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SOIL STRUCTURE INTERACTION ON SEISMICALLY ISOLATED STRUCTURES WITH ROCKING AND SWAY SPRINGS

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Abstract

Seismic isolation has become more widely used for structures and infrastructures in the recent time as it reduces the vibration of the superstructure and keeps the people inside safer with less relative movement of structural and non-structural elements. The seismic response of seismically isolated structures may be affected by the soil condition as ground motions on soft soil may affect the response of the seismically isolated structure. However, there are limited studies examining the effect of the soil condition on isolated structures during earthquake excitation. This study aims to inspect the effect of Soil-Structure Interaction (SSI) on seismically isolated reinforced concrete buildings equipped with Lead Rubber Bearings (LRBs) as isolators founded on different soil deposits i.e. Hard, Medium, Soft. The profiles of the deposits resemble the soil types in Eurocode 8 [1]. LRBs are modeled having bilinear hysteresis behavior resulting from the presence of the lead core which has a bilinear nature. SSI is simulated using sway and rocking springs and dashpots under the foundation of the structure using the cone model for the analysis of multi layers. In this paper three different cases were studied considering the soil influence in amplifying earthquake wave which is used as an input ground motion for the structures, also taking into account the SSI effect on structures due to the presence of soil deposits above the bedrock layer. The targeted structures are three seismically isolated structures of 5, 10 and 15 storeys modeled as Lumped Mass Models (LMMs), wherein the models were subjected to five strong ground motions and the responses for each earthquake were calculated. The responses were studied at isolation layer and super structure in terms of shear force and displacement and the average of the responses is discussed. From the analysis and calculation results it was found that soil amplification of the earthquake wave and SSI have a remarkable effect on the responses of the seismically isolated structures, whereas SSI effect on taller buildings is much more severe. It indicates the importance of considering the effect of SSI in the design of the seismically isolated structures especially for the high-rise buildings.

Keywords: Soil-Structure Interaction; Seismic Isolation; Time-history; Lumped mass model; Lead rubber bearing.

1. Introduction

Seismically isolated structures are more extensively used in the present time, especially in areas with high seismic activity. The main advantage of seismic isolation techniques is to increase energy dissipation of the structure during earthquake excitation by increasing the flexibility of the isolation level in the horizontal direction. This flexibility results in elongating the fundamental period of the structure so the corresponding acceleration response is much lower than the one in case of non-isolated conventional structures, this essentially results in decrease in the vibration energy needed to be dissipated by the superstructure. Application and design of seismic isolation in structures to control its response during earthquake had been thoroughly studied and reviewed by many scholars [2]. Many types of isolation devices are used for the seismic protection of structures, such as, High Damping Rubber Bearings (HDRBs), Lead Rubber Bearings (LRBs), Natural Rubber Bearings (NRBs) and Friction Pendulum System (FPS) which are the most commonly used systems for isolation together with linear sliders and/or passive damping devices as a combination of some of these systems to reach the target design response for the building [3]. The procedure of the analysis and design of seismically isolated structures most commonly assumes the soil condition beneath the structure to be fixed support where no interconnection between soil and structure is included, which means that SSI is not commonly considered in the design and analysis of the seismically isolated structures.

Generally, when the foundation and the soil beneath the structure are exposed to seismic event, the responses of the structure and the soil are not independent, this interrelation between the responses of the structure and the ground is called soil-structure interaction. Scholars and researchers found out that soil actually has a noticeable effect on the response of structures during earthquake excitation and since the 1960s scientists had made progress in investigating the effect of SSI [4]. Several models were developed to simulate SSI [5,6,7], Wolf et al. [5,6] proposed the cone model which is modeled by semi-infinite truncated cone, this cone model can be represented by springs and dashpots by calculating their equivalent stiffness and damping. Lu et al. [7] proposed a simplified non-linear sway-rocking model for preliminary design of SSI for a structure founded on soft clay soil. Along with the emergence of seismically isolated structures and having interest drawn to using these techniques especially in the buildings of high importance, it was then crucial to study SSI effect on seismically isolated structures [8,9,10]. Constantinou et al. [8] concluded that SSI caused reduction in base and interstory displacements and doesn't have much effect on seismically isolated structures. However, Spyrakos et al. [9] found out that SSI effect is substantial for low rise structures founded on soft soils having small mass ratio, also noted that the response greatly depends on the fundamental mode.

Moreover, the researchers used free field earthquake ground acceleration to perform the analysis, however, earthquake waves hit the bedrock layer might undergo further amplification due to the different soil formations underneath the structure. Seed and Idris [11] proposed soil analytical model and developed modulus reduction and damping curves for sandy soils using equivalent linear analysis. Quite a number of studies were done to investigate the different resulting spectra due to the influence of soil condition on amplifying the earthquake wave [12,13]. Sargın et al. [13] studied the effect of the earthquake wave amplification due to soil type on the response of base isolated buildings and it was concluded that responses of base isolated structure are augmented significantly due to soil amplification in near-fault zones.

After reviewing the previous earthquake wave amplification and SSI studies, it was notable that most of studies focus the effect of soil on amplifying the incoming earthquake wave without considering the SSI on the same time and vice versa, in this study the effect of SSI will be accounted into the structure together with an amplified earthquake wave due to the different soil types. This study conducts case studies of seismically isolated structures with different building heights considering SSI and amplified earthquake as an input ground motion in different soil conditions.

2. Target structural models

Three reinforced concrete seismically isolated structures of different heights (5, 10 and 15 storeys) are selected and used in this study. Superstructure elements are preliminary designed using ECP (Egyptian Code of Practice), while seismic isolation and foundation are designed using the BSLJ (Building Standard Law of Japan), 3D model of each building is modeled using STERA 3D software which is developed by one of the authors [14]. The plan dimensions for all buildings are kept the same as 28x28m, spans between columns are uniformly taken as 7m, the height of each floor is 3.5m and weight of each floor is taken uniform and equals 7000KN. Isolation level height is taken 1.5m and weights of isolation foundation for the 5,10 and 15 storeys are 10000KN, 15000KN and 20000KN respectively. Table 1 lists the aspect ratio for three different height structures, where B is the width of the structure. Table 2.1 and 2.2 shows the details of element sections.

