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Effects of Multiple Structure-soil-structure Interactions Considering the Earthquake Waveform and Structures Elevation Effects

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A B S T R A C T

The simultaneous effects of soil and existing structures are known as the site-city interaction (structure-soil-structure). The impact of site-city interaction on structure behavior is effective. Thus, this interaction in some regions decreases the responses while increases in other areas. In addition, the site-city interaction of many parameters including the soil type, density rate, height of buildings is effective for evaluation. So far, none of investigation has focused on the effects of nature and shape of seismic wave and the plate which affects these waves in site-city interaction in three dimensions. Thus, the present study aimed to consider the effect of parameters mentioned in structure and foundation responses. The results indicated that the highest reduction for Love wave occurs in acceleration responses of structure in the cluster relative to the individual state, compared to the rest of the waves. Therefore, the reduction is about 30 and 50% for the base and top nodes of structures, respectively.

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1. INTRODUCTION

Due to the growth of urbanization and impact of the shakes in inner city buildings on each other, especially when the cities are on sedimentary basins and soft soils, the effects of soil interaction and several structures together have been considered as an important issue. This is the case of multiple interactions between buildings in densely-populated areas in the urban areas, known as Site-City Interaction (SCI). The vibration of surface structures can create seismic waves in the soil. In fact, the structures act as a secondary source of seismicity and vibration in a city.

The proximity to the main frequencies of soil layers with the structures on the surface of earth is considered as one of the important issues in this regard [1, 2]. The effect of the SCI on free-field movements is very important since it decreases and increases the vibrations in some places, depending on the soil, density, and urban structural order [3,4].

These studies started from the analyses with one and two-dimensional aspect and developed into 3D analyses [5, 6].

Semblat et al. [7] examined the sedimentary basins in densely-populated urban areas based on a regular city model on a one-dimensional soil layer. In general, they concluded that SCI could lead to some significant changes in seismic wave field on the scale of sedimentary basin. Kham et al. [8] calculated the response of two-dimensional models of city-site against the SH wave distributed on vertical plane by using boundary element method and found that the multiple interactions are more effective during the resonance of the site-city.

Furthermore, Isbiliroglu [9] used numerical methods to evaluate the effect of large structures during an earthquake on the multiple interaction responses of structural groups. He first studied the symmetric structures in detail. Then, the asymmetrical structures including torsion effects were simulated.

Kumar and Narayan [10] examined the effect of SCI on a two-dimensional model of closely related

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structures in double resonance terms with regard to the shape of sedimentary zone substructure.

Based on the above-mentioned studies, there is no comprehensive study on the effect of shape and nature of earthquake waves and the plate affecting these waves on SCI. In this respect, one of the most important parameters is shape of seismic waves because during the seismic events, the waves travel through the soil body and while arrive at the structures, they are reflected and interfere with the other waves. As a result, shape, length and amplitude as well as propagation directions of waves could be influential as in some cases, decrease amplitude of each other and in some other cases, increase amplitude and energy. Besides, it should be mentioned that by accounting for the shape of waves, both vertical and horizontal ground movements could be analyzed as in most studies, the horizontal component has received attention mostly. Thus, the present study aimed to evaluate the effect of surface and volume waves on earthquake behavior in structural behavior in two states, regardless of structure-soil-structure interaction effect. This study is majorly focused on investigating into the site-city interaction (SCI) aiming to provide a more accurate estimate over response of structures while located close to each other. Structural models were considered as three-dimensional in both single structures (individual) and the ideal city structural group (clusters). In the single model, the site-city interaction is not considered, and these effects are considered in the group model.

2. MODELLING THE STRUCTURE-SOIL-STRUCTURE SYSTEM

SASSI 2000 software [11] was used to model structures and soil and analyze the system. This software is specialized at analyzing the soil-structure interactions (SSI) by which the structure and wave propagation in the soil elastic or viscoelastic half-space medium can be simulated in a frequency domain. In this study, three models were created in three dimensions, and three clusters were 3×3 and include nine identical structures, and the main difference between these three clusters is the height of the structures. These clusters of structures are symmetrical and the distance between the structures is similar. The specifications of the models are shown in Table 1.

2. 1. Structural Modeling

In all models, the structure is concrete with the storey height of 4 meters, the geometric and structural characteristics of all classes are the same, and each class contains 25 columns with the same distances distributed throughout the plan. The main period of the 10-, 20, and 40-storey structures is about 0.92, 1.46, and 3.14 seconds, respectively.

