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The Structure-Soil-Structure Interaction Effects on the Response of the Neighbouring Frame Structures

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Abstract

The Structure-Soil-Structure Interaction (SSSI) phenomenon between the neighbouring structures has been interested lesser than Soil-Structure Interaction. However, in urban environments, the structures have to be constructed in the neighbourhood, and it is inevitable that these structures affect each other's responses. This study examines the Structure-Soil-Structure Interaction effects on the response of the neighbouring frame structures. In this context, firstly the effects of the consideration of the underlying soil on the response of the structures (3-, 6-and 12-storey) are compared with the fixed base conditions. Subsequently, the variation in the acceleration and basement storey drift ratios of the structures are examined to determine the effects of the presence of the neighbouring different structures. The clear distances between the structures, structure storey numbers, soil stiffness, seismic motion and layout of the structures are the parameters taken into account. Finite element method is utilised to analyse the soil and the structures subjected to seismic excitation with direct method. It is concluded that the consideration of the neighbouring structures could positively or negatively change the responses of the structures based on the dynamic characteristics of the case.

Keywords

Dynamic Analysis; Soil-Structure Interaction; Structure-Soil-Structure Interaction; Seismic Response; Finite Element Method

1 INTRODUCTION

In crowded city-like environments, structures have to be constructed in the neighbourhood. Generally, only the concerned structure is taken into account when they are designed. In some cases, especially when the underlying soil does not meet the required conditions, the effect of it on the structure is taken into account. The effects of the underlying soil on the response of the structures is known as Soil-Structure Interaction (SSI). Detailed information about SSI can be obtained in Kausel (2010). However, if there are other structures located in the neighbourhood of the considered structure, the response of the structures change because of the scattered waves from each structure. This circumstance is known as Structure-Soil-Structure Interaction (SSSI).

The first known studies about the SSSI are performed by Warburton et al. (1971), Lee and Wesley (1973), and Luco and Contesse (1973), which are followed by Wong and Trifunac (1975). Although the idealised systems are investigated with simple approaches, they draw attention to the importance of the interaction between the neighbouring structures particularly in the range of low frequencies. After these pioneering studies, many researchers have tackled the SSSI phenomenon considering varied systems by diverse approaches.

Lin et al. (1987), Qian and Beskos (1996), Andersen (2018), and Wang and Zhou (2018) investigated the dynamic interaction between the neighbouring foundations. Besides, because of any kind of variation which is important for the

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nuclear structures, Imamura et al. (1992); Xu et al. (2004); Anderson et al. (2011); Roy et al. (2013); Yue et al. (2013); Ghiocel et al. (2014) examined the effects of the nearby structures for nuclear structures. Several researchers (Betti, 1997; Yahyai et al., 2008; Padron et al., 2009; Naserkhaki and Pourmohammad, 2012; Trombetta et al., 2012; Nateghi and Tabrizi, 2013; Alam and Kim, 2014; Knappett et al., 2015; Aldaikh et al., 2016; Ghandil et al., 2016; Kirkwood and Dashti, 2018; Bybordiani and Arici, 2019; Ngo et al., 2019) have investigated the effects of the nearby structures on the response of the varied structures for various cases.

Most of the studies in the literature state that the neighbourhood of structures can significantly change the response of the structures, however, these studies do not clearly indicate in which circumstance the SSSI effect should be considered. Several researchers (Imamura et al., 1992; Xu et al., 2004; Yahyai et al., 2008; Anderson et al., 2011; Ghiocel et al., 2014; Bybordiani and Arici 2019) state the negative effects of the SSSI effects, however some other researchers (Naserkhaki and Pourmohammad, 2012; Roy et al., 2013; Kirkwood and Dashti, 2018) indicate the positive effects of the SSSI on the response of the structures. But, several researchers (Padron et al., 2009; Trombetta et al., 2012; Nateghi and Tabrizi, 2013; Aldaikh et al., 2016; Wang and Zhou, 2018; Ngo et al., 2019) remark that SSSI effect can increase or decrease the response of the structures depending on the considered circumstances.

As seen from the above-mentioned studies, the SSSI effects can be important for the behaviour of structures. In the literature, the SSSI effects are generally considered with idealised systems in 2D. By using 3D structural models, the effects of SSSI on the response of the neighbouring structures are investigated for a few cases. In addition to these all, there is a substantial discrepancy between the outcomes of the studies in the literature. Therefore, in this study, the widespread frame structures are considered and the effects of the storey numbers, clear distances between the structures, the stiffness of the soil, seismic excitation, and the layout of the structures on the response of the structures are extensively examined to assess their significance. In order to evaluate the effect of the neighbouring structures on the response of the structures, the variations in the relative acceleration and the basement storey drift ratios of structures are taken into account, and the assessment of the calculated effects are compared with the case of standalone structures.

2 STATEMENT OF THE PROBLEM

The configurations of standalone or two neighbouring frame structures with shallow mat foundation resting on an elastic underlying soil medium are studied. Three different structures (3-, 6- and 12-storey) are considered, and the cases are comprised of the varied combination of these structures. The heights of these structures are 9.5m, 18.5m and 36.5m for 3-, 6- and 12-storey structures, respectively. The plans are the same for all buildings, and the plan size is 16m by 16m. The plans are equally spaced with four axes in each lateral directions. The sizes of the structural elements are assigned based on the studies about the structure stock of Turkey (Bal et al., 2008; Ozmen et al., 2015). The dimensions of the structural elements are presented in Table 1. The concrete grade is assumed as C25, and the live load is used to be 2kN/m^2 (ASCE, 2017).

The underlying soil medium is assumed as soft and stiff clays with shear wave velocities of 150m/s and 300m/s, respectively. The site classes are D and E according to ASCE (2017). Thereafter, the soil is named as soil type 1 for the soft clay soil and soil type 2 for the stiff clay soil. The Poisson ratios of both soil types are assigned to be 0.35 which is suitable with the clay soils (Das 2007), and the unit weight of the soil is assigned as 1800 kN/m^3. The thickness of the soil is considered as 48m. The soil is modelled as an elastic half-space on a rigid bedrock, and the level of groundwater is assumed to be below the level of the bedrock.

One of the investigated parameter in this study is the layout of the structures. Two different layout configurations are taken into account: In layout-1, the structures are aligned in the same line (Figure 1(a)), in layout-2, the structures are unaligned (Figure 1(b)). In the figures, “d” stands for the clear distances between the structures. In this study, the

Table 1 The characteristic properties of the structures.

Element	Dimension
Foundation Size (m/m)	16 / 16
Foundation Thickness (m)	0.5
Ground Floor Height (m)	3.5
The Other Floor Height (m)	3
Column Cross-Section Dimensions (cm/cm)	50/50
Beam Cross-Section Dimensions (cm/cm)	30/60
Slab Thickness (cm)	15

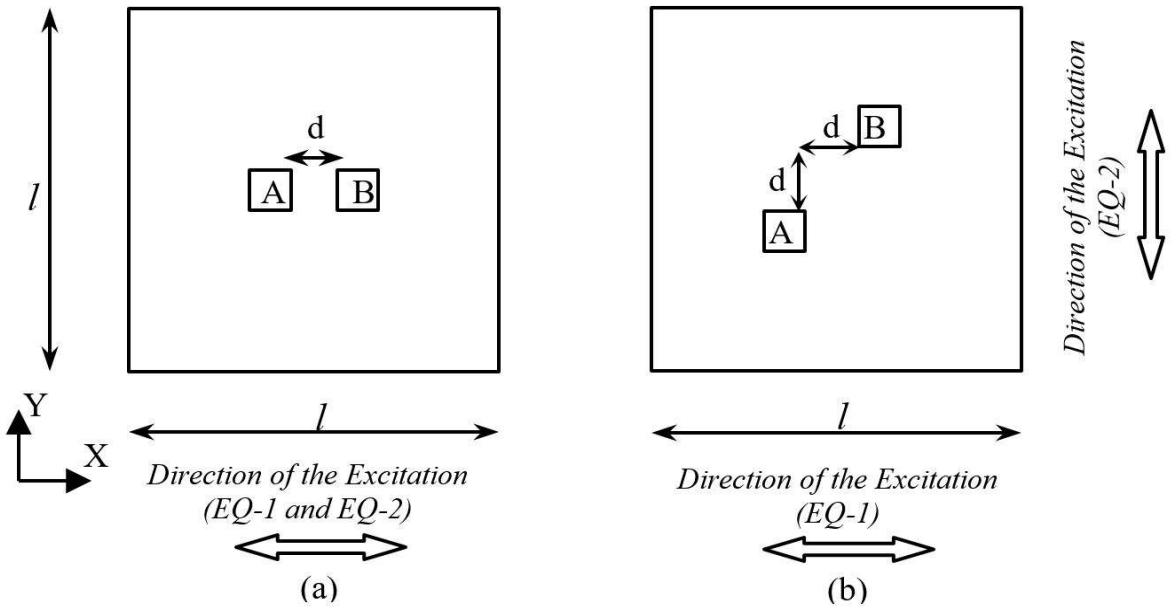

Figure 1 The plan view of (a) layout 1 and (b) layout 2.

considered clear distances are 2m, 4m, 8m, 16m, 32m and 48m. Layout 1 is analysed for one-directional earthquake excitation, and layout 2 is analysed for two-directional earthquake excitation.