Table 1 - Aspect Ratio for the different structures

No. of Storeys	Height(H) (m)	Aspect Ratio (H/B)
5	19	0.7
10	36.5	1.3
15	54	1.9

Table 2.1 - Details of columns sections (cm)

Floors	**5 Storeys**			**10 Storeys**			**15 Storeys**		
	Corner	**External**	**Internal**	**Corner**	**External**	**Internal**	**Corner**	**External**	**Internal**
11 → 15	/			/			40 x 40	50 x 50	70 x 70
6 → 10				40 x 40	50 x 50	70 x 70	50 x 50	70 x 70	100 x 100
1 → 5	40 x 40	50 x 50	70 x 70	50 x 50	70 x 70	100 x 100	70 x 70	100 x 100	120 x 120

Table 2.2 - Details of beams sections (cm)

Floors	**5 Storeys**	**10 Storeys**	**15 Storeys**
11 → 15	/	/	30 x 70
6 → 10		30 x 70	30 x 90
1 → 5	30 x 70	30 x 90	30 x 100

Lumped Mass Model (LMM) for the structure is also generated to be used for this study, the stiffness of each floor is represented by three springs equivalent to horizontal, vertical and rotational behavior to account for the flexibility of superstructure. Isolation floor is modeled as a lumped mass with two equivalent isolators at the base of the structure. To account for SSI, sway and rocking springs and dashpots were attached below the foundation as shown in Fig.1.

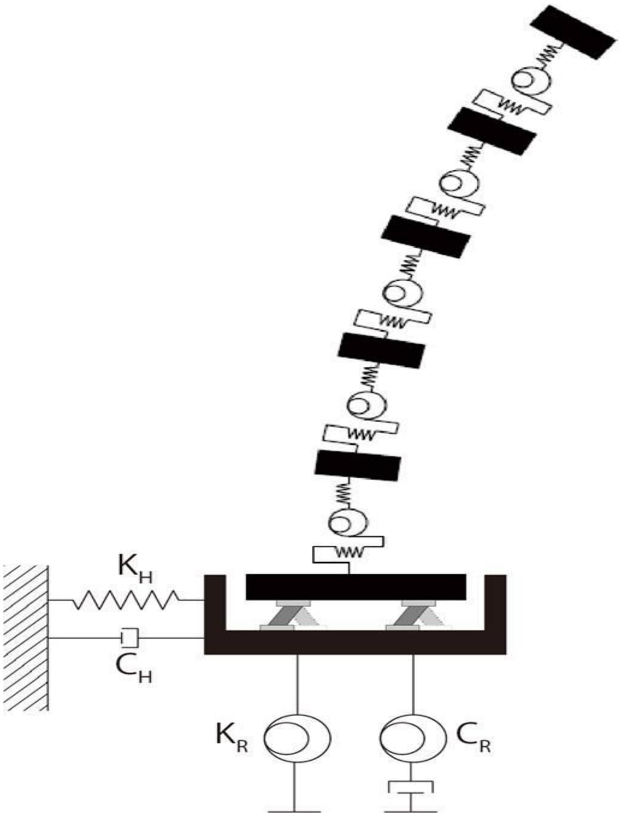

Fig. 1 - Sway rocking lumped mass model

3. Base isolation system characteristics

Isolation system is chosen and designed according to the BSLJ; the isolation system is composed of 16 identical LRBs for each structure where one LRB is fitted below each column in the 3D model for the structure. After generating the lumped mass model, two equivalent isolators were fitted at the isolation level to simulate the isolation system. Isolation devices chosen for the 5, 10 and 15 storeys are LH700, LH850 and LH950 respectively from the Bridgestone catalogue [15], where more details about isolator parameters are given in Table 3.

The lead core provides damping by deforming plastically when the isolator moves laterally during earthquake excitation and the steel plates placed in layers between the rubber provide an increase in vertical load bearing capacity of the isolator. Fig.2 demonstrates the bilinear hysteresis of LRB which is defined as a combination of an elastic and plastic models generating an elasto-plastic behavior. Where K_{eff} is the effective stiffness for one LRB isolator at 100% shear strain ($\gamma = 100\%$), K_1 is the initial stiffness, K_2 is the post yield stiffness and Q_d is the characteristic strength for the isolator. Fig.3 [15] illustrates the dimensions and details for LRB chosen for the 5 storeys building.

