displacements at various heights. This study overcomes the common simplifications in modelling the soil foundation. In this regard, it can be considered one of the few attempts to propose new design considerations for engineers and consultants.*

1 BACKGROUND

Base isolation (BI) is one of the most convincing solutions in order to protect structures from the destroying effects of earthquakes. This technique allows to decouple the structure from the ground by intentionally concentrating seismic energy dissipation in a unique element with low horizontal stiffness between the foundation and the structure. Many researches have been carried on this issue but few contributions have been focused on the effects of the soil structure interaction (SSI). Extensive research has been conducted in the past 30 years regarding the effects of soil–structure interaction (SSI) on the seismic response of civil engineering structures. Even if many codes suggest to neglect SSI [1], [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], [4]. The majority of publications study SSI simply by introducing springs, dashpots and artificial masses in the interface between the structure and the soil. This approach is generally accepted since modeling SSI is a challenging problem for numerical simulations. However, it could be insufficiently detailed in order to model the complexity of the problem. In particular, system response is directly connected with the mutual dynamic characteristics (natural frequencies) and thus with structural mass and stiffness, soil shear velocity and layer depth [5]. For this reason, the beneficial effects of BI can be strongly modified by soil deformability and energy dissipation in the ground [6], [8], [9].This study aims at overcoming all previous simplifications considering a 3D numerical simulations of a soil-structure system applied to a shear type building isolated at the base. In particular, the soil has been performed with nonlinear hysteretic materials and advanced plasticity models. The proposed approach enables to drive the assessment of BI technique with evaluation of soil non-linear response into a unique twist. In this regard, the paper aims at assessing the cases where BI becomes detrimental. In particular, the study shows how considering the structure fixed at the base is non conservative and underestimates dynamic effects.

2 CASE STUDY

This paper aims at reproducing the seismic response of a benchmark concrete structure on different deformable soils and isolated at the base. The soil has been performed with nonlinear hysteretic materials and advanced plasticity models. This approach enables to reproduce soil hysteretic elasto-plastic shear response (including permanent deformations) and damping foundation impedances by applying the open-source computational interface OpenSeesPL [10], implemented within the FE code OpenSees [11]. In particular, this platform is able to capture the effects of amplification and consequent accumulation of deformation in the ground. At the same time, the model of the structure allows to assess the structural performance, by considering accelerations and displacements at various heights. OpenSeesPL 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. This interface, had been originally calibrated for pile analysis. Here it has been modified in order to consider the presence of the system structure – foundation. Based on previous studies [12][13], the soil has been considered a one-layer homogenous cohesive material with a 20 m depth, that consists in a 3D FE mesh (68.4m x 74.4m x 20.5m) composed of 2992 brickUP linear isoparametric 8-nodes elements with 4025 nodes. Horizontally has been discretized in six layers, from center to the outward, while vertically in four layers; 0.5 m thickness for the first and 6.7 m for the others. The model base boundaries were been set at 20.5 m depth from ground surface (Figure 1). OpenSees is able to simulate real wave propagation adopting periodic boundaries by assuming that symmetry conditions can be adopted [14]. Displacement degrees of freedom of the left and right boundary nodes were tied together both longitudinally and vertically using the penalty method. In this regard, 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. The boundaries are located as far as possible from the structure as to decrease any effect on the response. For more details, see [6] and [12]. Connections between the structure and the soil are built up with specific elements called "equaldof" which are able to impose the displacements to be the same between the structure and the soil nodes. The mechanical behavior of the soil was modeled with the implemented material named Pressure Independent Multiyield. It consists of a nonlinear hysteretic material, using a Von Mises multi-surface kinematic plasticity approach together with an associate flow rule [16] and allows to control the magnitude of cycle-by-cycle permanent shear strain accumulation, [17]. Non-linear shear stress-strain back-bone curve is represented by a hyperbolic relation, which is defined by low-strain shear modulus and ultimate shear strength constants. For more details, see [17] and [18]. 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.