To numerically simulate the structures, the Lumped-Mass Stick Model has been utilized. In this respect, stories are modeled as a lumped mass which are connected to each other using the Beam elements. Numerical model of each structure is schematically shown in Figure 1. The value of each lumped mass, is equal to the building's mass in the height range of that lumped mass. The Beam elements have been modeled with respect to the geometric specifications at the concerned height range whose properties are presented in Table 2.

Besides, 3 translational degrees of freedom (DOF) have been accounted for each lumped mass and the rotational DOFs have been ignored.

TABLE 1. Specifications of the three models

	Number of stories	Distance between structures (m)	Plan dimensions (m^2)
Model 1	10	10	30 × 30
Model 2	20	15	40 × 40
Model 3	40	20	50 × 50

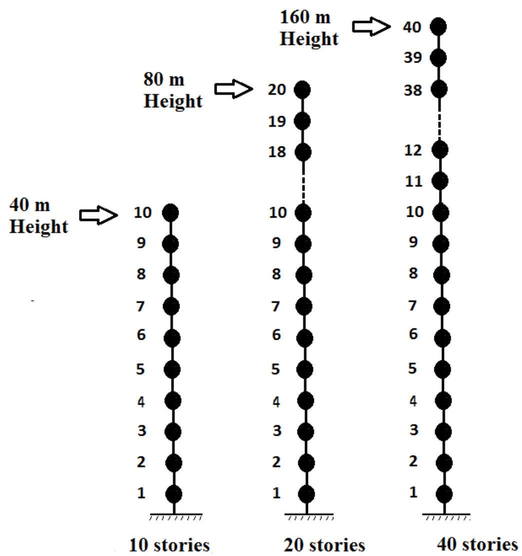


Figure 1. Lumped Mass Model of Structures

TABLE 2. Specifications of each storey of the models

	Storey mass (kg)	Area (m^2)	Shear area (m^2)	Moment of inertia (m^4)	Torsional inertia (m)
10 stories structure	$10^5 \times 9.1$	13.37	11.15	4664	9326
20 stories structure	$10^6 \times 1.62$	43.19	36	11875	23751
40 stories structure	$10^6 \times 2.53$	120.71	100.59	57585	114432

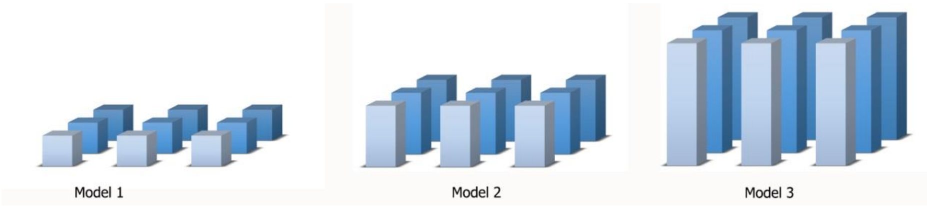


Figure 2. Structural Clusters of each of the models

Taking the overturning moment into account as well as building's weight, a rectangular foundation with dimensions the same as those of the buildings, with depth of 1, 2 and 4m for 10, 20 and 40-storey buildings, respectively, has been modeled. For the sake of modeling the foundation, 8-noded SOLID elements have been applied. Figure 2 displays a schematic plan of each model.

2. 2. Soil Modeling The soil which is modeled in the software is composed of a semi-infinite elastic environment with horizontal layering, located on viscoelastic half-infinitely semi-space [11]. in addition to the upper layers, the soil profile includes 10 additional layers with varying depth together with viscous absorbent boundaries. These 10 layers and the boundaries are used to simulate the semi-infinite soil media.

3. VERIFICATION

To validate the model, used the results reported by Lee et al. [12] in which a nuclear reactor was modeled by ABAQUS software in two dimensions by Lumped-Mass Stick method. This model is shown in Figure 3. To perform the verification, the structural specifications and soil presented in the related article are modeled in SASSI 2000 software.

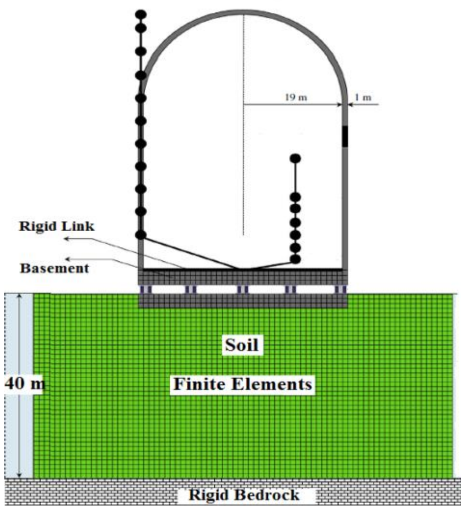


Figure 3. The model of a nuclear reactor by software [12]

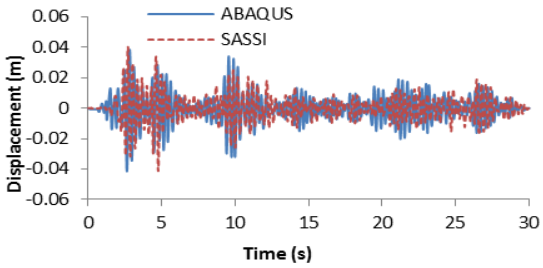


Figure 4. Adaptation of displacement time history of the structure top node was obtained from the SASSI with ABAQUS

The earthquake related to this analysis is the El-Centro 1940 N-S earthquake record.