3 FINITE ELEMENT MODEL

A series of dynamic analyses are achieved by the finite element analysis software ANSYS (2017). The direct approach which enables the solving of the structures and the soil in a single step is employed.

3.1 Modelling of the Structures

Three different moment-resisting frame structures are considered for the purpose of this study. The columns and beams of the structures are modelled with BEAM188 element, the slabs are modelled with SHELL181 element (ANSYS, 2017). As the linear material properties are used, the effective stiffness coefficient of ACI 318-14 (ACI, 2014) is used for bending elements to take into account the cracked sections. Because of the usage of BEAM188 element to model the structures, the stiffness of the element parts which remain in the rigid zones is increased by increasing the elasticity modulus.

A series of convergence analyses are performed to determine the optimum element size of the structures. The optimum element size is obtained as 0.40m for slabs and beams and 0.20m for the columns. Three-dimensional view of the model and the meshed 3- and 6- storey structures are given in Figure 2.

The structural elements are idealised as the linear-elastic materials with Rayleigh damping. The damping ratio of structures is assumed to be 0.05 (Ghazvini et al., 2013; Wang et al., 2013; Elias and Matsagar, 2017). Rayleigh damping is a linear combination of the mass and stiffness matrices, and it can be calculated by the following equation,

$$\left[C\right] = \alpha\left[M\right] + \beta\left[K\right] \tag{1}$$

where C, M, and K are the damping, mass and stiffness matrices of the system, respectively. “α” and “β” are the damping coefficients with units s^{-1} and s, respectively. If the damping coefficients are not known, assuming the ith and j^{th} modes have the same damping ratio (ξ), the coefficient can be calculated by the following equation,

$$\begin{Bmatrix}\alpha\\ \beta\end{Bmatrix} = \frac{2\xi}{\omega_i + \omega_j}\begin{Bmatrix}\omega_i\omega_j\\ 1\end{Bmatrix} \tag{2}$$

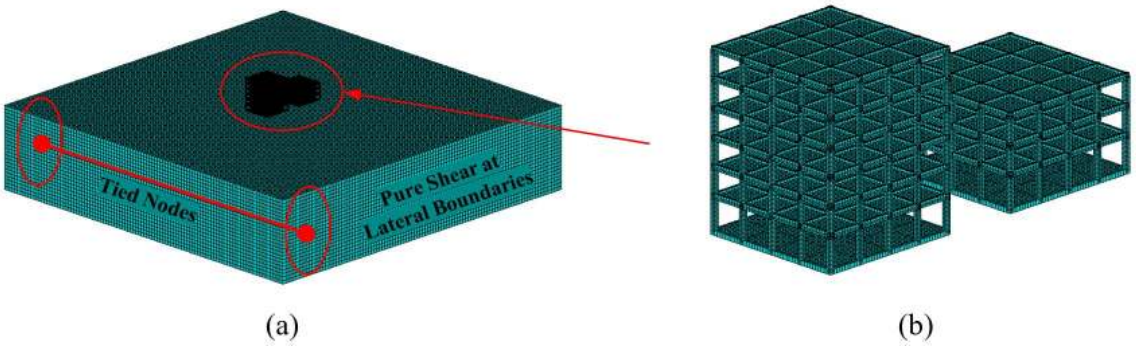

Figure 2 (a) Three-dimensional view of the model (b) the meshed models of 3- and 6-storey structures.

where ω_i and ω_j are the angular frequencies of the ith and j^{th} modes, respectively. As a result of the formulation of Rayleigh damping, the total damping is less than the assigned damping for the frequencies between ω_i and ω_j. Correspondingly the total damping is higher than the assigned damping for the frequencies other than the assigned frequencies. Because of the significant effect of the assigned frequencies on the damping ratio, the damping properties are assigned separately for each structures. The first mode frequency and the frequency that ensures 90% mass participation are considered as the angular frequency to define the Rayleigh damping coefficients of the structures.

3.2 Modelling of Soil Medium

The soil medium is modelled with SOLID185 elements (ANSYS, 2017). If the soil is modelled with finite elements, some conditions, which are the propagation of the seismic waves and the free-field behaviour at the lateral truncated boundaries of the soil medium, have to be satisfied. The first condition can be satisfied by controlling the finite element size of the soil medium. The required finite element size (Δh) to propagate the waves with a maximum frequency depending on the shear wave velocity of the soil can be calculated by the following equation:

$$\Delta h = \frac{\lambda}{n} = \frac{V_S}{n f_{\max}} \tag{3}$$

where λ is the wavelength, V_S is the shear wave velocity of the soil, f_{max} is the maximum frequency that is desired to propagate, and n is the desired number of the elements per wavelength. The desired number of elements per wavelength (n) can be chosen between 5 and 8, which usually provide satisfactory results (Livaoglu, 2014). The inadequacy of the finite element size can cause numerical damping. As the consideration of the waves less than 10Hz is sufficient for seismic analyses (Jeremic et al., 2009) and the seismic waves above 10-15Hz have a relatively small amount of the energy (Schnabel et al., 1972), the finite element size of the soil domain is assigned as 2m. The numerical validation of the assigned finite element size is also performed in ANSYS for soil type 1. The soil models which are meshed with different finite element size (1m, 2m, 4m and 8m) are subjected to sine-sweep waves. In Figure 3, the comparison of the Fourier amplitudes of 16m and 24m away from the top-center of the soil domain is presented for each model. The Fourier amplitudes are close to each other at the range of low-frequency, but some dissimilarity is observed in the high-frequency range. This result indicates the validity of the used finite element size.

The second requirement, which is ensuring the free-field motion at the laterals boundaries, can be ensured by the sufficiently large soil medium and assigning the appropriate boundary conditions. The size of the soil domain is determined by trial-error analyses and it is obtained as 208m by 208m. The free-field is ensured by introducing the kinematic constraints for the lateral truncated boundaries (see Figure 2(a)). The base boundary of the soil is assumed to be rigid bedrock, therefore the earthquake loading could be directly implemented at the base of the soil profile in terms of displacement time history (Bolisetti and Whittaker, 2015).

The soil damping ratio is assumed as 0.05 for both of the soil types and it is employed as Rayleigh type (Wang et al., 2013; Tamayo and Awruch, 2016; Amorosi et al., 2017). The fundamental frequency and the odd integer multiplier of the fundamental frequency are used in the calculation of Rayleigh coefficients for the soil medium. The odd integer is calculated by rounding up the ratio of the dominant frequency of the input motion (the highest frequency value that has a substantial Fourier amplitude) to the fundamental frequency of the soil.

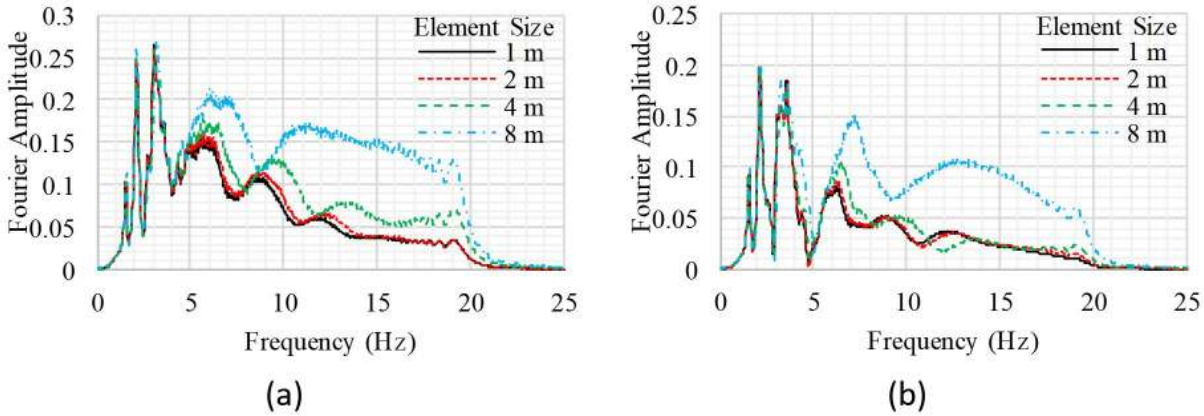

Figure 3 Comparison of the Fourier amplitudes for the nodes which are (a) 16 m and (b) 24 m away from the top center of the models which are meshed with several finite element sizes.

3.3 The Seismic Motion

In this study, two artificial earthquakes are produced based on the design response spectrum of Turkish Building Earthquake Specification (TBES) (DEM, 2018). The design response spectrum is produced using the following considerations: the location is assigned to be close to the city centre of 1999 Kocaeli Earthquake M_w=7.4, local site class is assumed as D, the return period is 475 years. The artificial earthquakes are produced via SeismoSignal (Seismosoft, 2016) for the moment magnitude and Joyner-Boore distance is M_w=7.2 and 12km, respectively. The peak ground acceleration (PGA) values of the earthquakes are 0.66g and 0.77g. Thereafter, the earthquakes are named according to their PGA values as Earthquake-1 for the earthquake with PGA of 0.66g and Earthquake-2 for the earthquake with PGA of 0.77g. The acceleration time history and the comparisons of the response spectrum of the earthquakes with the target spectrum are presented in Figure 4.

