Investigating Conventional FE Modelling for Dynamic Soil-Structure Interaction under Horizontal and Vertical Ground Motions

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SUMMARY:
This paper considers conventional finite element capabilities and investigates the effects of some important analytical modelling parameters on the dynamic response of structures under concurrent horizontal and vertical ground motions. It focuses on the effects of the structural type and aspect ratio, the soil mass, dimension of soil model and boundary conditions.

Structural systems include 5, 10 and 20 stories steel moment resisting and braced frames with three different height-to-base ratios. The soil-structure system is analyzed using 2D finite element models and linear dynamic method with a suite of selected and scaled ground motions. The base shear and interstory drift values are compared for the different models and the effect of different parameters are discussed.

The results show that among the models with soil mass those with tied boundary condition have clearly performed well in simulating the free field motion as well as producing more consistent results for different soil dimensions. In contrary to massless soil models the seismic response in models considering the soil mass may vary considerably as a function of soil model size, structural type and boundary condition.

Keywords: Soil Structure Interaction, Deconvolution Analysis, Boundary Elements, Vertical Ground Motion

1. INTRODUCTION

The Soil-Structure Interaction (SSI) has long been considered by civil and structural engineers as one of the important issues that may affects the actual behaviour and design of the structures (Wolf 1985, Kramer 1996). Observations made during large earthquakes have specifically emphasized the importance of the dynamic soil-structure interaction. Based on these observations generally the effect of soil-structure interaction may increase of reduce the dynamic response, compared to the response of the fixed based structure, depending on the characteristics of the soil and the structure (Nakhaei and Ghannad, 2008). Due to well known complexities during the past several decades the analysis of the dynamic soil-structure interaction under seismic loads has been carried out using varying extent of simplifications. The main complexities arise from the inherent complexities in dynamic problems, considerable uncertainties in soil properties as well as seismic input motion and the extent of parameters affecting the interaction problem, partly concerned with suitable modelling of the soil and its boundaries.

In recent years continuing progresses in analytical capabilities and speed of the computational tools has significantly facilitated the assessment of interaction problem and many accurate and sophisticated methods have been developed (Hall and Oliveto 2003, Schanz and Iankov 2009). Nonetheless practical use of these tools and methods has been limited by the lack of the standard procedures or sophistications beyond required level for design purposes (Nielson, 2009). The recommendations in existing guidelines or standards such as FEMA 356 (2000), FEMA 450 (2003), and ASCE7 (2005) mainly concerns with some simplified consideration to modify the response of a fixed base structure to account for the effects of SSI. More detailed guidelines may be found in ASCE 4-98 standard (ASCE, 2000). In addition most existing guidelines only consider the horizontal component of the ground motion.

There are two general methods of soil-structure analysis which are normally used in the research and the practice. One is the substructure method which defines an artificial border immediately below the base of the structural foundation, using the concept of dynamic impedance of the unbounded soil. The other method is normally called direct method which directly models part of the unbounded soil media. There are theoretical and practical advantages and disadvantages for both methods which can be found in extensive literatures related to the subject (e.g. Wolf, 1994). However, direct method appears to be more attractive when using general purpose finite element software.

This paper considers conventional finite element capabilities and investigates the effects of some important analytical modelling parameters on the dynamic response of structures under concurrent horizontal and vertical ground motions. Among various parameters affecting the soil-structure interaction it focuses on the effects of the structural type and aspect ratio, the soil mass, dimension of soil model and boundary conditions. In the following various aspect of finite element modelling, ground motion representation and analysis steps are presented. The results also discussed with regards to main considered parameters.