The displacement response of the node on the top of the structure from Lee et al. [12] was compared with the results obtained from the SASSI software.

According to many uncertainties in SSI and conventional methods to simulate it, according to Figure 4, it appears that a great agreement has been achieved in the occurrence time as well as peak points and in both analyses, maximum displacement is nearly equal to 4cm.

4. THE SITE-CITY INTERACTION ANALYSIS

The multiple structure-soil-structure interaction analysis was conducted for different structural models with different elevation under the effect of earthquake record in the form of four waveforms independently.

The earthquake related to this analysis is the El Centro 1940 N-S earthquake record that it's characteristics are shown in Table 3.

Acceleration responses were compared at 2 points on the foundation and the roof of the middle structure of each cluster with the corresponding structure responses in individual mode.

In addition to the maximum acceleration values, the Root Mean Square (RMS) parameter including the domain of node responses over the entire vibration time was compared, as shown in Equation (1).

$$RMS = \sqrt{\sum_{i=1}^{n} \frac{{y_i}^2}{n}} \tag{1}$$

where, y_i represent the range of responses, and n indicates the number of points of the time history graph (the number of responses).

TABLE 3. Specifications of the record

Earthquake Name	Year	Station Name	M (Richter)	PGA (g)	Vs30 (m/s)
Imperial Valley-02	1940	El Centro Array#9	6.95	0.32	213

Given the direction and shape of the earthquake, the waves created in the model were Pressure (P), Shear (S), Rayleigh and Love.

4. 1. The SH Wave Mode Initially, the three models were separately analyzed from the earthquake record in the form of the SH wave and the results are presented below. The acceleration response spectrum of 3 models for the base and roof nodes and The acceleration time history response for roof node of the 10-storey structure (Model 1) illustrated in Figures 5 and 6 (comparison between individually and cluster mode).

According to Figure 6 it can be stated that for SH wave the greatest difference in the acceleration response spectrum is for roof node and for 10, 20 and 40-storey structures in periods about in the range of 0.2 - 0.3, 0.3 - 0.4, 0.4 - 0.6, respectively. Of course, for 20-storey structure, this difference is less.

4. 2. The P Wave Mode The three models were separately analyzed from the earthquake record in the form of P wave and the results are presented below. The