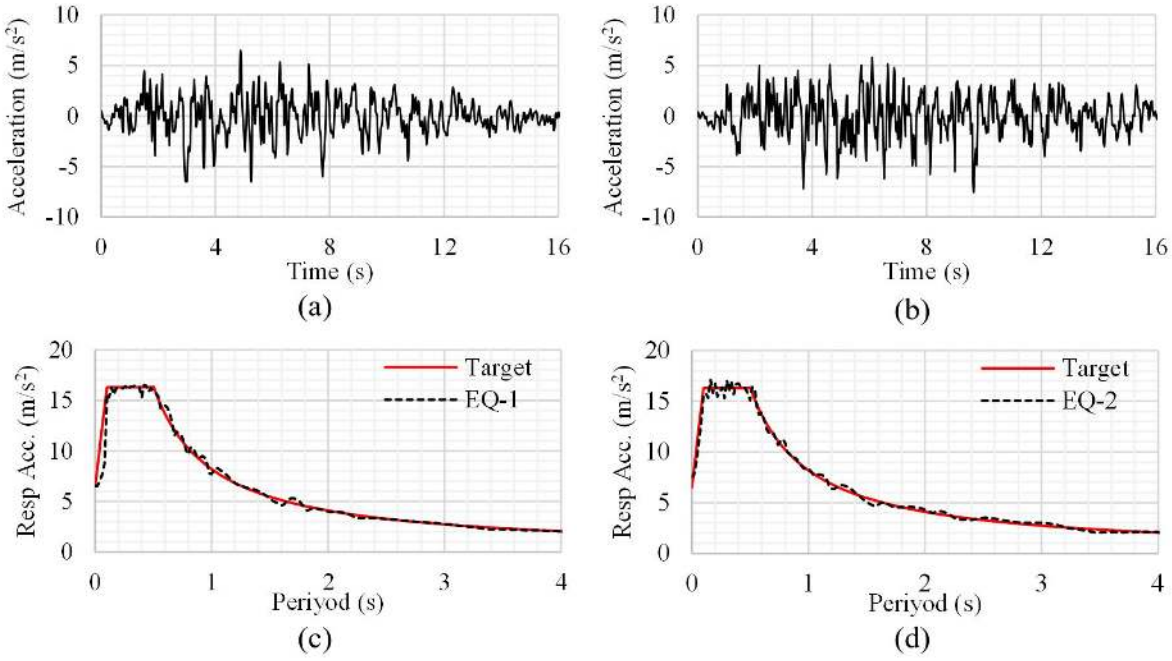

Figure 4 Time history of the (a) Earthquake-1 and (b) Earthquake-2, and the comparison of the target spectrum with the response spectrum of (c) Earthquake-1 and (d) Earthquake-2.

It is assumed that artificial earthquakes are obtained at the ground surface. Therefore, the earthquake is transferred to the bedrock level with the deconvolution procedures for soil type 2. Thus, the same bedrock motion is applied to the models, this application makes the possibility of the investigation of the soil type on the SSSI effects. Besides the earthquake loading, another load on the model is gravity. The gravity loading applied at the initial part of the dynamic loading as linearly increasing form.

4 THE EFFECTS OF THE SOIL-STRUCTURE INTERACTION

A set of analyses are performed to obtain the effects of the underlying soil on the response of the structures. For this purpose, the responses of the fixed base (FB) structures are compared with the responses of the structures considering the Soil-Structure Interaction effects. Firstly, the modal analysis is performed to obtain the variation in the frequencies of the structures with the consideration of the underlying soil. Thereafter, dynamic analyses are performed to obtain the variation in the response of the structures.

The effects of SSI on the periods of the structures are investigated by evaluating the variation in the first five modes of the structures. The results of modal analyses for the FB structures and the SSI cases for both of the soil types are presented in Table 2. As seen from Table 2, the consideration of the underlying soil enhances the flexibility of the structures which results in the increase in periods. This variation is more in the lower modes. Also, the stiffness of the structure has an importance in the level of the variation: the 3-storey structure, which is the stiffest structure, is the most affected from the consideration of the underlying soil. The stiffness of the underlying soil has an important role in the response of the structures: the lengthening in the fundamental periods of the structures located on soil type 1 is 9.7%, 4.6% and 2.1% for 3-, 6- and 12-storey structures, respectively. The increases in the fundamental periods of the structures for soil type 2 are 2.3%, 1.1% and 0.6%, in the same order. Since the third mode is torsional mode, there no variation

Table 2 The modal analysis results of the structures.

Soil Type	Base Cond.	Storey Number	Mode 1 (s)	Mode 2 (s)	Mode 3 (s)	Mode 4 (s)	Mode 5 (s)
1	SSI	3	0.314	0.314	0.256	0.107	0.107
	SSI	6	0.610	0.610	0.521	0.197	0.197
	SSI	12	1.238	1.239	1.057	0.405	0.405
2	SSI	3	0.293	0.293	0.256	0.088	0.088
	SSI	6	0.590	0.590	0.521	0.188	0.188
	SSI	12	1.220	1.220	1.058	0.397	0.397
N/A	Fixed	3	0.286	0.286	0.256	0.085	0.085
	Fixed	6	0.583	0.583	0.521	0.185	0.185
	Fixed	12	1.212	1.212	1.057	0.395	0.395

in the periods of the structures for this mode. The fundamental period of the soil mediums is 1.28 s and 0.64 s for the soil type 1 and 2, respectively.

The effects of SSI on the response of the structures are examined concerning the variation in acceleration, displacement, and the basement storey drift ratios. The structures with FB cases are analysed under the surface motion which is obtained by convolution of the bedrock motion to the ground surface. For the SSI cases, the bedrock motion is applied from the bottom of the soil as displacement time history. The results of the FB and SSI cases are presented in Table 3 and 4 for Earthquake-1 and Earthquake-2, respectively. Because of the effect of the soil type on the surface motion, the results in the tables are grouped based on the soil types.

The SSI effects are obvious for soil type 1 than the soil type 2. As the storey number of the structures decrease, the increase in the SSI effects is obtained. Because of the SSI effects, the acceleration response of the 3- and 6-storey structures attenuated significantly. The same kind of decrease is observed for the displacement and basement storey drift ratios of the structures but at a less level. The response of the 12-storey structure change in a small amount when the differences are compared with that of the other structures. It should be pointed out that, the fundamental period of the 12-storey structure is close to the fundamental period of the site for soil type 2. For this reason, the response of the 12-storey structure is exaggerated for the analyses of soil type 1. The same kind of amplification is observed for both of the FB and SSI cases. The form of the SSI effects is slightly different from that of other structures. The acceleration response, displacement response and basement storey drift ratios of the 12-storey structure increase for soil type 2.

When the basement storey drift ratios are compared, although there is significant variation in the acceleration response of the structures, the basement storey drifts ratios may not be affected that much. These results show the earthquake dependency of the storey drifts. In most cases, the variation of the structural responses is similar for Earthquake-1 and Earthquake-2. However, for a few cases, the response of the structures are slightly different, this may arise from the slight dissimilarities in the response spectrum of the earthquakes.

The comparison of the relative acceleration response of the FB and SSI cases for soil type-1 are presented in Figure 5. As seen from Figure 5, the consideration of the underlying soil changes not only the maximum acceleration of the structures but also all-time pattern of the responses. The differences are more obvious, especially for the lower storey structures.

Table 3 The response of the structures for FB and SSI cases for Earthquake-1.

Soil Type	Str. Base Condition	Storey Number	Maximum Acc. (m/s^2)	Var. of Max. Acc. (%)	Maximum Disp. (cm)	Var. of Max. Disp. (%)	B.S Drift Ratio (%)	Var. of B.S. Drift (%)
1	Fixed	3	25.42	--	7.07	--	0.83	--
	Fixed	6	19.23	--	12.66	--	0.73	--
	Fixed	12	60.35	--	169.32	--	5.03	--
	SSI	3	18.95	-25.42	6.80	-3.89	0.81	-3.03
	SSI	6	17.88	-7.01	11.71	-7.45	0.72	-1.23
	SSI	12	59.17	-1.96	175.61	3.71	4.97	-1.24
2	Fixed	3	25.54	--	4.29	--	0.47	--
	Fixed	6	24.87	--	16.38	--	1.01	--
	Fixed	12	17.52	--	29.91	--	1.01	--
	SSI	3	21.89	-14.28	4.03	-6.05	0.47	-1.01
	SSI	6	23.97	-3.59	16.58	1.21	1.02	1.19
	SSI	12	17.91	2.20	33.65	12.51	1.02	0.74

*Var.: Variation; B.S.: Basement storey; The "-" sign indicates the decrease in the response.

Table 4 The response of the structures for FB and SSI cases for Earthquake-2.