The study consists of reproducing a four-story (floor height: 3.4 m, total height: 13.6 m) reinforced concrete building, representative of realistic buildings. The number of columns (2 in the longitudinal direction (15 m spaced) and 4 in the transversal direction (10 m spaced), see Figure 1) has been chosen as a compromise between representativeness and computational time. Each column was discretized in sixteen elasticBeamColumn elements. The total high of the building is 14.1 m. The first 0.5 m were considered part of the foundation and connected to the soil as explained below. The study can be divided into two steps. First (paragraphs 3-5), eigenvalue analyses have been performed in order to assess the mutual effects of BI and soil deformability on the dynamic characteristics of the system (soil and structure). The second step (paragraph 6) consists of performing dynamic analyses in order to study the structural behaviour. The mesh was calibrated on a previous study [6] and realistic clay soils were performed. For all analyses, the Newmark transient integrator is used with γ=0.6 and β=0.3. Stiffness and mass proportional damping is added with a 2% equivalent viscous damping at 1 and 6 Hz.

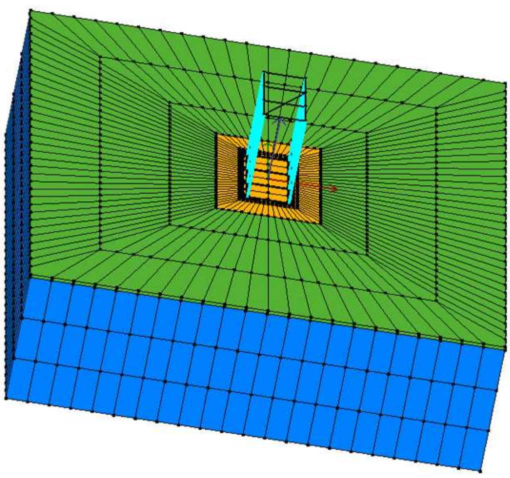

Figure 1: 3D system mesh performed in the study

3 EIGENVALUE ANALYSIS (NO BI)

In this paragraph, the effects of soil with several deformability have been studied. In particular, a hard soil (shear velocity equal to 1600 m/s, named soil A) has been used to reproduce rigid base conditions (SSI neglected). In order to verify this assumption, the acceleration inputs at the base of the mesh were compared to the accelerations at the top of the layers, which propagate at the base of the structure and they were found to be identical, as shown in [6] and [13]. Then, soil stiffness was varied in order to take into account SSI effects. In particular, soils were chosen in order to be representative of the typologies defined by the Eurocode (EC8, 3.1.2 Table 3.1). Table 1 details the soil properties adopted in the study. The original configuration (without isolation) has been considered here. Figure 2 shows the modal shapes in case of soil A. Table 2 shows period elongation due to the effects of soil deformability.

PARAMETERS	SOIL A	SOIL B	SOIL C	SOIL D
Mass density [kN/m^3]	22.0	21.0	20.5	18.0
Shear Modulus [kPa]	$5.63 \cdot 10^7$	$6.12 \cdot 10^6$	$1.72 \cdot 10^5$	$4.05 \cdot 10^4$
Bulk Modulus [kPa]	$7.51 \cdot 10^7$	$1.33 \cdot 10^6$	$5.17 \cdot 10^5$	$1.89 \cdot 10^5$
Poisson Coefficient	0.20	0.30	0.35	0.40
Cohesion [kPa]	10000	500	160	40
Shear wave velocity [m/s]	1600	540	290	150

Table 1: Soil parameters.

MODEL	T_1[s]	T_2[s]	T_3[s]	T_4[s]
Soil A	0.672	0.229	0.148	0.121
Soil B	0.700	0.232	0.152	0.121
Soil C	0.721	0.280	0.235	0.149
Soil D	0.808	0.358	0.235	0.166

Table 2: Natural periods elongation due to SSI effect.