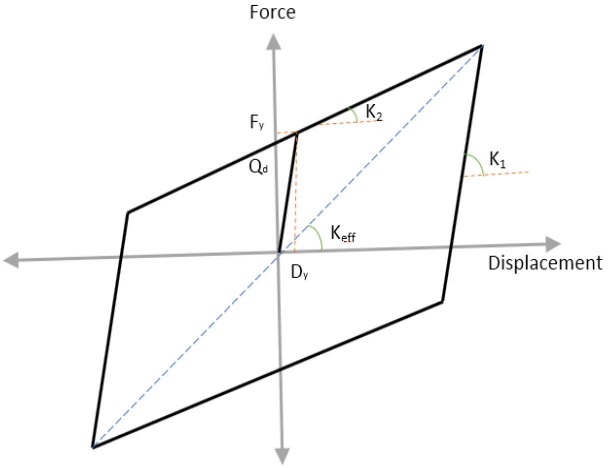

Fig. 2 - LRB hysteretic performance graph

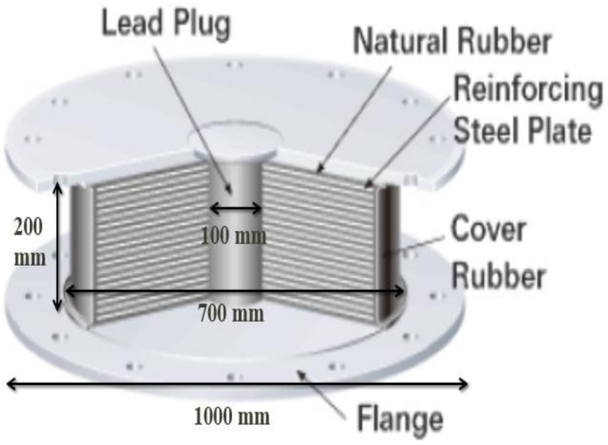

Fig. 3 - Components and section details for LH070G4

Table 3 - Isolator parameters

Building	Isolator	K_{eff} (KN/mm)	K_1 (KN/mm)	K_2/K_1	Q_d (KN)
5 Storeys	LH070G4	1.05	9.63	0.077	62.6
10 Storeys	LH085G4	1.56	14.4	0.077	90.1
15 Storeys	LH095G4	2.01	18.1	0.077	123

4. Cases of study

To capture the effect of soil on structure during earthquake excitation and determine the effect of considering SSI in the analysis of a structure, three cases illustrated in Fig.4 are selected.

Case 1 (Amplification + SSI): In this case, a bedrock input motion propagates through the soil layers, then the response wave at the surface layer where the target buildings are constructed is utilized as the input earthquake ground motion. The analytical model where same soil profile is assigned to the structure as sway and rocking springs to account for SSI is then analyzed with the amplified wave and responses are then calculated.

Case 2 (Amplification only + No SSI): In this case, a bedrock input motion propagates through the soil layer and the surface wave is inputted to the structure without SSI.

Case 3 (No Amplification + No SSI) this is the most commonly used case where the original recorded earthquake motion is used without considering amplification in the earthquake wave, and then it is inputted to the bare analytical model without having sway and rocking springs to consider SSI.

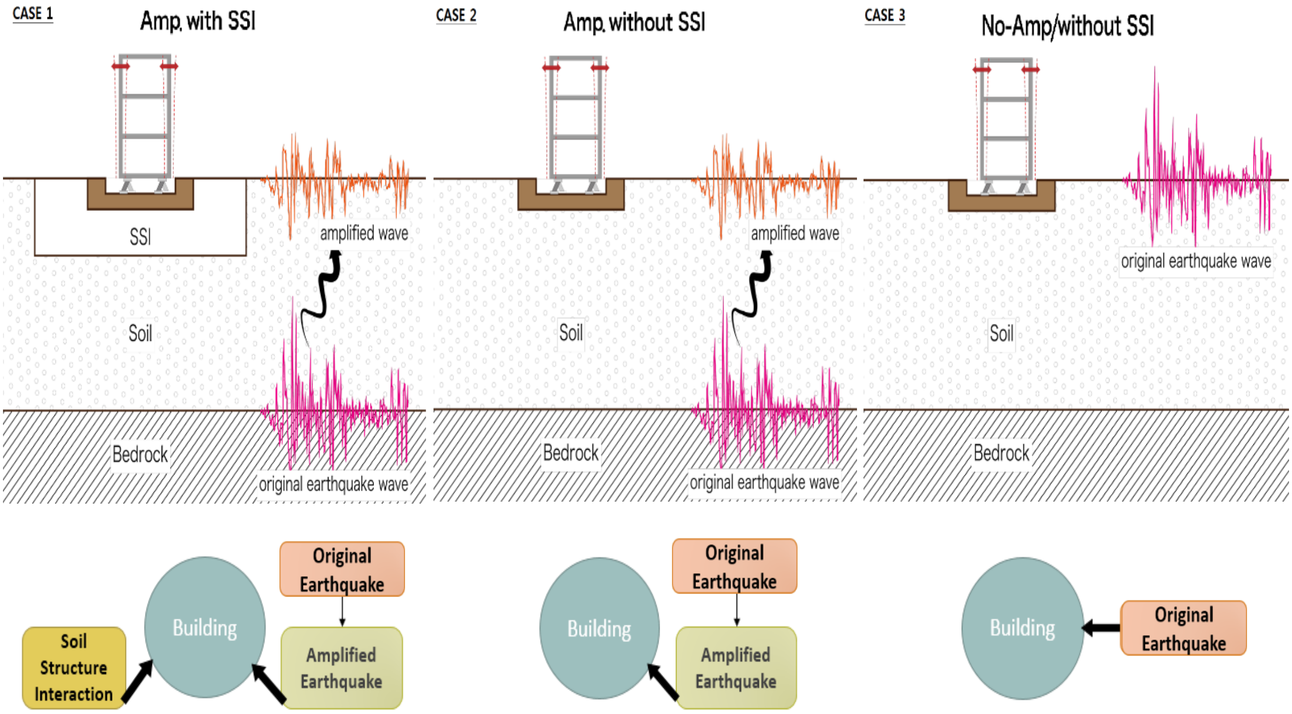

Fig. 4 - Cases of study

5. Soil modeling.

5.1 Soil profiles

In this study three different profiles of soil with thickness of 30m are used as soil deposits above bedrock layer. Soil profiles are defined as Hard, Medium and Soft, and each profile consists of four different layers of slightly different characteristics and thicknesses, Table 4 contains the properties of each profile and its layers. Soil profiles are chosen following the limits stated in Eurocode 8 (Section 3.1). Bedrock is assumed to have infinite thickness under the test soil profiles with the same input values for all cases, it is considered rigid with a very stiff properties ($V_s > 800$ m/s) so that it can resemble the stiff nature in rock formation. Ground water level is assumed to be below 40m depth, and its effect is out of scope of this study.