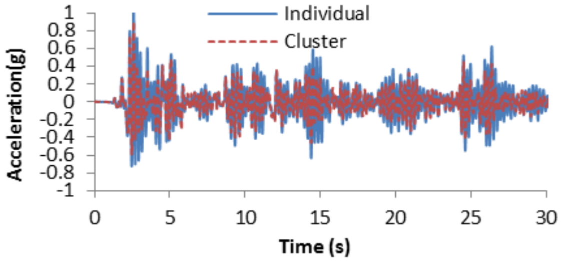


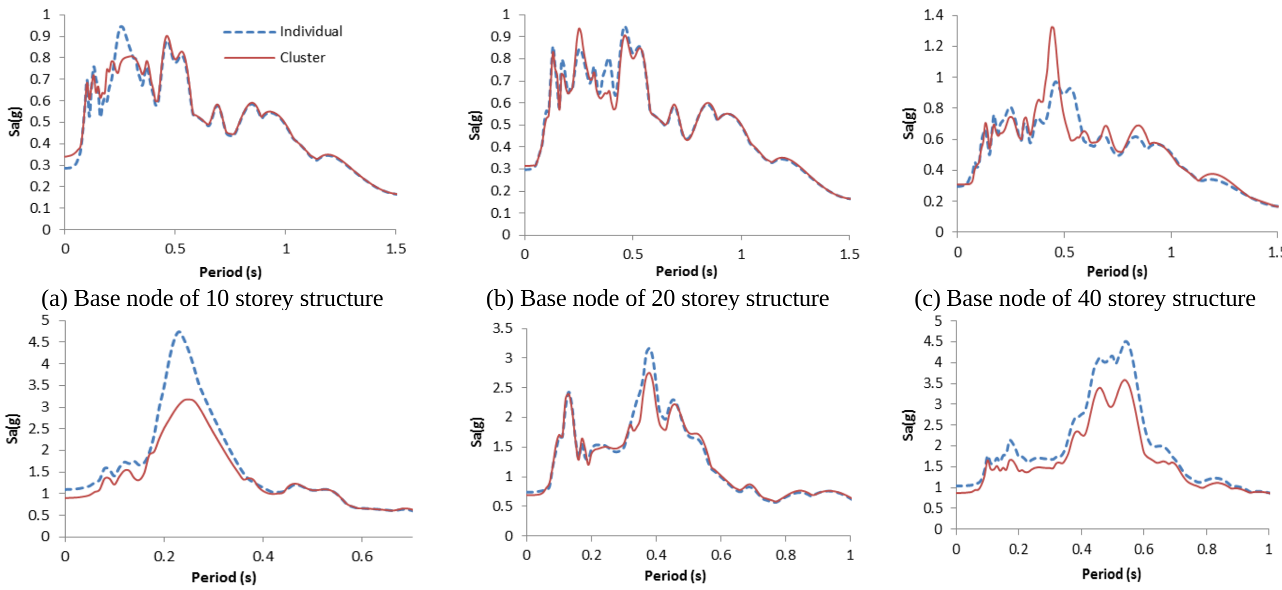
Figure 5. Acceleration time history responses of the 10-storey structure for roof node in the individual and cluster cases for SH wave

acceleration response spectrum of 3 models for the base and roof nodes and the acceleration time history response for roof node of the 10-storey structure (Model 1) illustrated in Figures 7 and 8.

According to Figure 8 it can be stated that for P wave the greatest difference in the acceleration response spectrum is for roof node and for 10, 20 and 40-storey structures in periods about between 0 and 0.3, 0.1 and 0.2, 0.3 and 0.4 respectively.

Of course in this case, for intermediate and short structures, the responses have increased in cluster mode than individual one.

4. 3. The Love Wave Mode The three models were separately analyzed from the earthquake record in the form of Love wave and the results are presented below. The acceleration response spectrum and transfer functions of 3 models for the base and roof nodes and



(a) Base node of 10 storey structure (b) Base node of 20 storey structure (c) Base node of 40 storey structure

(d) Roof node of 10 storey structure (e) Roof node of 20 storey structure (f) Roof node of 40 storey structure

Figure 6. The acceleration response spectrum of 10, 20 and 40-storey structures in the individual and cluster cases for the base node respectively (a), (b), (c) and for the roof node respectively (d), (e), (f) for SH wave mode

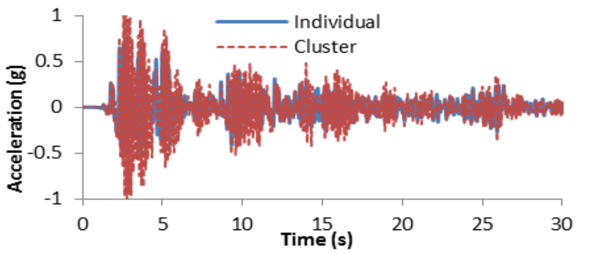


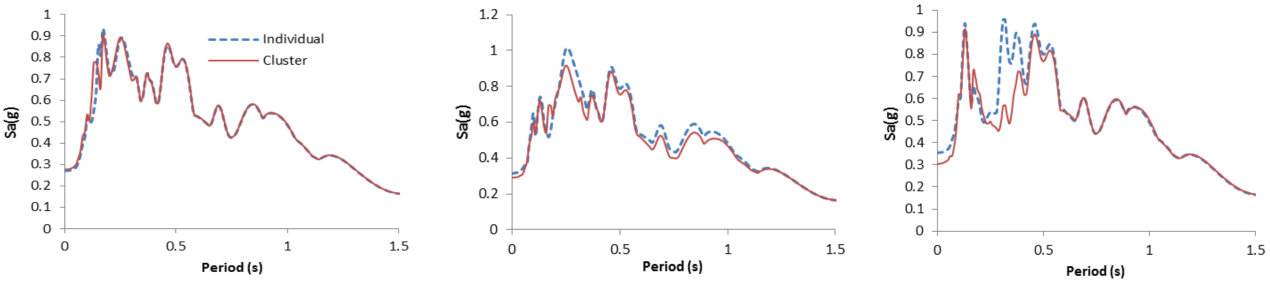
Figure 7. Acceleration time history responses of the 10-storey structure for roof node in the individual and cluster cases for P wave

the acceleration time history response for roof node of the 10-storey structure (Model 1) illustrated in Figures 9 and 10.