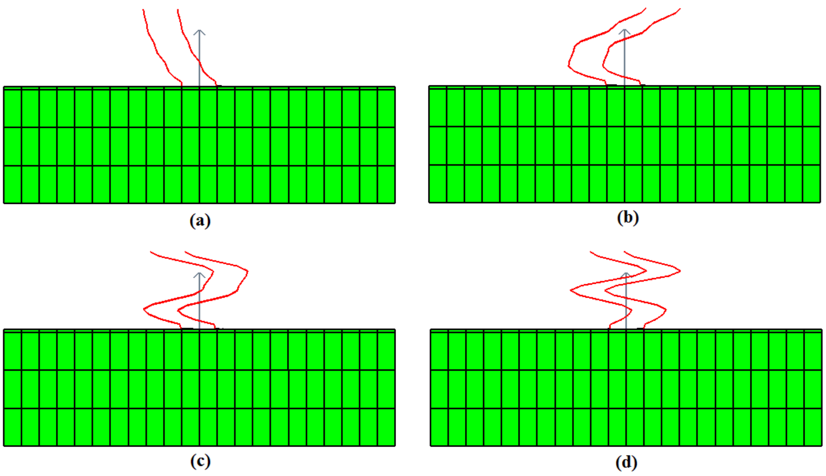

Figure 2: Modal shapes (soil A), 1st mode (a), 2nd mode (b), 3rd mode and 4th mode (d)

4 BASE ISOLATION (NO SSI)

This paragraph details the implementation of base isolation, without taking into account the effects of soil deformability. The hard soil (shear velocity equal to 1600 m/s, soil A) has been used to reproduce rigid conditions, with usually base isolation is designed.

The natural period of the isolated structure has been taken equal to 3.35 s. From the total seismic mass (M=16240 kN s^2/m), it is possible to determine the overall stiffness needed (K_{is}) for the isolated system by the following equation:

$$k_{is} = \frac{4 \cdot \pi^2 \cdot M}{T^2} = 19.00 \frac{kN}{mm} \tag{1}$$

Considering the structural scheme (4x2 columns), the stiffness for each isolator results:

$$k = \frac{k_{is}}{8} = 2.38 \frac{kN}{mm} \tag{2}$$

The lead rubber bearing (LRB) named LRN (D700B750Z550) has been selected from ALGA (Table 3, [19]).

In this paper, the isolation has been modelled with a linear relationship, by applying the so called elastomericBearing element, by Opensees library [11].This element needs the calibration of three parameters: the initial elastic stiffness (here K = 7.38 kN/mm), the yield strength (here Fy = 3099 kN) and the post-yield stiffness ratio (here alpha = 1).

	D [mm]	H [mm]	G [MPa]	T_e [mm]	S_{max} [mm]	K_r [kN/mm]	K_{lead} [kN/mm]	K_{eff} [kN/mm]	F_y [kN]
LRN(D700B750Z550)	700	384	0.9	210	420	1.47	25.72	2.46	439

Table 3: Characteristics of LRB obtained from ALGA and calibrated for the model.

5 EIGENVALUE ANALYSIS (BI)

In this paragraph the effects of soil with several deformability and base isolation have been studied at the same time. The above isolation device has been considered firstly founded on the hard soil case (soil A) and then on soils B, C and D. Figure 6 shows BI shape modes in case of soil A. Table 4 shows the periods of the structure with several soil conditions. The fundamental period increases for all the soil conditions to 3.35 s.

The results show that soil deformability does not affect the periods when isolation is applied and thus that isolation performs its function by decoupling the structure from the soil. Comparing with the non isolated cases (Table 2), the increases are more significant for soil A than in case of soil D.

This demonstrates that the efficiency of base isolation technique increases with rigid soils and that it depends significantly on the deformability of the soil, as shown in [6].

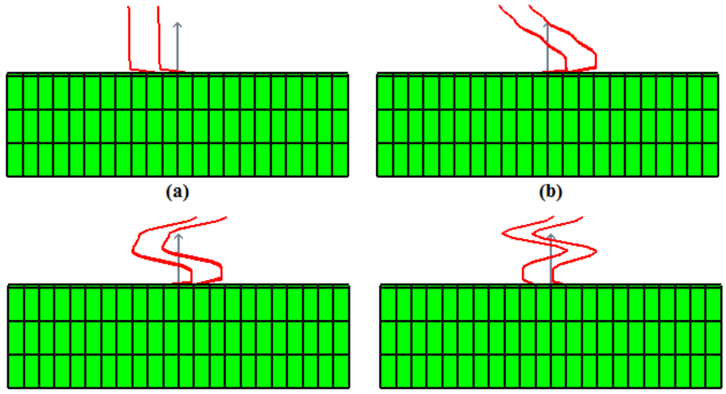

Figure 3: Modal shapes of isolated structure (soil A), 1st mode (a), 2nd mode (b), 3rd mode and 4th mode (d).