The primary shear modulus of the soil (G_0) is calculated using Eq. (1) depending on the shear wave velocity (V_s), the acceleration of gravity (g) and unit weight (γ) of each layer in each profile. More accurate values for shear modulus (G) and damping ratios (δ) are then determined by iterations using equivalent linear method.

$$G_0 = \frac{\gamma {V_s}^2}{g} \tag{1}$$

Table 4 - Soil properties for different soil deposits

Soil Medium	**Layer Number**	**Thickness (H) (m)**	**Unit Weight (ɣ) (t/m^3)**	**Shear Velocity (V_s) (m/s)**	**P wave Velocity (V_p) (m/s)**	**Soil Layer Period (T) = $4H/V_s$ (Sec)**
Soft	1	3	1.6	100	190	0.12
	2	7	1.7	120	210	0.23
	3	6	1.75	130	250	0.18
	4	14	1.8	170	320	0.33
Medium	1	3	1.6	170	320	0.07
	2	7	1.7	220	420	0.13
	3	6	1.75	260	490	0.09
	4	14	1.8	350	660	0.16
Hard	1	3	1.6	340	640	0.04
	2	7	1.7	430	810	0.07
	3	6	1.75	520	980	0.05
	4	14	1.8	700	1310	0.08
Bedrock	1	Infinite	2.36	1000	1880	-

5.2. Soil amplification model.

Equivalent linear ground response analysis is used to approximate the non-linear behavior of the soil by calculating the equivalent shear modulus and the equivalent damping ratio for soil utilizing iterative procedure.

For the purpose of wave amplification through propagation into the soil profiles, ProShake software [16] which is an equivalent linear analysis software to calculate the amplification of input earthquake wave is used. The programming tool uses the method proposed by Seed and Idris [11] to evaluate the seismic response of semi-infinite horizontal layers of soil deposits. They developed shear modulus reduction and damping curves for sandy soils, which is used in different formations in this study (Hard, Medium and Soft) as soil deposits.

Five sets of earthquake ground motion records were used as input motions for numerical study. All earthquakes are bedrock layer records and hence, these earthquakes were used as input motions at the bedrock level of soil profiles for further amplification due to different type of soil deposit. Table 5 lists the details of the earthquakes used for the study.

Table 5 - Earthquake ground motion records

	Earthquake	**Station**	**PGA (g)**	**Year**
1	Imperial Valley	EL Centro	0.344	1940
2	TAFT	Kern County	0.185	1952
3	Loma Prieta	Treasure island – Santa Cruz Mtns.	0.16	1989
4	Petrolia	Cape Mendocino - 1023	0.422	1992
5	Northridge	Topanga Fire Station	0.33	1994

Each earthquake wave was analyzed through the different soil profiles using ProShake software. Fig.6 shows the acceleration response spectra with 5% damping of the different earthquakes after amplification due to the different soil profiles in comparison with the original earthquake wave.