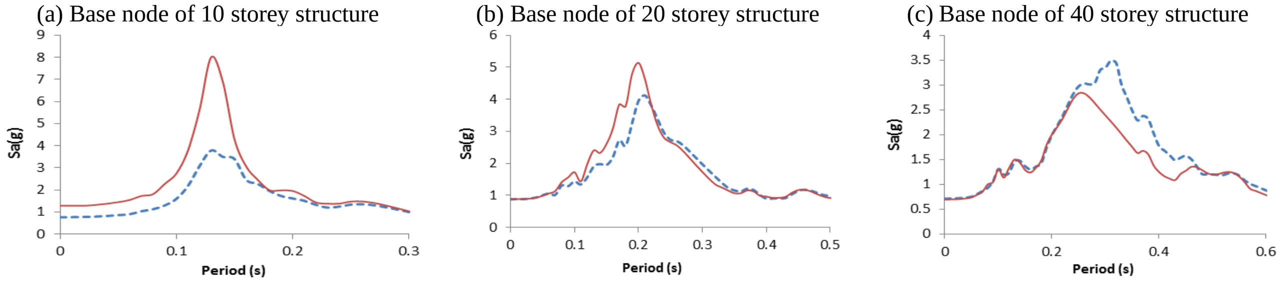
According to Figure 10 it can be stated that for love wave for both the base and roof nodes, the values of the acceleration response spectrum of 3 structures in cluster mode are lower than individual one with great difference for all periods.

4. 4. The Rayleigh Wave Mode The three models were separately analyzed from the earthquake record in the form of Rayleigh wave and the results are presented below. The acceleration response spectrum and transfer functions of 3 models for the base and roof nodes and the acceleration time history response for roof node of the 40-storey structure (Model 3) illustrated in Figures 11 and 12.

According to Figure 12 it can be stated that for Rayleigh wave the greatest difference in the acceleration response spectrum is for roof node and for 10 and 20-storey structures in periods about between 0.2 and 0.4, 0.3 and 0.6, respectively and for 40-storey structure almost for all periods.



(a) Base node of 10 storey structure (b) Base node of 20 storey structure (c) Base node of 40 storey structure



(d) Roof node of 10 storey structure (e) Roof node of 20 storey structure (f) Roof node of 40 storey structure

Figure 8. The acceleration response spectrum of 10, 20 and 40-storey structures in the individual and cluster cases for the base node respectively (a), (b), (c) and for the roof node respectively (d), (e), (f) for P wave mode

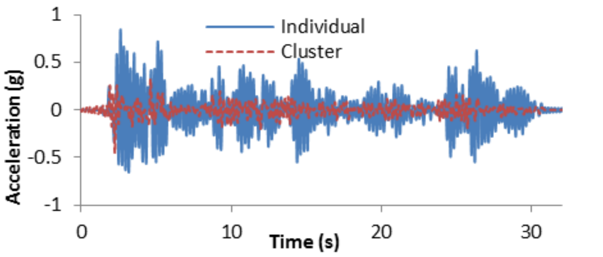
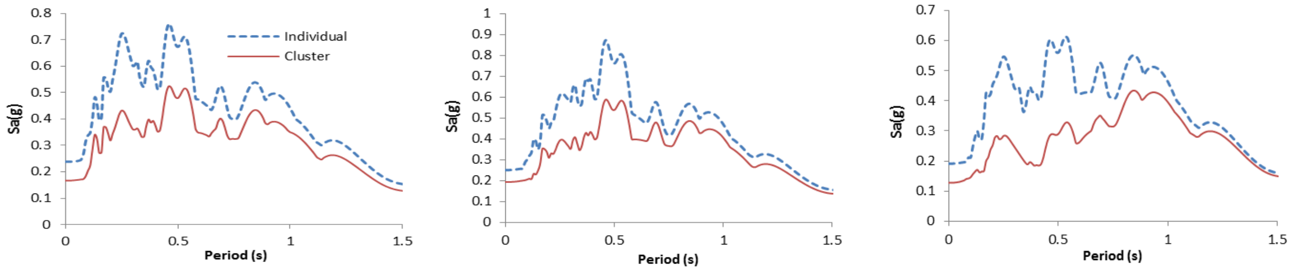