MODEL	$T_{1(iso)}$[s]	$T_{2(iso)}$[s]	$T_{3(iso)}$[s]	$T_{4(iso)}$[s]
Soil A	3.349	0.297	0.158	0.122
Soil B	3.352	0.297	0.158	0.122
Soil C	3.356	0.297	0.158	0.122
Soil D	3.370	0.297	0.167	0.158

Table 4: Natural period of base isolated model with different soils considered.

6 DYNAMIC ANALYSES

In this paragraph, dynamic analyses have been performed. Seven input motions were selected, as show in Table 5 and Figure 4. They were selected in order to significantly affect the dynamic characteristics of the structure and applied along the x-axis (longitudinal direction). The results obtained with input n.2 in terms of acceleration and displacement time histories have been shown in Figure 5 and 6 (at the various floor: z = 13.6 m, 10.2 m, 6.80 m and 3.40 m). In the figure, the name FIX-A indicates the values obtained with the fixed base model in correspondence with soil A, while BI-A indicate the obtained results for BI model. Thanks to its deformability, soil D reduces the effects of earthquakes and thus, the effectiveness of isolation become less significant (-53%). In terms of displacements, it is possible to see that due to the presence of the isolation, the displacements are concentrated at the base. The upper floor do not have any significant drift. In the cases of fixed base, the displacements are concentrated at all floors.

Table 6 shows the comparison between the fixed (FIX) and the base isolated (BI) structure for various soil conditions in terms of maximum accelerations and maximum displacements. The ratios (in terms of accelerations and displacements) between these two configurations is shown in the last two columns. The best reduction in terms of accelerations was achieved with soils A (-88%), B (-88%) and C (-79%). The maximum increase in terms of displacements has been obtained with soil A (61%), then it is observed a decrease with soil B (25%) and C (19%). A different trend is seen when soil D has been performed (36%).

Figure 7 shows a comparison between the spectra obtained with fixed model and BI model, considering SSI effects. Table 8 summarizes the results in terms of spectral accelerations obtained with all the input motions shown in Table 5.

In particular, the results obtained with soil A has been considered as a reference to compare those obtained with the other soils. Column 4 of Table 8 shows the ratio between the maximum values of pseudo-acceleration between fixed structure and BI model in correspondence with the considered soils. The last two columns in Table 8 (b), (c) and (d) show the ratio between soil A and the considered soil, both in case of fixed structure and BI respectively.

Input motion	Station	PGA [g]	PGV [cm/s]	PGD [cm]	Duration [s]
n.1 Landers (1992)	Lucerne Valley	0.72	147.45	265.14	25.00
n.2 Northridge (1994)	Rinaldi Receiving	0.89	185.08	60.07	12.50
n.3 Northridge (1994)	Sylmar Converter	0.70	135.82	58.20	17.50
n.4 Northridge (1994)	Sylmar Hospital	0.87	139.54	50.37	15.00
n.5 Hyogo-Ken (1995)	Takatori	0.47	155.44	44.95	20.00
n.6 Erzincan (1992)	Erzican	0.44	125.80	53.30	12.50
n.7 El Centro (1940)		0.35	38.47	82.44	17.50

Table 5: Input motions (in longitudinal direction).