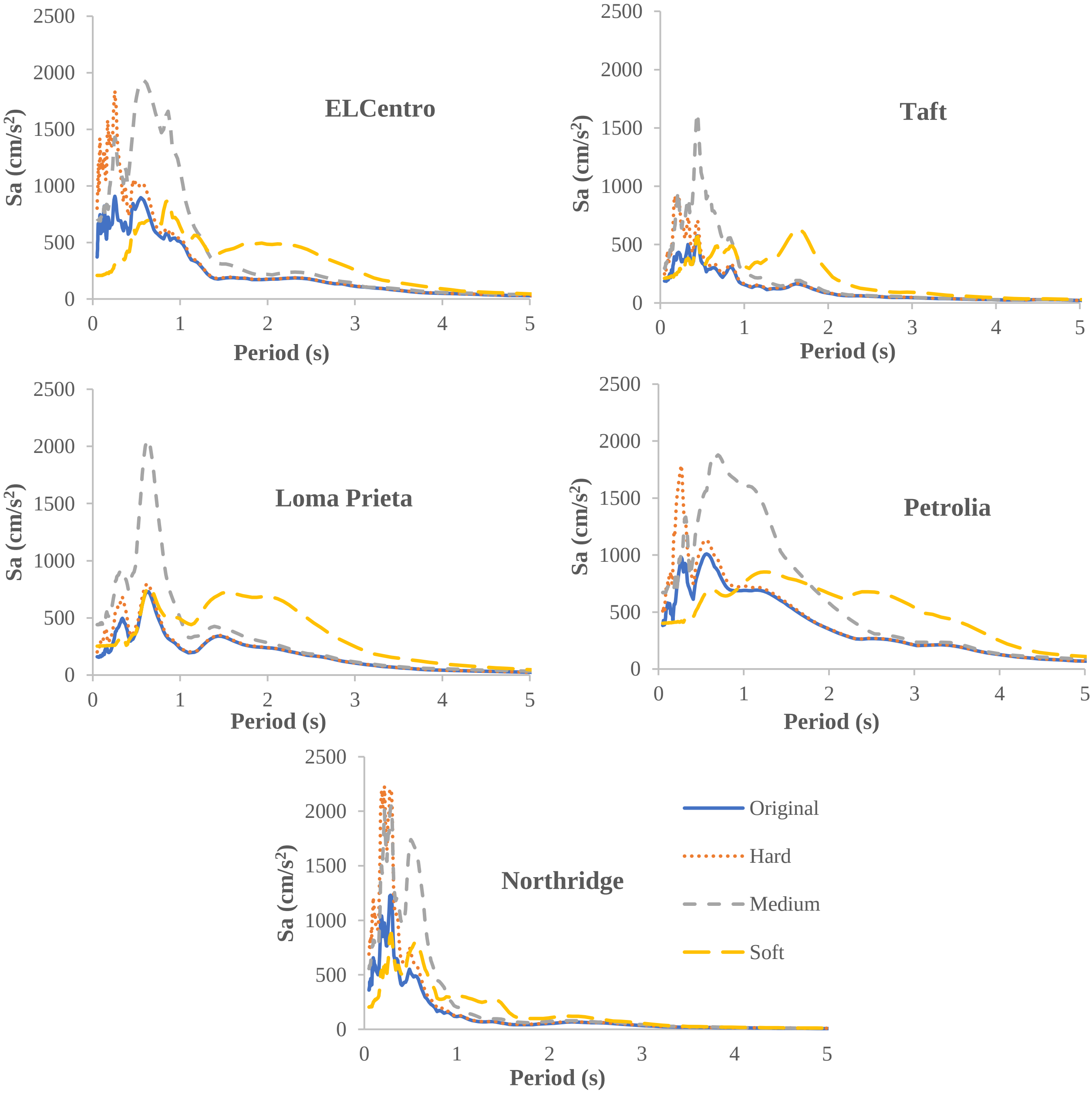

Fig. 6 – Acceleration response spectra of demand earthquakes after amplification (5% damping).

5.3. Soil structure interaction model

As shown in Fig.1, sway and rocking springs and dashpots are attached below the foundation to account for SSI. The rocking and sway stiffnesses mainly depend on the soil shear modulus *G*, size of foundation, and Poisson ratio *ν*. Eq. (2) to Eq. (5) are used to calculate the required parameters for the sway and rocking stiffness (K_H, K_R) and damping (C_H, C_R) used to account for SSI for a circular rigid foundation on semi-infinite uniform ground. An equivalent radius r_0 is calculated by Eq. (6) from the square shaped foundation in this study.

$$K_H = \frac{8Gr_0}{2-\nu} \qquad (2) \qquad , \qquad K_R = \frac{8Gr_0^3}{3(1-\nu)} \qquad (3)$$

$$C_H = A\rho V_s \qquad (4) \qquad , \qquad C_R = \frac{0.85r_0^4}{(1-\nu)}\rho V_s \qquad (5)$$

$$r_0 = 2\sqrt{\frac{bc}{\pi}} \qquad (6)$$

Where A is the area of foundation, ρ is the average density for soil layers, V_s is the average shear wave velocity, G is the shear modulus of the soil approximated from the primary shear modulus G_0, G/G_0 are chosen according to the type of deposit soil beneath the structure and it is taken equal to 0.9, 0.75, 0.5 for Hard, Medium, Soft respectively and ν is taken as 0.3 for all types of soil, b and c are half the dimensions of the rectangular footing, in this study a square footing shape was used (b=c).

For the stratified ground, the cone model proposed by Wolf [17] and simplified by Iiba et. al [18] neglecting the reflection and refraction coefficients at the boundary of the soil layer is used to obtain the stiffness and damping for the sway and rocking springs and dashpots. STERA 3D software [14] adopts this cone model to account SSI.

6. Numerical analysis

The purpose of this study is to test the influence of soil condition on the response of structures of different heights. In this study base isolated structures were tested and the results are discussed as follows:

6.1 Fundamental period

Table 6 shows the fundamental periods of the three models in different soil cases. Where, T_i is the fundamental period for fixed base structure, T_b is the fundamental period of seismically isolated structure with rigid soil, and T_{Hard}, T_{Medium}, T_{Soft} are the fundamental periods of seismically isolated structure with Hard, Medium and Soft soils respectively. The fundamental period of seismically isolated structure T_b is calculated from the effective stiffness K_{eff} for LRB at the design displacement and mass M of superstructure which is represented in the following equation Eq. (7).

$$T_b = 2\pi\sqrt{\frac{M}{K_{eff}}} \qquad (7)$$

Concerning soft soil which causes the largest lengthening in the fundamental period, in the 15 storeys model the fundamental period after considering the SSI has about 27% increase, while for the 5 storeys, the fundamental period has increased by almost 10%. It was observed that as the structure becomes taller the change in the period is higher.

Table 6 - Fundamental period values (sec)

Building	**T_i**	**T_b**	**T_{Hard}**	**T_{Medium}**	**T_{Soft}**	**$((T_{Soft}-T_b)/T_b)$**
5 Storeys	0.7	1.1	1.15	1.16	1.25	**9.65%**
10 Storeys	0.9	1.38	1.41	1.43	1.66	**20.73%**
15 Storeys	1.1	1.58	1.65	1.69	2	**26.98%**

6.2 Displacement and shear at each story

The responses of the three seismically isolated LMMs (5, 10 and 15 storeys) were analyzed and concluded for the three different cases, Case 1, Case 2 and Case 3, as explained in Section 5. The average of responses of the target buildings for the five earthquakes mentioned in Section 6 are presented and discussed below.

6.2.1 Results for 5 storeys

Fig.7 and Fig.8 present the response displacements and shear forces at each floor due to the different cases. In case of soft soils, the increase in displacements and shear forces at the isolation level (between Case 2 and Case 3) as a result of earthquake wave amplification reaches 149% and 93% respectively. In case of medium soil, the difference in displacements and shear forces reaches 33% and 21% respectively. In case of hard soil, the change in responses whether shear force or displacement is approximately zero which means that it is almost identical to the results where no amplification and no SSI are considered (Case 3). Consideration of SSI for the 5 storeys model has more distinct effect in case of soft soil than medium or hard soil. In case of soft soil, it is observed that the displacement is relatively reduced to around 1.3% in Case 1 (Amplification + SSI) from Case 2 (Amplification + No SSI), however in case of medium and hard soils, it is almost identical (less than 0.5% difference) among Case 1, 2 and 3.

6.2.2 Results for 10 storeys

Fig.9 and Fig.10 present the response displacements and shear forces at each floor of the structure. In case of hard soil, the displacements and shear forces in Case 2 are almost same as Case 3. In case of medium soil, the change in displacements and shear forces at the isolation level (between Case 2 and Case 3) due to earthquake wave amplification is almost 31% and 20% increase respectively. In case of soft soil, the increase in displacements and shear forces is observed to be approximately 104% and 68% respectively.