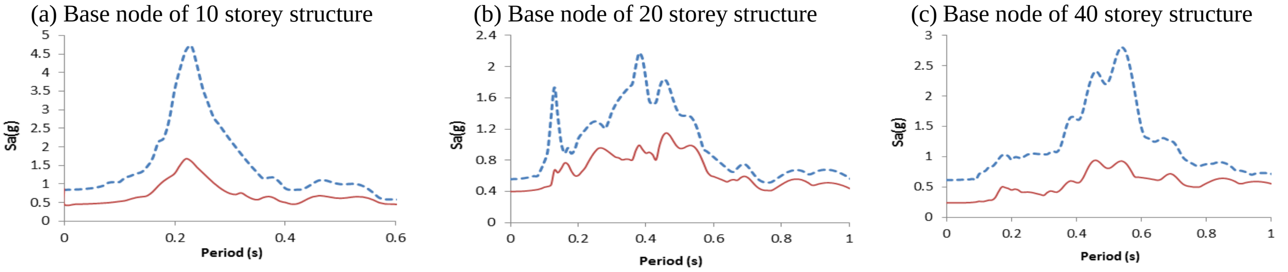
Figure 9. Acceleration time history responses of the 10-storey structure for roof node in the individual and cluster cases for Love wave

5. EVALUATION OF RESPONSE OF STRUCTURES

Figures 13 and 14 display the results of the all the analyses related to the four-wave modes including the maximum value of acceleration time history response and the RMS acceleration parameter for the three structural models for the upper node of the structure. Figures 15 and 16 illustrate the results for the nodes on the foundation. Thus, we observed the interaction of the structures in one cluster with each other in relation to the individual structure for four-wave modes.



(a) Base node of 10 storey structure (b) Base node of 20 storey structure (c) Base node of 40 storey structure



(d) Roof node of 10 storey structure (e) Roof node of 20 storey structure (f) Roof node of 40 storey structure

Figure 10. The acceleration response spectrum of 10, 20 and 40-storey structures in the individual and cluster cases for the base node respectively (a), (b), (c) and for the roof node respectively (d), (e), (f) for Love wave mode

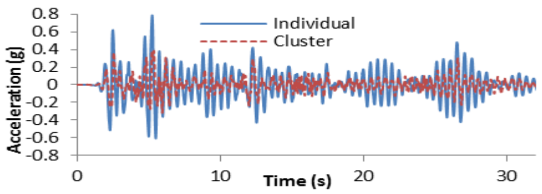
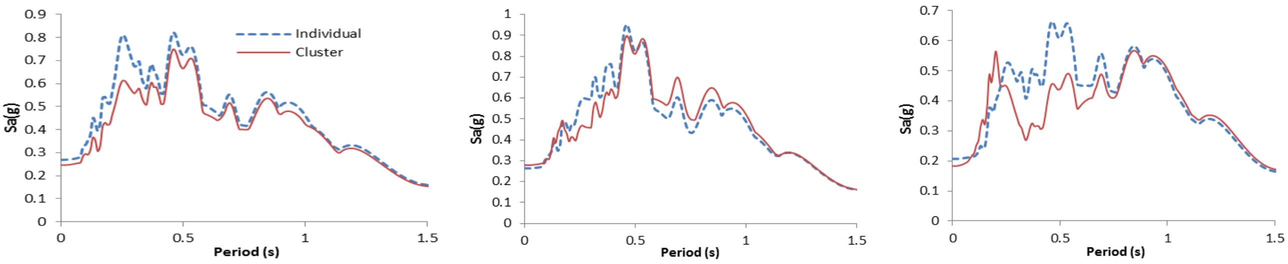


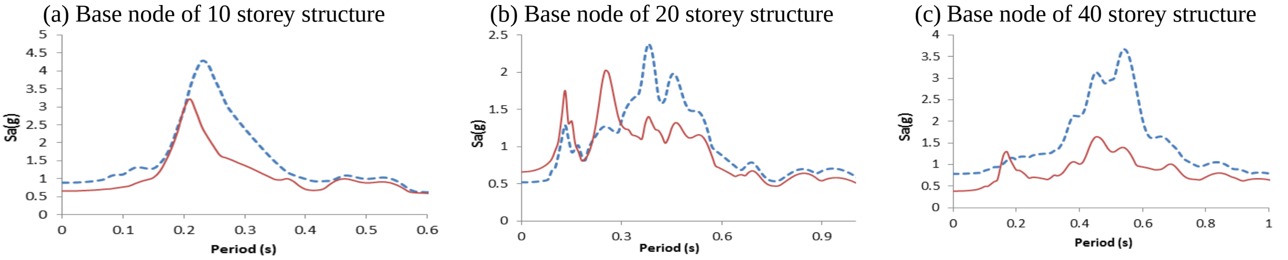
Figure 11. Acceleration time history responses of the 40-storey structure for roof node in the individual and cluster cases for Rayleigh wave

The assessment of behavior of the structures against the SH wave for the roof node indicated a reduction of the maximum acceleration response by 18, 7, and 16% in terms of the site-city interaction for 10-, 20- and 40-storey structures respectively, while it reduced the RMS by 26, 7 and 33%. In this case, the placement of the structures along with each other reduced the responses.