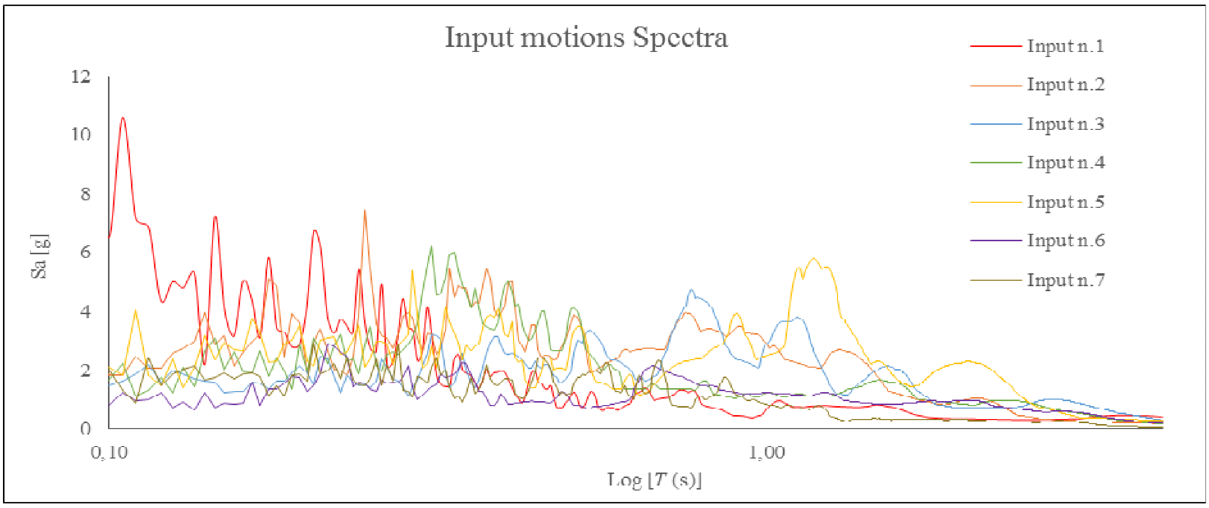

Figure 4: Response spectra

MODEL	Max Acc (13.6 m) [g]		Max Disp (13.6 m) [mm]		FIX-ACC	FIX-DISP
	FIX	BI	FIX	BI	BI-ACC	BI-DISP
Soil A	1.96	0.24	357	575	-88.0%	+61.1%
Soil B	2.03	0.24	463	579	-88.0%	+25.1%
Soil C	1.17	0.24	712	844	-79.2%	+18.6%
Soil D	0.31	0.15	474	645	-53.4%	+36.1%

Table 6: Comparison between Accelerations and Displacements of FIX and BI model for soil in Table1.