Effect of SSI can be more noticed in the 10 storeys model than in the 5 storeys model where the change in displacements at the isolation level (between Case 1 and Case 2) reaches 6% decrease in case of soft soil, whereas in case of medium and hard soils the decrease in displacement is very limited reaching about 1%. Moreover, SSI also resulted in a decrease in the shear force absorbed by the structure as shown in Fig.10. It shows that in case of soft soils the shear force in Case 1 is decreased by about 4.75% from the shear force in Case 2, however in case of medium soil the shear force is decrease by nearly 1.3%, and in case of hard soil it decreased by almost 0.6%.

6.2.3 Results for 15 storeys

Fig.11 and Fig.12 illustrate the response displacements and shear forces at each level of the structure. In case soft soil, the displacements and shear forces are increased by about 83% and 19% respectively at the isolation level (between Case 2 and Case 3) as a result of earthquake wave amplification. In case of medium and hard soil, the displacements and shear forces are approximately the same as the 10 storeys model.

The values obtained from Case 1 which includes the consideration of SSI are showing a great difference from Case 2 compared to the other 2 structures. The reduction in the displacements and shear forces at the isolation level for the 15 storeys model is the largest among the three structures and reaches its maximum in case of soft soil, where the change in the responses of displacements and shear forces (between Case 1 and Case 2) at the isolation level almost equals 8% and 6% decrease respectively, while in case of medium soil the change is approximately 1% for both shear force and displacement, and change in hard soil is hardly 2%. On the other hand, the displacement in the top floor in Case 1 is observed to be more than Case 2 unlike the situation at the isolation level. The increase in displacements in the top floor equals approximately 3% in case of medium soil and about 4% in case of soft soil, this pattern can be returned to higher aspect ratio of the 15 storeys, which results in a stronger rocking interaction, and this will provoke more questions about stability for overturning for taller structures.