Soil Type	Str. Base Condition	Storey Number	Maximum Acc. (m/s^2)	Var. of Max. Acc. (%)	Maximum Disp. (cm)	Var. of Max. Disp. (%)	B.S. Drift Ratio (%)	Var. of B.S. Drift (%)
1	Fixed	3	25.52	--	7.60	--	0.98	--
	Fixed	6	18.20	--	11.88	--	0.84	--
	Fixed	12	56.38	--	173.36	--	5.32	--
	SSI	3	20.20	-20.86	6.15	-19.07	0.72	-25.96
	SSI	6	16.88	-7.28	11.87	-0.04	0.72	-13.55
	SSI	12	53.33	-5.41	166.38	-4.03	4.29	-19.37
2	Fixed	3	26.61	--	5.00	--	0.64	--
	Fixed	6	19.73	--	15.16	--	1.16	--
	Fixed	12	17.98	--	31.93	--	1.22	--
	SSI	3	27.52	3.40	4.50	-10.11	0.49	-23.21
	SSI	6	19.65	-0.37	14.61	-3.58	0.94	-18.85
	SSI	12	18.57	3.25	30.85	-3.37	1.04	-14.91

*Var.: Variation; B.S.: Basement storey; The "-" sign indicates the decrease in the response.

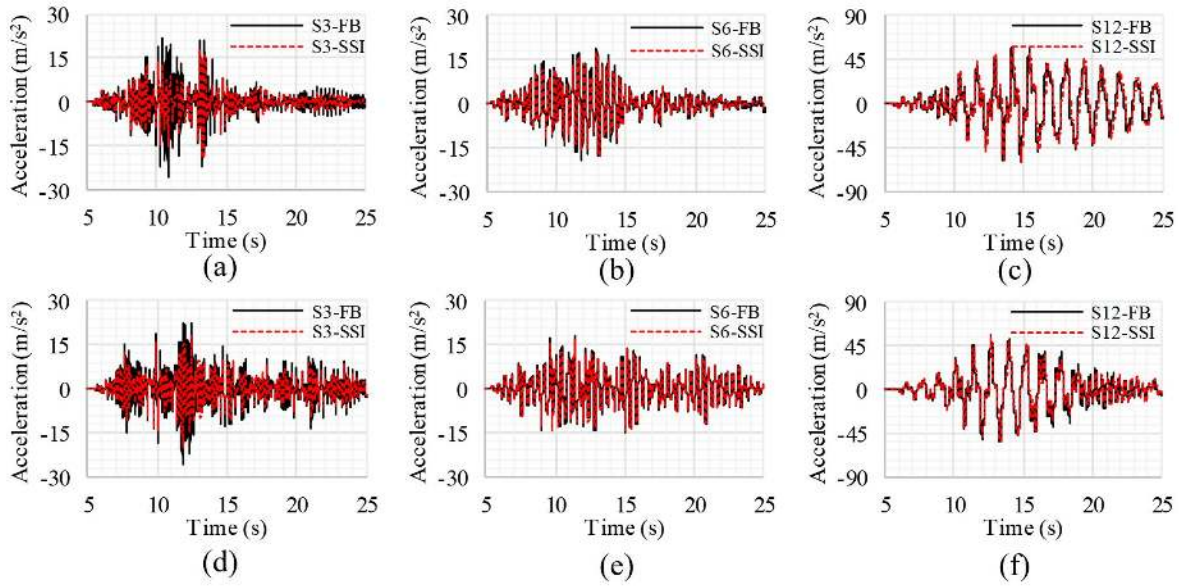

Figure 5 Acceleration response of (a) 3-storey, (b) 6-storey (c) 12-storey structure for Earthquake-1 and acceleration response of (d) 3-storey, (e) 6-storey (f) 12-storey structure for Earthquake-2.

5 THE EFFECTS OF STRUCTURE-SOIL-STRUCTURE INTERACTION

In order to evaluate the SSSI effects on the response of the structures, the response variation of the two neighbouring frame structures is examined for several cases. The investigated parameters are the structure type, the clear distance between the structures, the layout of the structures, the type of the underlying soil, and the seismic excitation. The response of the structures is evaluated considering the variation of relative acceleration and the basement storey drift ratio values of the neighbouring structures with respect to the cases of standalone structure (considering SSI effects). The analyses results are grouped based on the alignment of the structures.

5.1 The Case of the Aligned Structures

The cases in which the structures are aligned on the same lines are examined in this section. The cases are subjected to Earthquake-1 and Earthquake-2 separately to obtain the level of seismic motion dependency of the results.

The Effects of the SSSI on the Acceleration Response

The variation of the maximum acceleration values of structures in the neighbourhood of different structures under each earthquake for soil type 1 are presented in Figure 6. In this figure, the horizontal line demonstrates the reference case which indicates the response of the concerned structure.

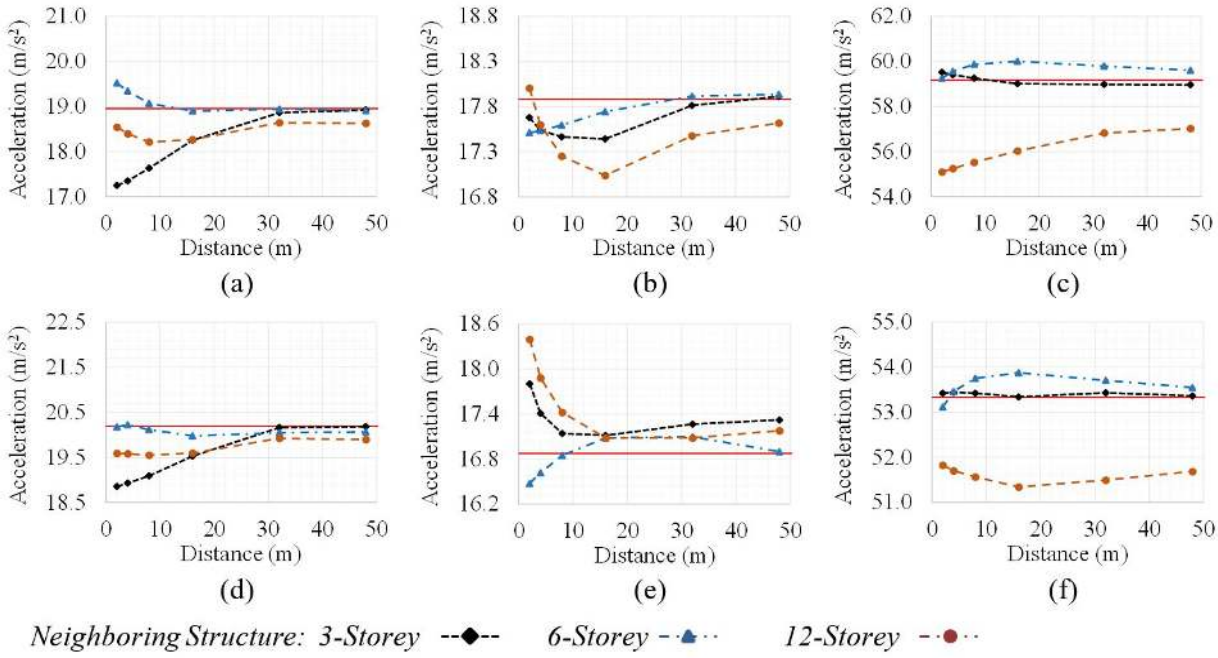

Figure 6 Variation of the peak acceleration of (a) 3-storey, (b) 6-storey (c) 12-storey structures in the neighbourhood of different structures subjected to Earthquake-1, and variation of the results of (d) 3-storey, (e) 6-storey and (f) 12-storey structures for the same cases subjected to Earthquake-2 for soil type 1.

As seen from Figure 6(a), the acceleration response of the 3-storey structure decreases if there is an identical structure in the neighbourhood and subjected to Earthquake-1. The maximum level of this reduction occurs when the neighbouring structure is 2m away, and the decrease is about 9%. If the neighbouring structure is 6-storey, the response of the 3-storey structure increases up to 3% for the cases of the close distances. However, if the neighbouring structure is 12-storey structure, the response of the 3-storey structures decreases by about 4%. Similarly, the response variation of the 3-storey structure in the neighbourhood of varied structures under Earthquake-2 is almost similar to the responses of Earthquake-1 (Figure 6(d)).

As seen from Figure 6(b), when the 6-storey structure is subjected to Earthquake-1 and it is in the neighbourhood of varied structures, the peak variation in the acceleration response of the structure due to the SSSI effects are observed for the distance of 16m. The maximum level of variation is about 5%. Under Earthquake-2, the response of the 6-storey structure is different than Earthquake-1 (Figure 6(e)). In this case, the response of 6-storey structure tends to increase when there is an identical or 12-storey structure in the neighbourhood. The level of this increase is about 9%. The effects of neighbouring 3-storey structure on the response of 6-storey structure changes depending on the clear distance.

As seen from Figure 6(c) and 6(f), when the 12-storey structure is subjected to Earthquake-1 or Earthquake-2, the acceleration response of the 12-storey structure is not significantly affected from the presence of lower storey structure in the neighbourhood. However, when the neighbouring structure is identical, the response of the 12-storey structure decreases almost 7%, and this effect remains almost constant for the examined distances. The reason for these results is the resonance state of the 12-storey structure, when it is located on the soil type 1.