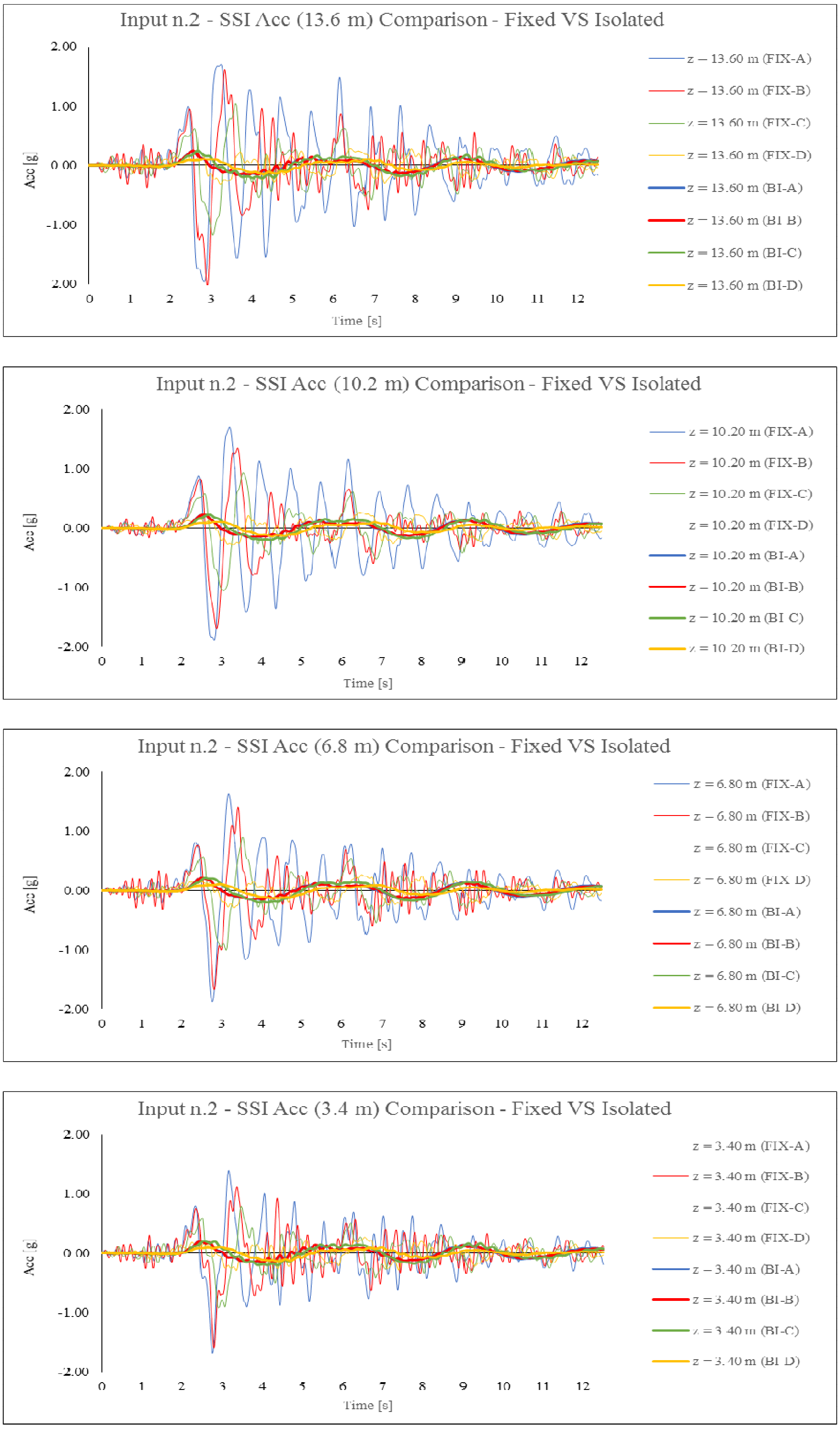

Figure 5: Comparison between acceleration time histories at various heights (input n.2).