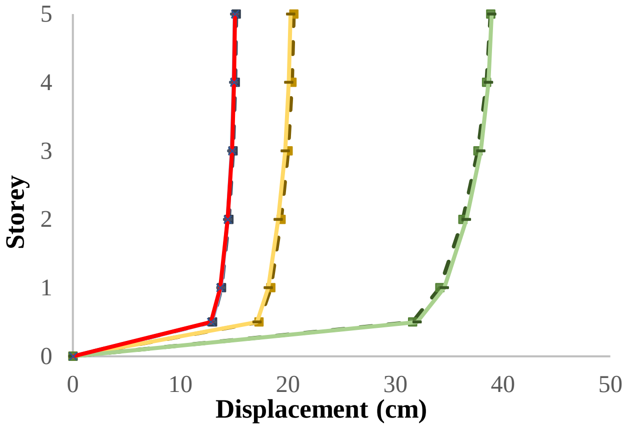

Fig. 7 - Displacements at each floor – 5 Storeys

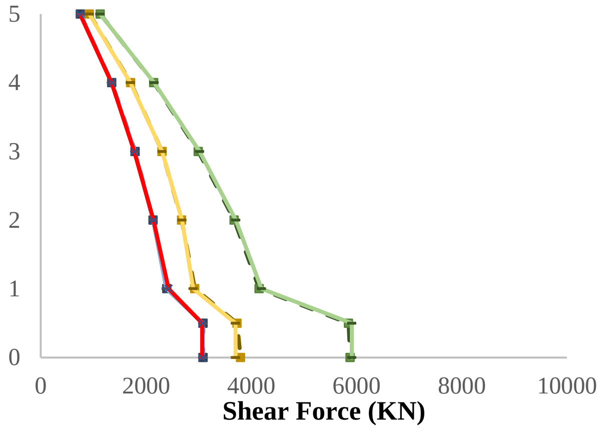

Fig. 8 - Shear Force at each floor – 5 Storeys

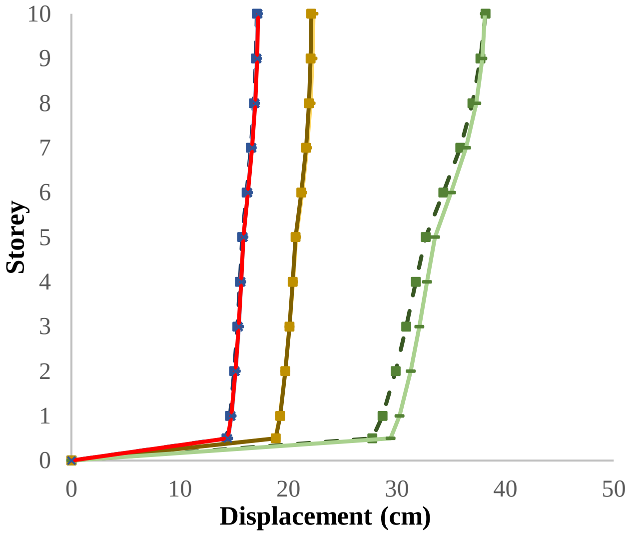

Fig. 9 - Displacements at each floor – 10 Storeys

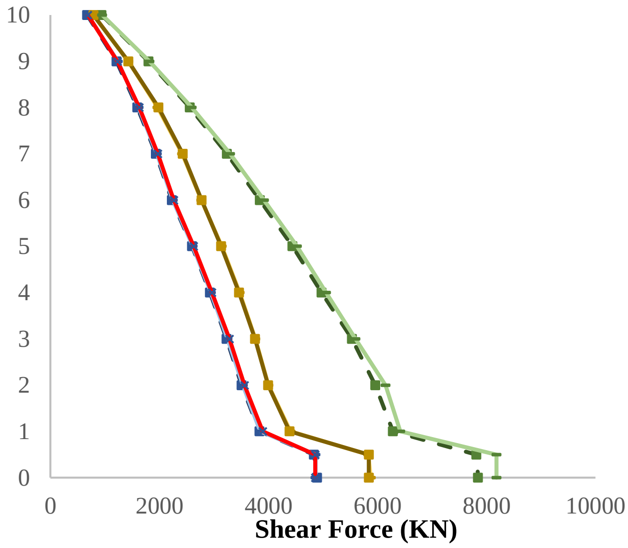

Fig. 10 - Shear Force at each floor – 10 Storeys

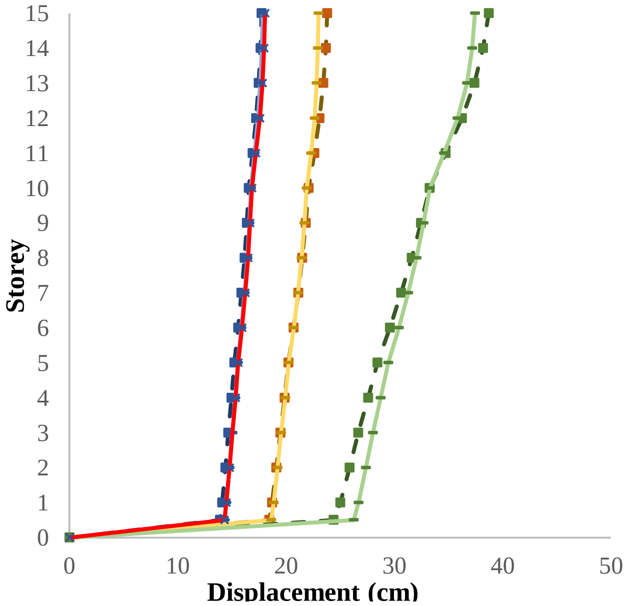

Fig. 11 - Displacements at each floor – 15 Storeys

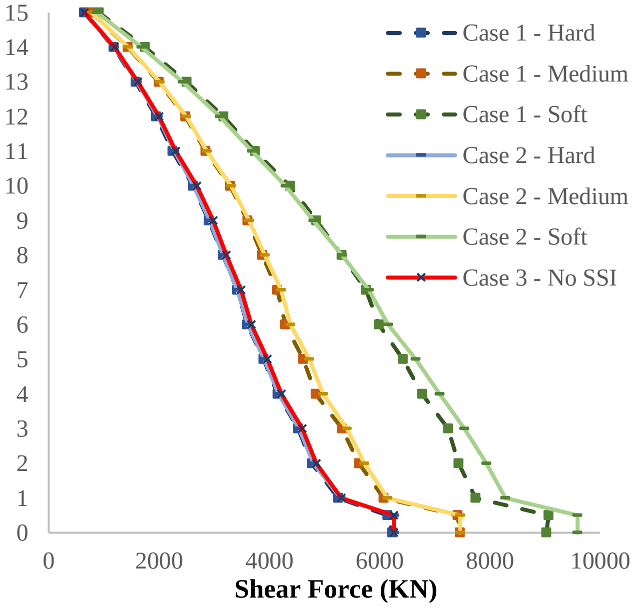

Fig. 12 - shear force at each floor – 15 Storeys

6.3 Sway and rocking effect

The responses of the structures can be divided into two parts; 1st part (illustrated in Fig.13) is related to the displacement resulting at isolation level and super structure, 2nd part (illustrated in Fig.14) is the responses of the seismically isolated buildings considering SSI which is represented by horizontal displacement (Sway) and rotational angle (Rocking). Table 7 lists the average of the maximum responses from the different cases of study for the three target structures. There is no large difference in sway displacement among the three structures, and the highest sway displacement is observed in case of soft soils. On the other hand, rocking displacement becomes more prominent in case of 15 storeys, these results confirm the previous discussion about the increase in displacements in the top floor of the 15 storeys model.

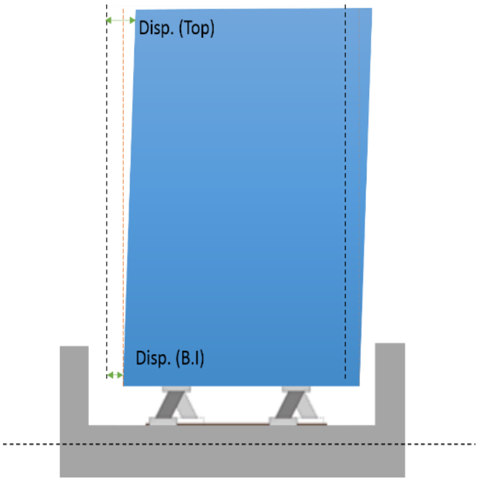

Fig. 13 Seismic isolation displacements

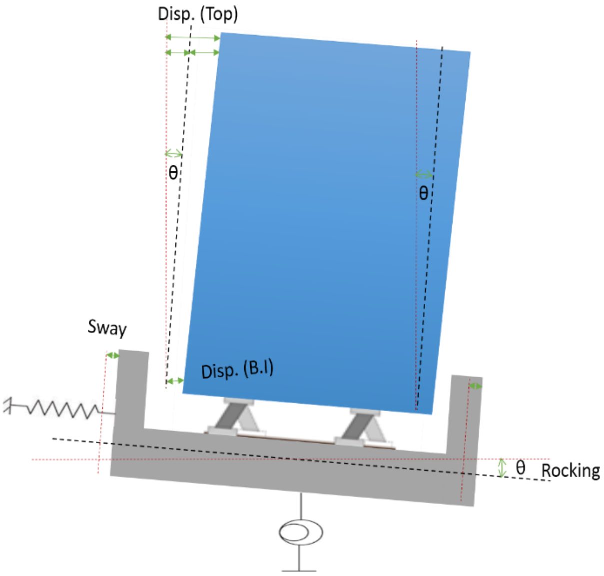

Fig. 14 Responses in the Sway-Rocking model

Table 7 – Sway and Rocking responses for different cases (cm, rad)