The variation of the maximum acceleration values of structures in the neighbourhood of different structures under each earthquake for soil type 2 is presented in Figure 7.

As seen from Figure 7(a), the acceleration response of the 3-storey structure decreases if it is in the neighbourhood of an identical structure for the distances less than 16m. If the distance is more than 16m, the response of the structure increases about 2%. If the neighbouring structure is 6-storey structure, the response of the 3-storey structure decreases 2%, and this effect is almost constant for the examined distances. If the neighbouring structure is 12-storey structure, the response of the 3-storey structures increase slightly for the close distances, then it follows the same trend as in the neighbouring of the 6-storey structure. For Earthquake-2, the response of the 3-storey structure decreases about 6% for close distances but this effect decreases with the increase in the clear distances. The neighbouring 6- or 12-storey structure does not significantly change the response of the 3-storey structure (Figure 7(d)).

As seen from Figure 7(b), if there is an identical structure in the neighbourhood of 6-storey structure, the response of the structure decreases by about 2%. The most favourable distance for this case is 16m. However, if there is a 3-storey

structure in the neighbourhood of 6-storey structure, the response of the 6-storey structure increases about 3% and this effect diminishes after the distance of 32m, and the neighbouring 12-storey structure does not considerably change the

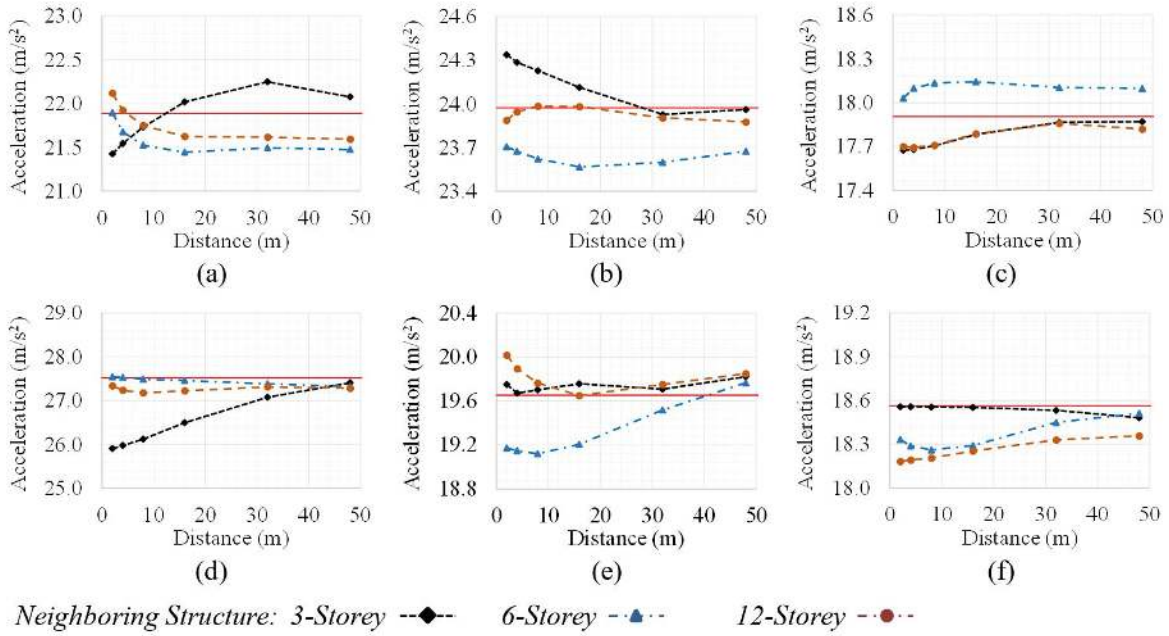

Figure 7 Variation of the peak acceleration of (a) 3-storey, (b) 6-storey (c) 12-storey structures in the neighbourhood of different structures subjected to Earthquake-1, and variation of the results of (d) 3-storey, (e) 6-storey and (f) 12-storey structures for the same cases subjected to Earthquake-2 for soil type 2.

response of the 6-storey structure. For Earthquake-2, the neighbouring identical structure decreases the response of the 6-storey structure about 3%. When there is 3- or 12-storey structure in the neighbourhood of 6-storey structure, the acceleration response of the 6-storey structure marginally increases (Figure 7(e)).

As seen from Figure 7(c), when there is a 3- or 12-storey structure in the neighbourhood of 6-storey structures, the response of the 6-storey structure decreases. If there is a 6-storey structure in the neighbourhood of 12-storey structure, the response of the 12-storey structure increases about 2% for the same excitation. For Earthquake-2, the response of the 12-storey structure decreases more than 2% if there is a 6- or 12-storey structure in the neighbourhood. The presence of the 3-storey structure does not significantly alter the response of the 12-storey structure.

The Effects of the SSSI on the Drift Ratios

The variation of the basement storey drift ratio of the structures is also examined to evaluate the effect of the SSSI on the structures. The basement storey drift ratio of the structures for SSSI cases are compared with that of the SSSI cases to evaluate the influences.

The variation of the maximum basement storey drift ratios of varied structures in the neighbourhood of different structures under each earthquake for soil type 1 are presented in Figure 8.

As seen from Figure 8(a), the presence of the 3- or 12- storey structure decreases the basement storey drift ratio of the 3-storey structure more than 6%. For these cases, the effects of 12-storey structure are observed for longer distances if it is compared with the effect of 3-storey structure. The presence of neighbouring 6-storey structure marginally amplifies the basement storey drift ratio of 3-storey structure for short distances, and this effect diminishes with increasing distance. When the cases analysed for Earthquake-1 are solved under Earthquake-2, similar results are obtained for both cases (Figure 8(d)).

As seen from Figure 8(b), the basement storey drifts ratio of the 6-storey structure slightly increase if there is an identical structure in the neighbourhood. If the neighbouring structure is 3-storey, the drift ratio of 6-storey structure slightly increases. When the neighbouring structure is 12-storey, the response of the 6-storey structure changes similarly with the case of the nearby structure of 3-storey, but the variation is two times higher. For Earthquake-2, the nearby identical structure increases the response of the 6-storey structure more than 2% (Figure 8(e)). If the neighbouring structure is 3-storey, the variation of the drift ratio depends on the clear distance. In the case of the neighbouring structure is 12-storey, the response of 6-storey structure increases more than 2% for close distances.

As seen from Figure 8(c) and (f), for Earthquake-1 and Earthquake-2, the basement storey drift ratio of the 12-storey structure is only affected when there is an identical structure in the neighbourhood. The presence of nearby 3- or 6-storey structure does not considerably change the response of the structure.

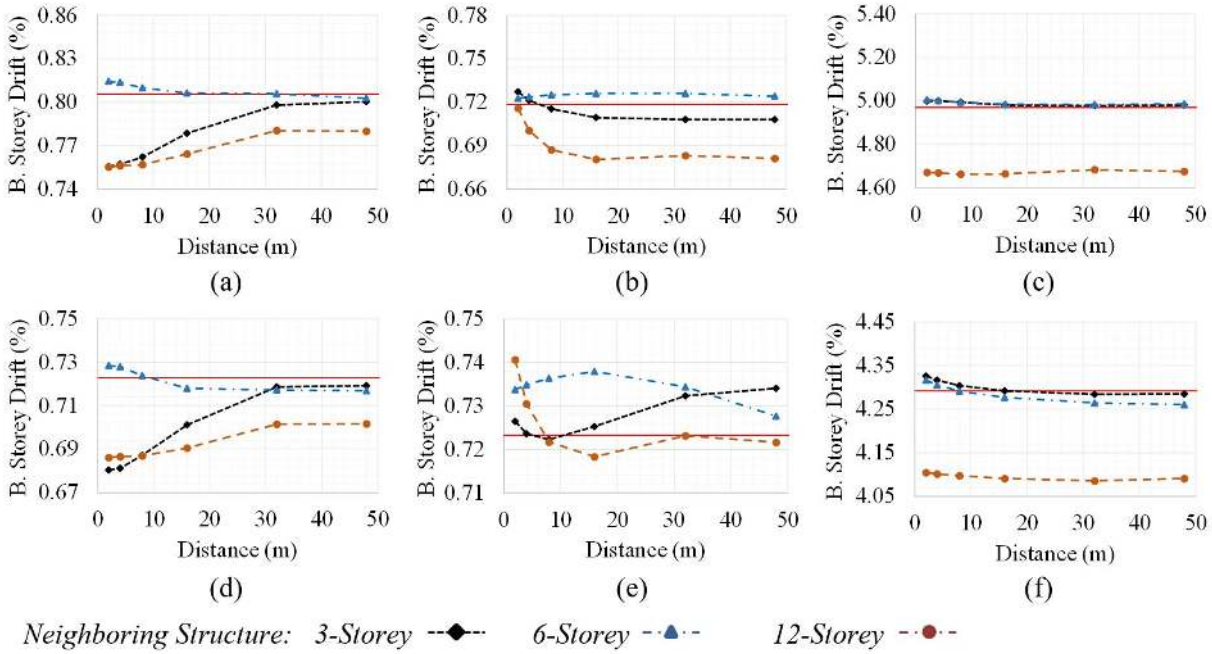

Figure 8 Variation of the peak basement storey drift ratio of (a) 3-storey, (b) 6-storey (c) 12-storey structures in the neighbourhood of different structures subjected to Earthquake-1, and variation of the results of (d) 3-storey, (e) 6-storey and (f) 12-storey structures for the same cases subjected to Earthquake-2 for soil type 1.