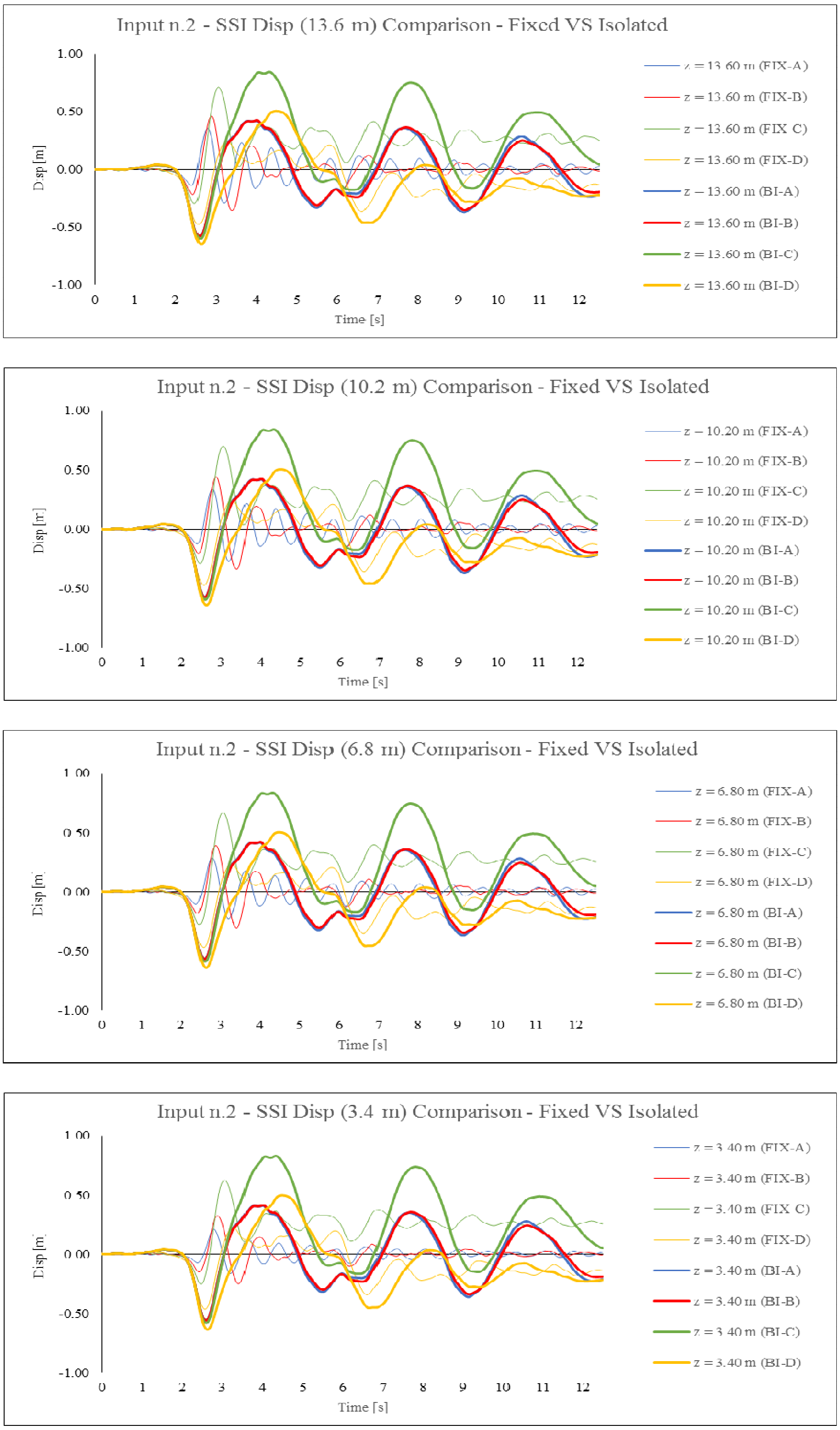

Figure 6: Comparison between displacement time histories at various heights (input n.2).