In the mode of the system analysis against the P wave, the maximum acceleration response values of the



(a) Base node of 10 storey structure (b) Base node of 20 storey structure (c) Base node of 40 storey structure



(d) Roof node of 10 storey structure (e) Roof node of 20 storey structure (f) Roof node of 40 storey structure

Figure 12. The acceleration response spectrum of 10, 20 and 40-storey structures in the individual and cluster cases for the base node respectively (a), (b), (c) and for the roof node respectively (d), (e), (f) for Rayleigh wave mode

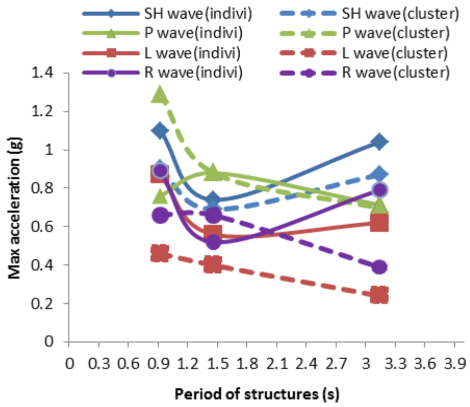


Figure 13. Maximum response acceleration of the models in individual and cluster mode for roof node

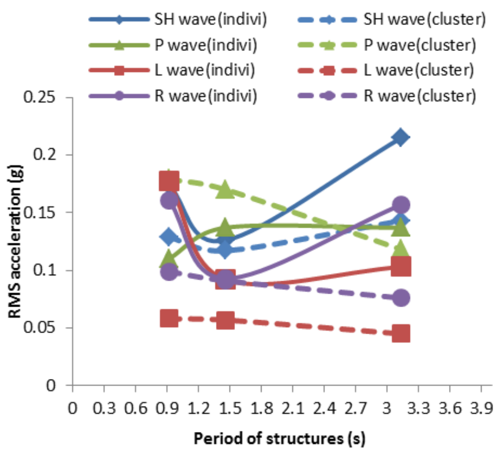


Figure 14. RMS acceleration of the models in individual and cluster mode for roof node

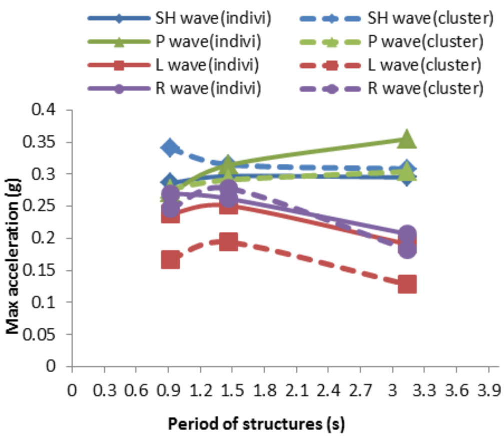


Figure 15. Maximum response acceleration of the models in individual and cluster mode for base node

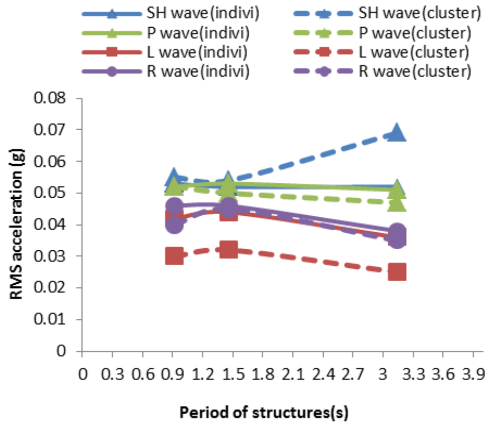


Figure 16. RMS acceleration of the models in individual and cluster mode for base node

roof node in the cluster mode increased 70% for the 10-storey structure, without modification for the 20-storey structure, and 2% decrease for the 40-storey structure, while the RMS acceleration for the 10- and 20-storey structures increased by 63 and 24%, respectively, and decreased by 14% for the 40-storey structure. In other words, the placement of the structures along with each other increased the responses for short and intermediate and reduced for high structures.

In analyzing the effect of the Love wave on the structures for the roof node, the effect of the site-city interaction for the 10-, 20- and 40-storey structures caused a decrease of 47, 29, and 61% in the maximum acceleration response and a decrease of 67, 38, and 56% of RMS acceleration response. The placement of the structures along with each other reduced the responses.