2. SPECIFICATIONS OF THE SOIL AND STRUCTURAL SYSTEM

The soil-structure system used for this study consists of a soil layer with constant depth and a steel frame which is located on the top of the soil layer. Two types of structural systems are assumed for the structures: moment resisting frame and concentrically braced frame. All the structures are symmetric and assumed to have similar number and size of spans and constant storey height of 3 meters. To consider the effect of the structural aspect ratio on the soil-structure interaction effects each type of structural system include three frames with 5, 10 and 20 stories corresponding to structural aspect ratio of (height : base) 1:2, 1:1 and 2:1, respectively. The geometry of 10 storey moment resisting and braced frames is shown in Figure 1. Other structures have similar geometrical specifications except that their number of stories is different. A continuous reinforced concrete foundation is also assumed for all structures. Assuming 4m spaced frames, gravity loads on the structures are assumed to be 3080 kg per unit length of the beams based on Part 6 of National Building Regulations (INRB, 2006). These structures have been analysed using the seismic loads calculated based on the Iranian seismic code (Standard 2800, BHRC, 2005) assuming a fixed base, soil type III and maximum ground acceleration of 0.35g and designed according to Part 10 of National Building Regulations (INRB, 2008). The soil is assumed to have the following specifications: shear wave velocity of 300 m/s, deformation modulus of E= 466 N/mm^2, poison ratio v=0.35 and density of 18 KN/m^3. These specifications are consistent with the type III soil in Standard 2800 (BHRC, 2005).

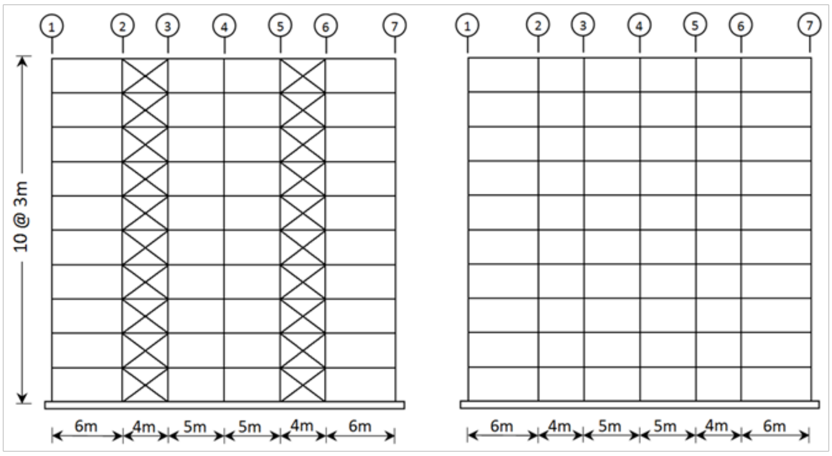

Figure 1: The geometry of 10 storey braced and moment resisting frames

3. FINITE ELEMENT MODELLING

Finite element modelling of the soil-structure problem is tackled here using conventional modelling capabilities normally available in most of the standard finite element programs. In this study the computer program SAP2000 (CSI, 2008) is used for the soil structure interaction modelling. The soil is assumed to be a single layer of 80 meter deep. This is more than 2.5 times the base width of the considered structures. The soil is modelled using two dimensional plane strain elastic elements. Two alternatives of soil modelling are used: one which includes the mass of the soil and other which ignores the mass (massless). The damping is assumed as 4% of the critical damping using Rayleigh damping definition. The members in the frame structures are modelled using beam elements. The construction of the soil-structure model is completed using nonlinear GAP connector elements between the reinforced concrete foundation of the structure and the soil. The nonlinear GAP elements consist of an elastic spring and an incorporated opening so that no tensile forces are transmitted between the structure and the soil and the behaviour of the element is linear elastic under compressive forces. For the model used in this research zero initial opening has been assumed. The stiffness of the spring is calculated so that the compressive forces are transmitted with negligible relative displacements between the foundation of the structure and the soil. For this purpose the GAP elements are defined every one meter along the length of the structural foundation with sufficiently high spring stiffness value (10^4 KN/m). In addition it is assumed that the sliding between the foundation and the soil is negligible. This is modelled by imposing an equal horizontal displacement constraint for all corresponding foundation and soil nodes.

To reduce the numbers of the elements the soil element sizes are increased as we move further away from the structure. For appropriate modelling of dynamic interaction the soil mesh sizes are limited to $\lambda/10$ where λ is the wave length for the waves propagating within the soil (Chowdhury and Dasgupta, 2009).