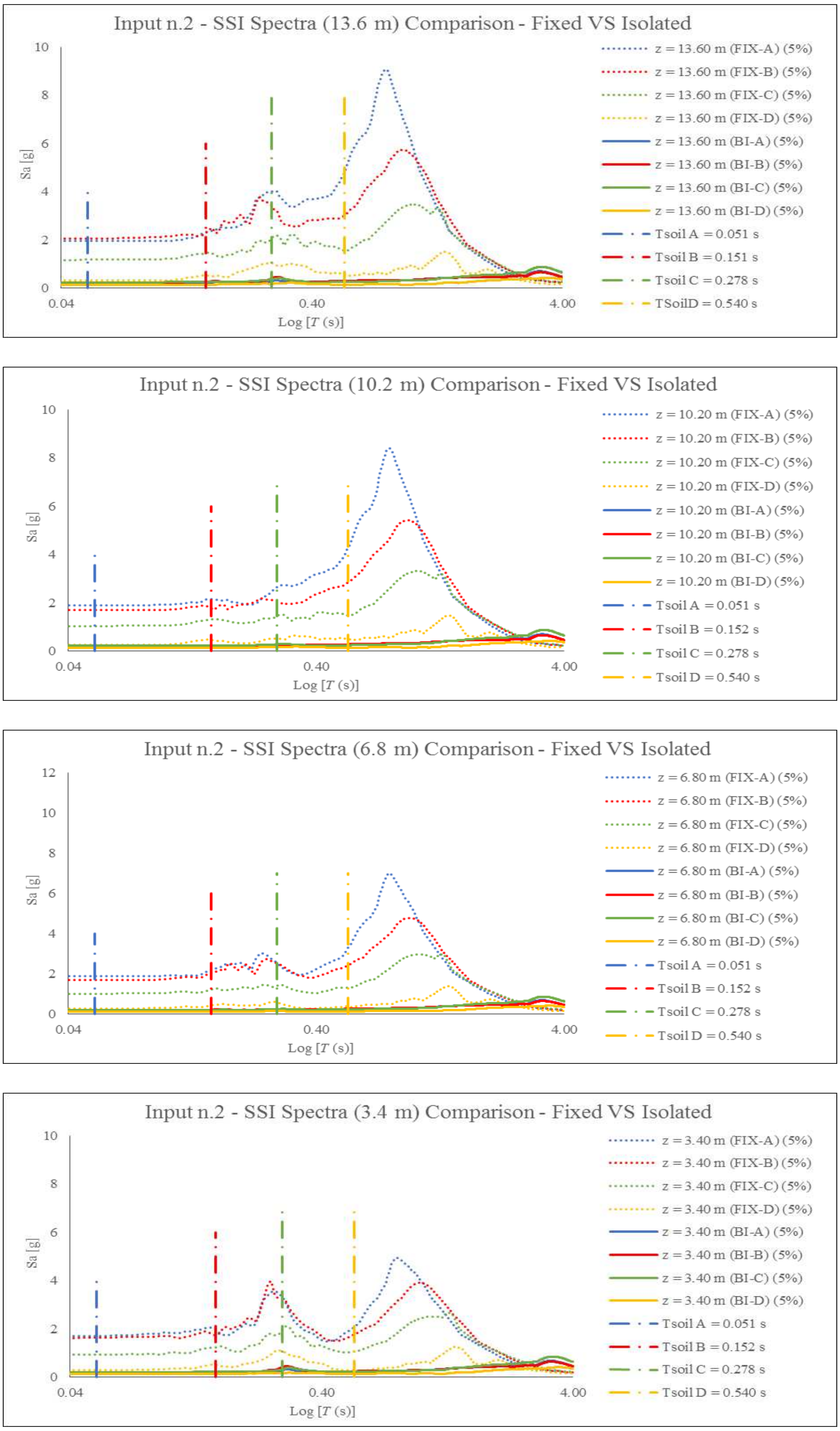

Figure 7: Comparison between spectra at various heights (input n.2).

SOIL A	Max Sa (z = 13.6 m) [g]		FIX-A
	FIX-A	BI-A	BI-A
Input n.1	3.86	1.52	-60.6%
Input n.2	9.08	0.70	-92.2%
Input n.3	11.86	1.52	-87.2%
Input n.4	3.27	1.11	-66.1%
Input n.5	6.99	1.12	-84.0%
Input n.6	6.43	1.25	-80.6%
Input n.7	3.61	0.39	-89.2%

(a)

SOIL B	Max Sa (z = 13.6 m) [g]		FIX-B	FIX-A	BI-A
	FIX-B	BI-B	BI-B	FIX-B	BI-B
Input n.1	3.72	1.44	-61.3%	-3.6%	-5.3%
Input n.2	5.73	0.67	-88.4%	-36.8%	-5.2%
Input n.3	5.85	1.54	-73.7%	-50.7%	+1.3%
Input n.4	3.22	1.02	-68.3%	-1.5%	-8.1%
Input n.5	7.10	1.07	-84.9%	+1.6%	-4.5%
Input n.6	2.39	1.14	-52.3%	-62.8%	-8.8%
Input n.7	2.20	0.36	-83.6%	-39.1%	-7.7%

(b)

SOIL C	Max Sa (z = 13.6 m) [g]		FIX-C	FIX-A	BI-A
	FIX-C	BI-C	BI-C	FIX-C	BI-C
Input n.1	2.10	1.44	-31.4%	-45.6%	-5.3%
Input n.2	3.48	0.88	-74.6%	-61.7%	+25.3%
Input n.3	4.10	1.52	-62.9%	-65.4%	+0.0%
Input n.4	2.12	1.02	-51.9%	-35.2%	-8.1%
Input n.5	4.55	1.04	-77.1%	-34.9%	-2.8%
Input n.6	2.32	1.15	-50.4%	-63.9%	-8.0%
Input n.7	1.89	1.42	-24.9%	-47.6%	+264.1%

(c)

SOIL D	Max Sa (z = 13.6 m) [g]		FIX-D	FIX-A	BI-A
	FIX-D	BI-D	BI-D	FIX-D	BI-D
Input n.1	0.97	1.23	+26.8%	-74.9%	-19.1%
Input n.2	1.53	0.43	-72.0%	-83.2%	-39.4%
Input n.3	0.97	3.19	+228.9%	-91.8%	+109.9%
Input n.4	1.08	0.99	-8.3%	-67.0%	-10.8%
Input n.5	1.77	1.10	-37.9%	-74.7%	+5.8%
Input n.6	0.95	1.53	+61.1%	-85.2%	+22.4%
Input n.7	1.11	0.44	-60.4%	-69.3%	+12.8%

(d)

Table 8: Comparison between Sa obtained with fixed and base isolated model, with soil in Table1.

7 CONCLUSIONS

The paper shows a numerical study aimed at investigating BI technique as a solution to protect structures to the destroying effects of earthquakes. The presented study aims at overcoming the linear equivalent simplifications by performing the soil with nonlinear hysteretic materials and advanced plasticity models. 3D numerical simulations of a soil-structure system have been applied to several soil conditions. 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.

The study was divided into two steps. The first step consisted in calculating the effects of BI on the fundamental periods of the structure. The benefit of BI has been assessed in terms of variation of fundamental periods. The study reproduces also several dynamic analyses that help to estimate the mutual effects of the soil and the isolation. Acceleration and displacement time histories at several level of the structure have been considered in order to assess the effects of soil isolation on the system performance. Further analysis will aim at reproducing more complex systems.

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