		5 Storeys			10 Storeys			15 Storeys		
		Hard	**Medium**	**Soft**	**Hard**	**Medium**	**Soft**	**Hard**	**Medium**	**Soft**
Case 1	**Disp. (B.I)**	12.98	17.32	31.61	14.29	18.81	27.74	13.90	18.45	24.38
	Disp. (Top)	15.20	20.55	38.86	17.09	22.32	38.19	17.75	23.8	38.72
	Sway ($x10^{-2}$)	0.02	0.13	1.18	0.04	0.19	1.48	0.04	0.23	1.22
	Rocking ($x10^{-4}$)	0.19	0.32	2.43	0.55	0.94	6.81	0.69	1.40	7.95
Case 2	**Disp. (B.I)**	12.93	17.13	32.02	14.44	18.85	29.41	14.33	18.63	26.27
	Disp. (Top)	15.06	20.25	38.96	17.18	22.13	38.12	17.85	23.0	37.44
Case 3	**Disp. (B.I)**	12.85			14.41			14.32		
	Disp. (Top)	18.07			17.21			15.09		

7. Conclusions

To examine the effect of Soil Structure Interaction (SSI) on the response of seismically isolated structures, three different cases of different combinations as mentioned in Section 5 (Case 1, Case 2 and Case 3) were studied. SSI is considered using sway and rocking springs and dashpots which are adopted in STERA 3D software. Three structures of different heights (5,10 and 15 storeys) built on three types of soils (Hard, Medium and Soft) are simulated to test their behavior using time-history analysis while utilizing amplified earthquake waves as input ground motions according to the type of soil deposit. The amplification of the earthquakes in the soil is analyzed using ProShake software.

The averages of the resulting responses from the five input earthquakes were discussed. The fundamental period for each structure on each type of soil was calculated. Displacements and shear forces for each floor and the responses at the isolation level were evaluated. The following are main conclusions achieved in this study:

I. Soil amplification of input earthquake has a great effect in increasing the response of the structure, especially in case of soft soils, while almost no effect in case of hard soils.

II. Low rise structures have the highest difference in responses as a result of earthquake wave amplification, it can be explained from the acceleration response spectrum presented in Fig.6.

III. SSI reduces the responses of the structures where it reduces the base displacements and shear forces in all models, especially in case of soft soil.

IV. High rise structures have the highest difference in response when SSI is included in the analysis, while low rise structures have a limited difference in response.

V. Soft soils have the largest sway interaction, but there is no large difference among three structures.

VI. Rocking interaction doesn’t have much effect in low-rise structures; however, it has a very apparent effect in high-rise structures, and it causes an increase in the top displacement.

8. References

[1] Eurocode 8 (1996): *Design provisions for earthquake resistance of structures*. London. British Standards Institution.

[2] Naeim F, Kelly JM. (1999): *Design of seismic isolated structures: from theory to practice*. John Wiley & Sons.

[3] Skinner RI, Robinson WH, McVerry GH (1993): *An introduction to seismic isolation*. John Wiley & Sons.

[4] Anand V, Kumar SS (2018): Seismic soil-structure interaction: a state-of-the-art review. *Structures*, Vol. 16, Elsevier, 317-326.

[5] Meek JW, Wolf JP (1992): Cone models for homogeneous soil. I. *Journal of geotechnical engineering*, 118 (5), 667-685.

[6] Wolf JP (1997): Spring-dashpot-mass models for foundation vibrations. *Earthquake engineering & structural dynamics*, 26 (9), 931-949.

[7] Lu Y, Marshall AM, Hajirasouliha I (2016): A simplified Nonlinear Sway-Rocking model for evaluation of seismic response of structures on shallow foundations." *Soil Dynamics and Earthquake Engineering*, 81, 14-26.

[8] Constantinou MC, Kneifati MC (1988): Dynamics of soil-base-isolated-structure systems. *Journal of Structural Engineering*, 114 (1), 211-221.

[9] Spyrakos CC, Maniatakis Ch A, Koutromanos IA. (2009): Soil–structure interaction effects on base-isolated buildings founded on soil stratum. *Engineering Structures*, 31 (3), 729-737.

[10] Karabork T, Deneme IO, Bilgehan RP (2014): A comparison of the effect of SSI on base isolation systems and fixed-base structures for soft soil. *Geomechanics and Engineering*, 7(1), 87-103.

[11] Idriss IM, Seed HB (1968): Seismic response of horizontal soil layers. *Am Soc Civil Engr J Soil Mech*.

[12] Dhakal RP, Lin SL, Loye AK, Evans SJ (2013): Seismic design spectra for different soil classes. *Bulletin of the New Zealand Society for Earthquake Engineering*, 46(2), 79-87.

[13] Sargın S, Gazi H, Alhan C, Oztoprak S (2017): Effect of Soil Amplification on the Response of Base-Isolated Buildings under Near-Fault Earthquakes. *Proceedings of the 2nd World Congress on Civil, Structural, and Environmental Engineering CSEE’17, Barcelona, Spain*

[14] Saito T. STERA 3D V10.3; Technical manual Ver 6.3, http://www.rc.ace.tut.ac.jp/saito/index-e.html

[15] Bridgestone Corporation (2017), *Seismic isolation product line-up, version 2017 vol.1*, Tokyo, Japan, https://www.bridgestone.com/products/diversified/antiseismic_rubber/index.html

[16] ProShake; ground response analysis program Version 2.0, http://www.proshake.com/index.html

[17] Wolf JP. (1994): Foundation vibration analysis using simple physical models. *Pearson Education*.

[18] Iiba M, Miura K, Koyamada K (2000): Simplified Method for Static Soil Stiffness of Surface Foundation. *Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan*.