In terms of the boundary conditions for the analytical model a fixed boundary is assumed at the base of the soil model while for vertical soil boundaries three alternatives are investigated as described below:

- *Free boundaries*: In this alternative the displacement at the side boundaries are free from any constrains. In other words independent displacements at two vertical soil boundaries can take place. This is used as a simple and fast modelling alternative to investigate its effectiveness compared with two other alternatives.
- *Tied boundaries*: in this alternative the corresponding nodes on two vertical boundaries at two side of the soil model are tied to each other so that their horizontal and vertical displacements to be the same at all times during the analysis. Tied boundaries are based on the assumption that at the sufficiently far distances from the structure the effect of the structure on the soil vibration is negligible (Zeinkiewicz et al., 1989).
- *Transmitting boundaries*: By transmitting boundaries here we mean those which are used to represent the effect of the truncated soil by using viscous dampers at the boundaries. These are also referred as absorbing and viscous boundaries in the literature. These boundaries, which can fully absorb body waves propagating normal to the boundary, were initially proposed by Lysmer and Kuhlemeyer (1969). Accordingly The damping coefficient for the horizontal and the vertical dampers are defined in the following by Eqns. 3.1 to 3.3:

$$C_h = -\rho V_p A \,, \quad C_v = -\rho V_s A \qquad (3.1)$$

$$V_p = \sqrt{K/\rho} \,, \quad V_s = \sqrt{G/\rho} \qquad (3.2)$$

$$G = \frac{E}{2(1+\nu)}\,,\ \ K = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (3.3)$$

In these equations C_h and C_v are the coefficient of horizontal and vertical viscous dampers, V_p and V_s are the compressive and shear wave velocities in the soil, respectively, and A is effective nodal area for the node that is connected to the damper. In addition ρ, E, G, K and ν are mass density, elastic modulus, dynamic shear modulus, bulk modulus and poisons ratio of the soil material.

An example of soil-structure model with the transmitting boundaries is shown in Figure 2. The constructed soil-structure system is subjected to time history dynamic analysis with a set of selected and scaled ground motions. Fast Nonlinear Analysis (FNA) method of the computer program is used for the analyses which considers the nonlinearity merely in the GAP elements and ignores any other possible nonlinearity in the system.

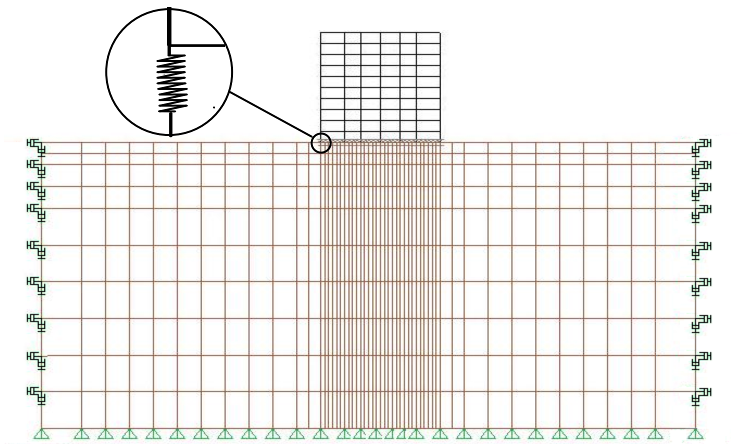

Figure 2: A schematic representation of the FE model for the soil-structure system with transmitting boundaries

4. EARTHQUAKE GROUND MOTIONS

For dynamic analyses three earthquake ground motions, each with horizontal and vertical components, were selected (PEER, 2010). The selection was based on soil type and the seismic hazard scenario considered in the design of the structures. As the effect of the vertical ground motions are to be investigated the ground motions are selected using the near field earthquakes that normally have strong vertical components. The specifications of the selected ground motions are summarised in Table 1. The ground motions are assumed to be representatives of the earthquake motion at the surface of the soil layer (i.e free field motions). After selection, the ground motions are then scaled to the acceleration response spectra with 5% damping used in design stage of the structures, based on the scaling procedure of the seismic standard 2800 (BHRC, 2005).

Table 1: Characteristics of the selected earthquake ground motions

Earthquake	Station	Component	PGA (g)	PGV (cm/s)	Mag.	Distance from the fault (km)	USGS Site Classification
Cape Mendocino	89156 Petrolia	Horizontal x	0.59	48.4	7.1	9.5	C
		Vertical z	0.163	24.5			
Duzce Turkey	Duzce	Horizontal x	0.348	60	7.1	8.2	C
		Vertical z	0.357	22.6			
Loma Prieta	47125 Capitola	Horizontal x	0.529	36	6.9	14.5	C
		Vertical z	0.541	19.4			

Both horizontal and vertical acceleration time histories for the selected ground motions are shown in Figure 3.