Based on the results of the system analysis against Rayleigh wave, for 10 and 40-storey structures, the acceleration response maximum values of the roof node in the cluster mode were 26 and 51%, respectively, and the RMS acceleration decreased by 39 and 52%, respectively. In fact, the structures together with each other reduced the responses. However, the acceleration response maximum value in cluster mode increased by 27% for the 20-storey structure.

The assessment of the behavior of the structures against the SH wave for the base node indicated an increase of the maximum acceleration response by 19, 6, and 4% in terms of the site-city interaction for 10-, 20- and 40-storey structures, respectively; but it increased the RMS by 4, 4 and 33%. Placement of the structures along with each other increased the responses.

In analyzing the impact of the P wave on the structures for the base node, the effect of the site-city interaction on the 20- and 40-storey structures caused a decrease of 7 and 14% in the acceleration response maximum values and 6 and 8% in the RMS acceleration response. Regarding a 10-storey structure, there is almost no change in the responses in cluster mode compared to the individual mode. In other words, the site-city interaction reduced the responses.

Based on the results of the system analysis against the Love wave for base node, the effect of the site-city interaction for the 10-, 20- and 40-storey structures caused a decrease of 30, 23, and 33% in the maximum acceleration response and a decrease of 29, 27, and 31% of RMS acceleration response. The placement of the structures along with each other reduced the responses.

In analyzing the impact of the Rayleigh wave, for 10 and 40-storey structures, the acceleration response maximum values of the base node in the cluster mode were 9 and 13%, respectively, and the RMS acceleration decreased by 13 and 8%, respectively. In fact, the structures together with each other reduced the responses. However, the acceleration response maximum value in cluster mode increased by 6% for the 20-storey structure, compared to the individual mode.

6. CONCLUSIONS

In this study, the influence of inclusion of SCI on responses of base and top (roof) nodes of the structure by considering the shape of wave and height of structure has been studied. In fact, 3 groups of structures (each group comprised of 9 buildings) have been modeled that their main difference is their height (10, 20 and 40-storey frames). Moreover, three individual structures with different heights have been modeled. Afterwards, the grouped and individual structures are subjected to earthquake record such that the concerned earthquake in 4 times in form of 4 different wave shapes is applied to the individual and grouped structures. Then, structural responses are compared with response of the structure located in the middle of the group. It was found that in general, response of the structure located in a group is smaller than that of the individual ones proving the fact that adjacent structures reduce the responses and when Love wave type is propagated, maximum reduction is observed. Moreover, effect of height was assessed and found that SCI decreases the responses.

Regarding the seismic behavior of roof nodes, the effects of site-city (the placement of structures alongside each other) reduced the acceleration responses of all structures in SH, Rayleigh and Love waves (on average about 20, 30 and 50%), which is the largest reduction in response in love wave. For P wave, the site-city interaction for short and intermediate structures increased the responses of structures (on average about 40%). Probably the reason for this increase is due to the vertical propagation of earthquake and the overlap of vertical components released from structures.

In addition, increasing the height of structure does not have a direct and incremental effect on the effect of site-city interaction. In many analyses, the effect of multiple interactions between buildings in 10- and 40-storey is more than 20 floors.

Further, given the seismic behavior of foundation, the site-city effects reduced acceleration of foundation in different structures in P, Rayleigh and Love waves (on average about 5, 7 and 30%), the maximum of which is related to Love wave. Finally, it increased the acceleration of foundation in different structures in the SH wave due to the site-city interaction effects (on average about 15%).

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Persian Abstract

چکیده

اثرات همزمان خاک و تعداد سازه های موجود، به عنوان اندرکنش ساختگاه–شهر (سازه–خاک–سازه) شناخته می شود. این موضوع در مناطق با تراکم ساختمانی زیاد بسیار مهم می باشد. لحاظ اثر اندرکنش ساختگاه–شهر بر رفتار سازه تاثیر گذار می باشد. در بررسی اندرکنش ساختگاه–شهر پارامتر های زیادی از جمله جنس خاک و میزان تراکم و نظم ساختاری شهری، ارتفاع ساختمانها تاثیر دارد. در این تحقیق تاثیرات طبیعت و شکل موج لرزه ای و صفحه ای که این امواج اثر می کنند و ارتفاع ساختمانها در اندرکنش ساختگاه–شهر بصورت سه بعدی در بام و فونداسیون سازه بررسی شده است. از نتایج کلی این تحلیل اینکه در حالت اعمال زلزله به شکل موج love نسبت به بقیه امواج، بیشترین کاهش در پاسخهای شتاب سازه در گروه نسبت به حالت منفرد اتفاق افتاده است بطوریکه این کاهش بطور میانگین برای گره پایه سازه در حدود ۳۰ در صد و برای گره بالای سازه در حدود ۵۰ درصد بوده است.