The variation of the maximum basement storey drift ratios of structures in the neighbourhood of different structures under each earthquake for soil type 2 are presented in Figure 9.

As seen from Figure 9(a), the neighbouring of the identical structure slightly changes the response of the 3-storey structure: the drift ratios slightly decrease for the distances less than 20m and the drift ratios are slightly increase for longer distances. The presence of the neighbouring 6- or 12-storey structure decrease the basement storey drift of the 3-storey structure. For Earthquake-2, the drift ratio of 3-storey structure decrease about 6% when there is an identical structure in the neighbourhood (Figure 9(d)). The response of the 3-storey structure is not affected when it is in the neighbourhood of 6- or 12-storey structure.

As seen from Figure 9(b), the drifts ratio of the 6-storey structure decrease if there is an identical or 12-storey structure in the neighbourhood. But, if the neighbouring structure is 3-storey, the drift ratio of the structure decreases

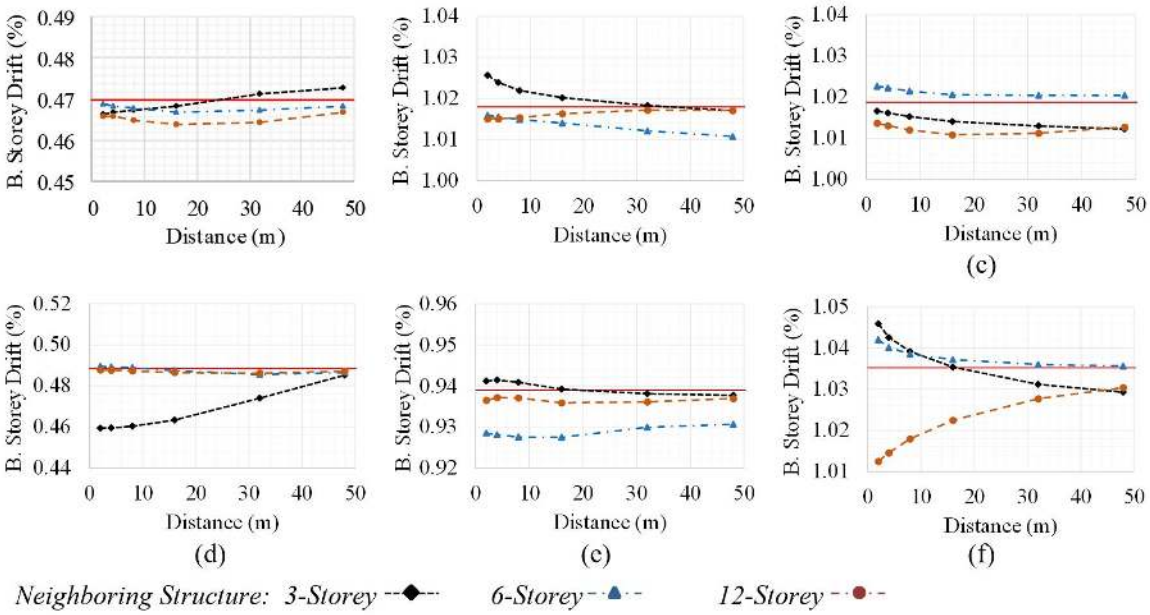

Figure 9 Variation of the peak basement storey drift ratio of (a) 3-storey, (b) 6-storey (c) 12-storey structures in the neighbourhood of different structures subjected to Earthquake-1, and variation of the results of (d) 3-storey, (e) 6-storey and (f) 12-storey structures for the same cases subjected to Earthquake-2 for soil type 2.

about 2%. For Earthquake-2, the nearby identical structure decreases the response of the 6-storey structure (Figure 9(e)). If the neighbouring structure is 3- or 12-storey structure, the variation in the drift ratio of 6-storey structure is negligible.

As seen from Figure 9(c), the basement storey drift ratio of the 12-storey structure decreases when it is in the neighbourhood of an identical or 3-storey structure. If the neighbouring structure is 6-storey, the drift ratio of the 12-storey structure slightly increases. For Earthquake-2, the presence of a neighbouring structure decreases the storey drift of the 12-storey structure more than 2% (Figure 9(f)). If the neighbouring structure is 3-storey, the drift ratio of the 12-storey structure increases for the distance less than 16m, and it decreases for the distances more than 16m. If the neighbouring structure is 6-storey, it causes a slight increase in the basement storey drift ratio of the 12-storey structure.

5.2 The Case of the Unaligned Structures

The scattering waves from the structures when the cases of the structures are not aligned on the same line may be different from the cases of the aligned structures. In this section, this phenomenon is investigated. For this purpose, Earthquake-1 and Earthquake-2 are simultaneously applied to the models in the X- and Y-directions, respectively.

The Effects of the SSSI on the Acceleration Response

The variation of the maximum relative acceleration of the varied structures in the neighbourhood of different structures for soil type 1 are presented in Figure 10. In Figures 10(a)-(c) and (d)-(f) the results of varied structures in the X- and Y-directions are presented, respectively.

As seen from Figure 10(a), the acceleration response of the 3-storey structure decreases or increases up to 3%, when there is an identical or 12-storey structure in the neighbourhood. The level and positive or negative changing of the response of the structures varies with the clear distance between the structures. When the 3-storey structure is in the neighbourhood of 6-storey structure, the response of 3-storey structure increases. The maximum level of this variation is observed when the clear distance is 16m. The changing in the structural responses with the clear distance in the Y-direction is similar to the X-direction. If the neighbouring structure is identical, the response of the 3-storey structure decreases up to 4% for the distances less than 16m (Figure 10(d)). When the clear distance is about 32m, the response of the structure somewhat increases due to the SSSI effects. If the neighbouring structure is 6- or 12-storey, the response of the 3-storey structure decreases up to 3.5%, and the similar kind of variation in the response of the 3-storey structure with distance is observed for these cases.

As seen from Figure 10(b), the acceleration response of the 6-storey structure increases slightly for the clear distances less than 10m, but the effects increase for the distances longer than this value. If the neighbouring structure is

3-storey, the response of the 6-storey structure change positively or negatively depending on the clear distance, the unfavourable distance is 16m for this case. If the neighbouring structure is 12-storey, the response of the 6-storey structure changes positively or negatively depending on the clear distance: the response of the structure decreases up

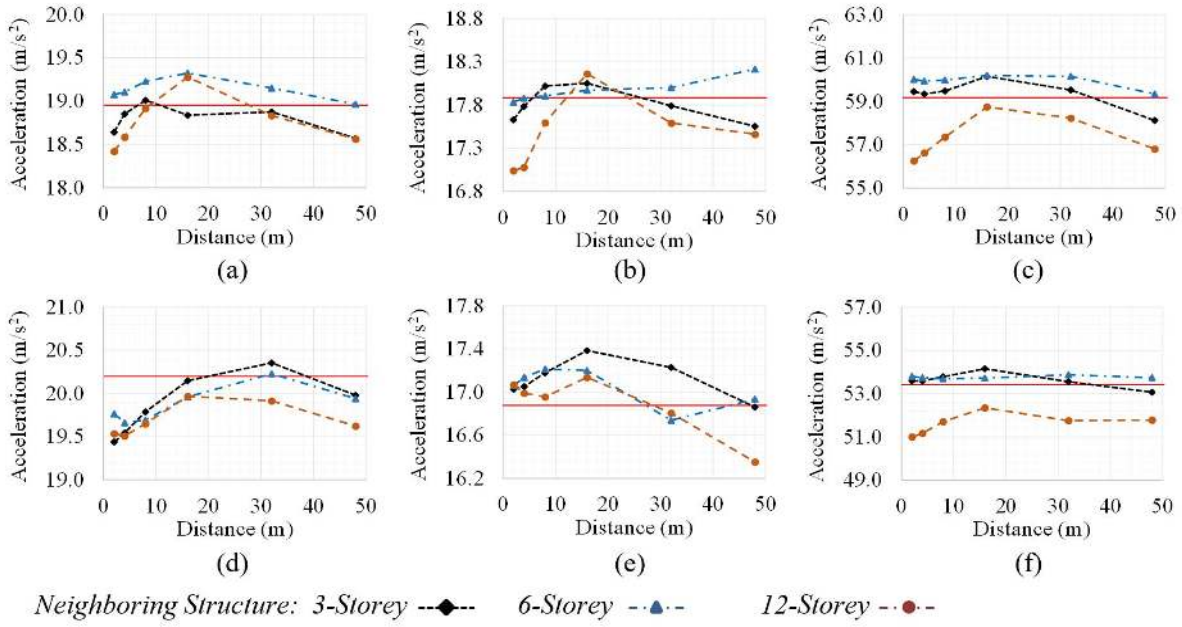

Figure 10 Variation of the peak acceleration of (a) 3-storey, (b) 6-storey (c) 12-storey structures in the neighbourhood of different structures in the X-direction, and variation of the results of (d) 3-storey, (e) 6-storey and (f) 12-storey structures for the same cases in the Y-direction for soil type 1.

to 5% for the close distances. The neighbouring of the 12-storey structure causes the increase in the response of the structure for 16m clear distance and the response of the structures decreases about 2.5% for the clear distance of 48m. In the Y-direction, the same dependency on the clear distance is also observed (Figure 10(e)). The response of the 6-storey structure slightly increases if there is another identical structure, and the level of the variation changes with the clear distance. If the neighbouring structure is 3-storey, the peak response variation is obtained at the clear distance of 16m, which is more than 3%. When the neighbouring structure is 12-storey, the response of the 6-storey structure slightly increases for the clear distances less than 25m, and the response of the structure decreases more than 3% for the clear distances more than 25m.