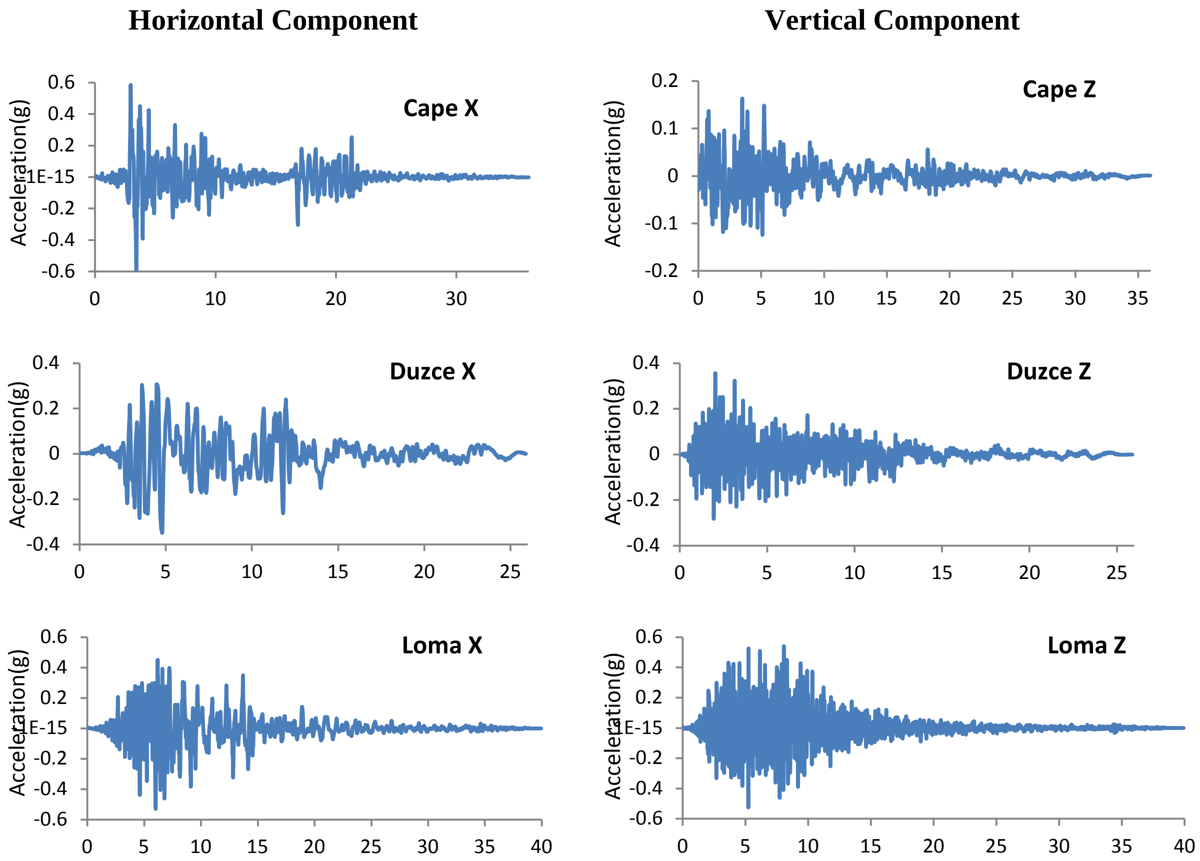

Figure 3: Ground motion time histories used in the analyses

The scaling procedure considers three pairs of ground motions all scaled to their own PGA. In the next step for each pair the 5% damped acceleration response spectra are calculated and combined using SRSS rule to produce a combined spectrum for each pair. The combined spectra for all three pair of ground motions are then averaged and compared with standard design spectrum within the range of 0.2T and 1.5T, where T is the fundamental period of the considered structure. The scaling factor is defined so that the average values remain greater than the corresponding values in design spectrum for all periods in the above range. As a result the scaling value for each structure is different and depends on its fundamental period. The calculated scaling factors are shown in Table 2.