As seen from Figure 10(c), the response of 12-storey structure decreases up to 5% if it is in the neighbourhood of the identical structure. However, the variation in the responses is negligible for the range of 16m to 32m. If the nearby structure is 3- or 6-storey, the response of the 12-storey structure does not change considerably. For the Y-direction, similar kind of variation in the response of 12-storey structure is observed with the results of the X-direction (Figure 10(f)).

The variations of the maximum relative acceleration of the varied structures in the neighbourhood of different structures for soil type 2 are presented in Figure 11. In Figures 11(a)-(c) and (d)-(f) the results of varied structures in the X- and Y-directions are presented, respectively.

As seen from Figure 11(a), the acceleration response of the 3-storey structure change positively or negatively depending on the clear distance: for the range of distances less than 4m and more than 32m, the response of the structure decreases, and the response increases for the other examined clear distances. When the neighbouring structure is 6- or 12-storey structures, the response of the 3-storey structure decreases up to 2.5%. For the Y-direction, the neighbourhood of 3-storey structure decreases the response of the identical structure more than 3% for the distances less than 16m. For the same cases, the response of the 3-storey structure increases for the distances more than 16m (Figure 11(d)). The neighbourhood of 6- or 12-storey structure also increases the response of the 3-storey structure with the level of 2.5%.

As seen from Figure 11(b), the acceleration response of the 6-storey structure decreases up to 2% when there is an identical structure in the neighbourhood. If the neighbouring structure is 3-storey, the response of the 6-storey structure changes depending on the distance: the response of the structure increases for the distances less than 8m, the response of the structure decreases for the distances more than 8m. The neighbourhood of the 12-storey structure causes a similar

change in the response of the 6-storey structure. For the Y-direction, the presence of 6-storey structure decreases the response of the 6-storey structure for the clear distances less than 16m (Figure 11(e)). However, if the distance is more than 16m, the response of the structure increases. When the 3- or 12-storey structure is in the neighbourhood of 6-storey structure, the response of the 6-storey structure changes slightly.

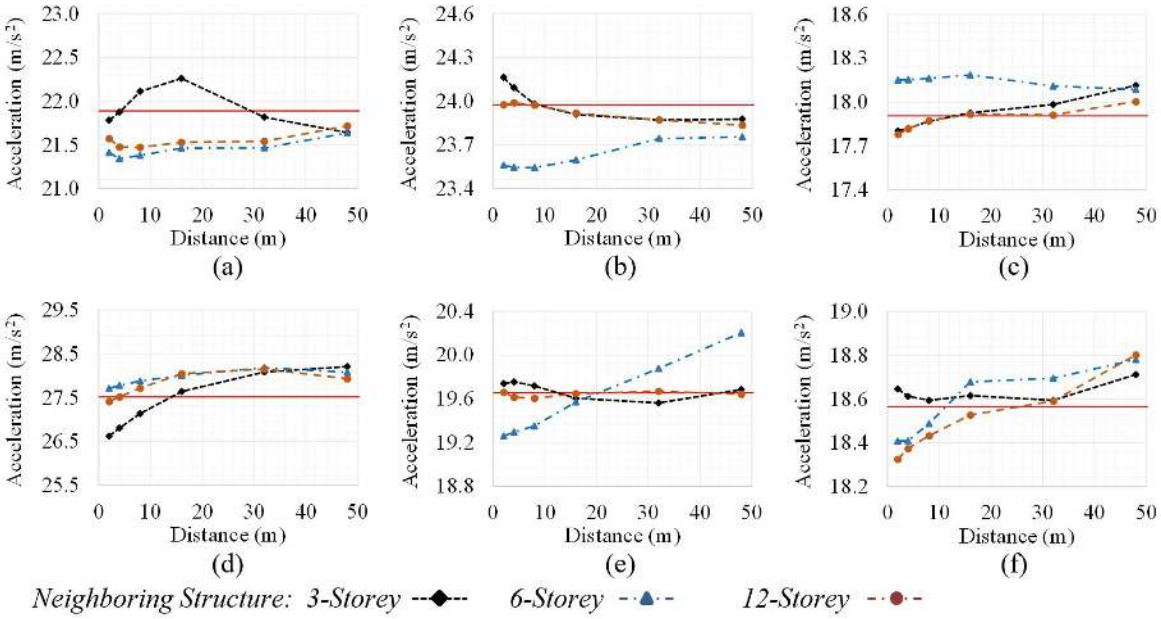

Figure 11 Variation of the peak acceleration of (a) 3-storey, (b) 6-storey (c) 12-storey structures in the neighbourhood of different structures in the X-direction, and variation of the results of (d) 3-storey, (e) 6-storey and (f) 12-storey structures for the same cases in the Y-direction for soil type 2.

As seen from Figure 11(c), the neighbouring of 3- or 12-storey structure slightly changes the response of the 12-storey structure: the response of the 6-storey structure decreases for the clear distances less than 16m, and the response of the structure increases up to 3% for the clear distances more than 16m. If the neighbouring structure is 6-storey, the response increases for all of the examined distances up to 3%. For the Y-direction, if the neighbouring structure is 6- or 12-storey, the response of the 12-storey structure decreases for the clear distance less than 16m (Figure 11(f)). If the clear distance is larger than this value, the response of 12-storey structure increases. When the neighbouring structure is 3-storey, the response of the 12-storey structure slightly increases.

The Effects of the SSSI on the Basement Storey Drift Ratios

The evaluation of the effect of the unaligned neighbouring structure on the basement storey drift ratios of the structures is assessed for several cases. The variation of the maximum basement storey drift ratios of structures which are in the neighbourhood of unaligned structures under each earthquake for soil type 1 are presented in Figure 12. In Figures 12(a)-(c) and (d)-(f), the basement storey drift ratios of the varied structures are presented for the X-and Y-directions, respectively.

As seen from Figure 12(a), the neighbouring of an identical structure decreases the drift ratio of the 3-storey for out of the range of 16m to 32m. When the neighbouring structure is 6-storey, the drift ratio of 3-storey structure is negligible. When the neighbouring structure is 12-storey, the drift ratio of 3-storey structure decreases about 4.5%. For the Y-direction, the effect of neighbouring identical structure on the drift ratio of the 3-storey structure causes similar result as in the cases of the X-direction (Figure 12(d)). The neighbouring of 6-storey structure decreases the drift ratio of the 3-storey structure and the level of effect changes with the clear distance. If the neighbouring structure is 12-storey, the drift ratio of 3-storey structure decreases up to 4.5%.

As seen from Figure 12(b), the presence of an identical structure is decreased the drift ratio of 6-storey structure. If the neighbouring structure is 3-storey, the response of 6-storey structure decreases up to 3%. The neighbouring structure is 12-storey, the response of 6-storey structure decreases more than 6%. For the Y-direction, the neighbouring 3- or 6-storey structure change positively or negatively the drift ratio of 6-storey structure depending on the clear distance (Figure 12(e)). If the neighbouring structure is 12-storey, the variation in the drift ratio of 12-storey structure is

negligible for the close distance, but for the distances more than 32m the level variation in the drift ratio of the 6-storey structure is more than 2.5%.

As seen from Figure 12(c), the neighbouring identical structure decreases the drift ratio of 12-storey structure more than 4%. If the neighbouring structure is 3- or 6-storey, the response of 12-storey structure is not affected from the presence of the neighbouring structure. Similar kind of variation is observed in the drift ratio of the 12-storey structure in the Y-direction (Figure 12(f)). But for this direction, the presence of the nearby identical structure decreases the response of the structure more than 7%.

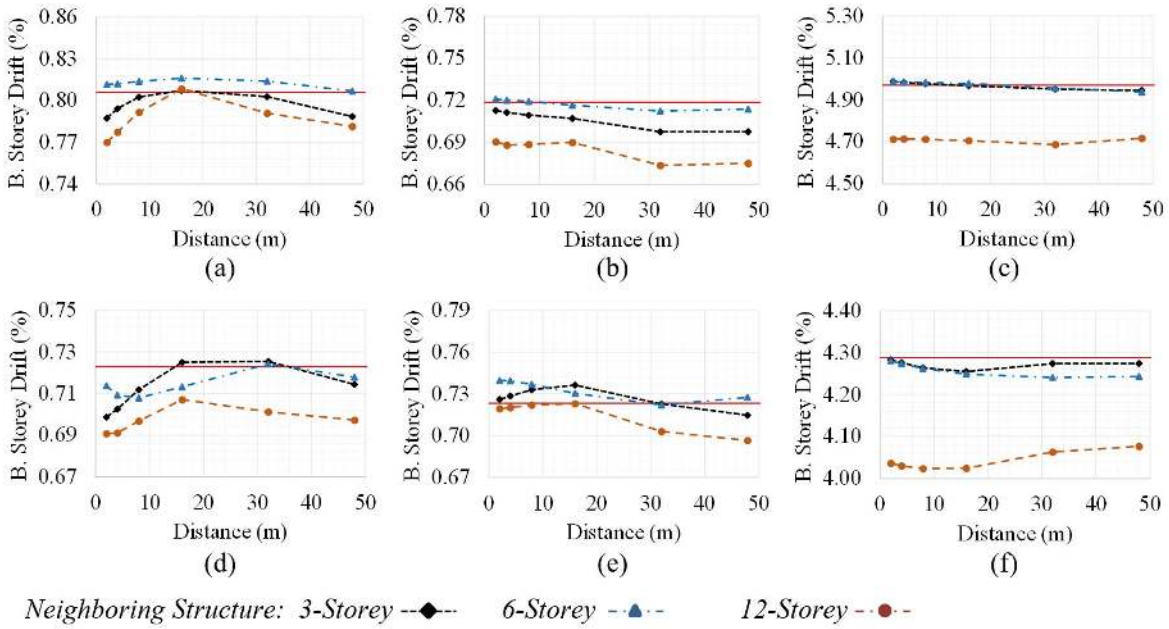

Figure 12 Variation of the peak basement storey drift ratio of (a) 3-storey, (b) 6-storey (c) 12-storey structures in the neighbourhood of different structures in the X-direction, and variation of the results of (d) 3-storey, (e) 6-storey and (f) 12-storey structures for the same cases in the Y-direction for soil type 1.

The variation of the maximum basement storey drift ratios of structures in the neighbourhood of unaligned structures under each earthquake for soil type 2 are presented in Figure 13. In Figures 13(a)-(c) and (d)-(f), the basement storey drift ratios of the varied structures are presented for the X-and Y- directions, respectively.

As seen from Figure 13(a), the presence of the identical structure decreases the storey drift ratio of the 3-storey structure. The peak variation in the storey drift ratios is more than 4% and it is observed at 32m clear distance. The similar effects are observed in the neighbourhood of 6- and 12-storey structures. For the Y-direction, the neighbouring identical structure decreases the drift ratio for the distances less than 16m, and the same cases increases the drift ratio of 3-storey structure for the distances more than 16m (Figure 13(c)). The neighbourhood of 6- or 12-storey structure increases similarly the storey drift ratio of 3-storey structure.

As seen from Figure 13(b), the presence of an identical structure decreases the drift ratio of 6-storey structure. If the neighbouring structure is 3- or 12-storey, the response of 6- storey structure change slightly. For the Y-direction, the neighbouring of 3-, 6-, or 12-storey structure decreases the storey drift ratio of 6-storey structure in the same trend with distance (Figure 13(e)).

As seen from Figure 13(c), the neighbouring identical or 3-storey structure marginally affect the response of the 12-storey structure. If the neighbouring structure is 6-storey, the storey drift ratio of 12-storey structure vaguely increases. In the Y-direction, the neighbouring identical structure decreases the drift ratio of the 12-storey structure about 2% (Figure 13(f)). If the neighbouring structure is 3-storey, the response increases for close distance and the decrease in the storey drift ratio is observed with the distance. In the same direction, the neighbouring 6-storey structure insensibly changes the response of 12-storey structure.

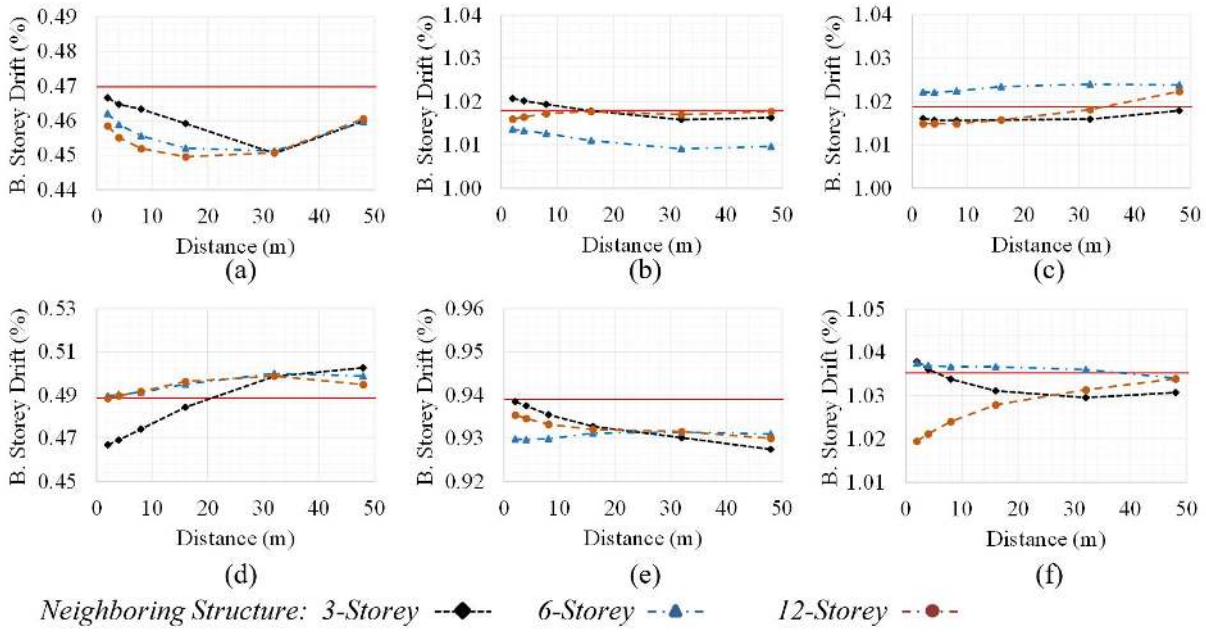

Figure 13 Variation of the peak basement storey drift ratio of (a) 3-storey, (b) 6-storey (c) 12-storey structures in the neighbourhood of different structures in the X-direction, and variation of the results of (d) 3-storey, (e) 6-storey and (f) 12-storey structures for the same cases in the Y-direction for soil type 2.

6 CONCLUSION

A series of 3D dynamic analysis of the frame structures considering the neighbouring structures are performed in this study to reveal the phenomenon of through-soil interaction of two neighbouring frame structures. Some particular parameters are chosen to perform the analyses. The parameters are the storey number of the structures, the clear distance between the structures, the stiffness of the underlying soil, and the layout of the structures. The structures are analysed under two different seismic excitations. The relative acceleration and the basement storey drift ratios are presented in order to assess the SSSI effects on the neighbouring structures. The conclusions drawn from the results are as follows;

- The consideration of the soil increases the flexibility of the structures, which results in the variation in the dynamics characteristics of the structures.
- As the stiffness of the soil increases, the importance of the consideration of the underlying soil becomes insignificant.
- The level of SSSI effects on the response of neighbouring structures is higher for soft soil cases than the cases of stiff soil.
- In case of the identical structures in the neighbourhood, the level of the SSSI effects on the response of the structures changes depending on the distance for the cases the structures are aligned. The peak variations are observed for the close distances, and the general trend is the decrease in the responses.
- In case of the dissimilar structures in the neighbourhood, the variation in the response of the neighbouring structures can be positive or negative for the cases in which the structures are aligned. The change highly depends on the dynamic characteristics of both structures and the dynamic excitation.
- When the neighbouring structure is high-storey, the SSSI effect is observed over longer distances when the variations are compared with the effects of the lower storey structures.
- In case of the aligned layouts, the peak variation in the structures is observed at the close distances, however, the peak variation is observed in the mid-distance for the unaligned layouts.
- In case of the unaligned layouts, the variation in the response of the structures can be positive or negative. This change highly depends on the clear distance.
- The variation in the structural responses due to the SSSI effects depends on the earthquake. Different results are obtained when the same cases subjected to different earthquakes.

Consequently, it is obtained that the response of the neighbouring structure can change because of the SSSI effects. The effects of SSSI change the response of the system with the scattered waves from the structures, and this is not a one-way phenomenon. Therefore, further studies have to be performed to implicitly understand the effects of the neighbouring structures on structural response. The effects of the neighbouring structure should be considered in the design of the new structures, as well as, these effects should be considered when the evaluation of the durability of the existing structures in the neighbourhood of other structures.

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