Table2 : Scaling factors calculated for selected ground motions for all structures

Structure	S5 BraceF	S5 BendF	S10 BraceF	S10 BendF	S20 BraceF	S10 BendF
T_1 (s)	0.587	1.59	1.34	2.7	3.2	3.3
Scaling factor	1.87	3.98	3.98	3.98	3.98	3.98

Notes: BraceF means Braced Frame ; BendF means Bending Frame ; S5 means 5 Storey

Ground motions are applied at the fixed base of the soil model. For massless soil models the free field ground motions are directly applied, as the soil model does not affect the propagating waves. However for models that include the soil mass it is necessary to use ground motions which are representatives of the actual seismic motion at the base of the soil layer. To estimate the seismic motion at some depth below the ground surface deconvolution analyses are required. This is done using one dimensional wave propagation approach proposed by Idriss and Seed (1968) and implemented in some computer programs such as EERA (Bardet et al., 2000). In this study EERA has been used for deconvolution analyses.

5. ASSESSMENT OF FREE FEILD MOTION

Since the deconvolution process is carried out by EERA program to validate the process and verify the capability of the SAP2000 soil layer modelling in reproducing the free field motion a series of test runs are carried out on the FE model that only includes the soil layer. The motions generated by deconvolution analysis are fed back to the base of the soil layer in SAP2000 model and the acceleration response spectrum at the surface of the soil is compared with the initial free field spectrum. This is done for all ground motions, three alternative of the soil vertical boundary modelling and at two different points on the ground surface: one being close to the location of structure (near point) and the other one being far from the structure and near to the vertical boundary (far point). For all these analyses a soil layer of 300m wide and 80m deep is used.

The results of these test runs (Mordi, 2011) shows that the model with tied boundary in all cases and in both near and far points demonstrates a good agreement with the original record, when the horizontal component of the earthquake is considered. For vertical component similar results with slightly lesser agreement is obtained. While the results of the other two boundary modelling alternatives (free and transmitting) show much lower agreement level than the tied boundary. Additional analyses considering various sizes of soil domain showed that the model with tied boundary is not sensitive to the size of the soil model when it is increased or reduced by a 50% with regards to the original size (300x80 m, as explained above). Based on these investigation tied boundary model was used in the rest of the research as a base model to compare the results of the other alternatives.

6. SOIL STRUCTURE INTERACTION ANALYSES

Various analyses are carried out in this section to investigate the effects of imporatnt parameters on the SSI analyses. First by adding the structure to the soil layer the effect of the structure on the soil response at the vicinity of the structure is considered.

6.1. Effect of structure on free field response

The six structures introduced in section 2 are individually located on a soil layer with the size of 300×80m (width ×depth) and tied side boundary conditions. The soil-structure system is subjected to all 6 components of 3 ground motions. The soil model is modelled considering the mass of the soil. The acceleration spectra for a point near to the structure at the soil surface are compared in two different models: the model excluding the structure (base) and the model including the structure. The fundamental period on the fixed base structure is compared with the combined system of soil and the structure in Table 3. The table shows that by adding the structure to the soil layer the fundamental mode of the combined system become closer to the period of the soil layer without structure (1.041 sec). The variation depends on the mass and stiffness of the added structure.

Table 3 : Fundamental periods for the frame structures with fixed base and combined soil-structure model (with tied boundary condition**)**

Modeled system	S5 BracF	S10 BracF	S20 BracF	S5 BendF	S10 BendF	S20 BendF
Fixed base Structure	0.587 s	1.349 s	3.229 s	1.597 s	2.728 s	3.300 s
Combined soil-structure model	1.039 s	1.066 s	1.626 s	1.053 s	1.190 s	1.531 s

A sample of the results for this investigation is shown in Figure 3 for Duzce earthquake. Similar results were obtained for two other earthquakes. It can be seen that for small structures (5 storey) the effect of the structure is to reduce the component of spectral acceleration at a point near to the structure. While for larger structures (20 storey) considerably increased effects are seen. It is generally concluded that the addition of the structure changes the characteristics of the ground motion around the structure. This effect is considerably higher for taller structures.

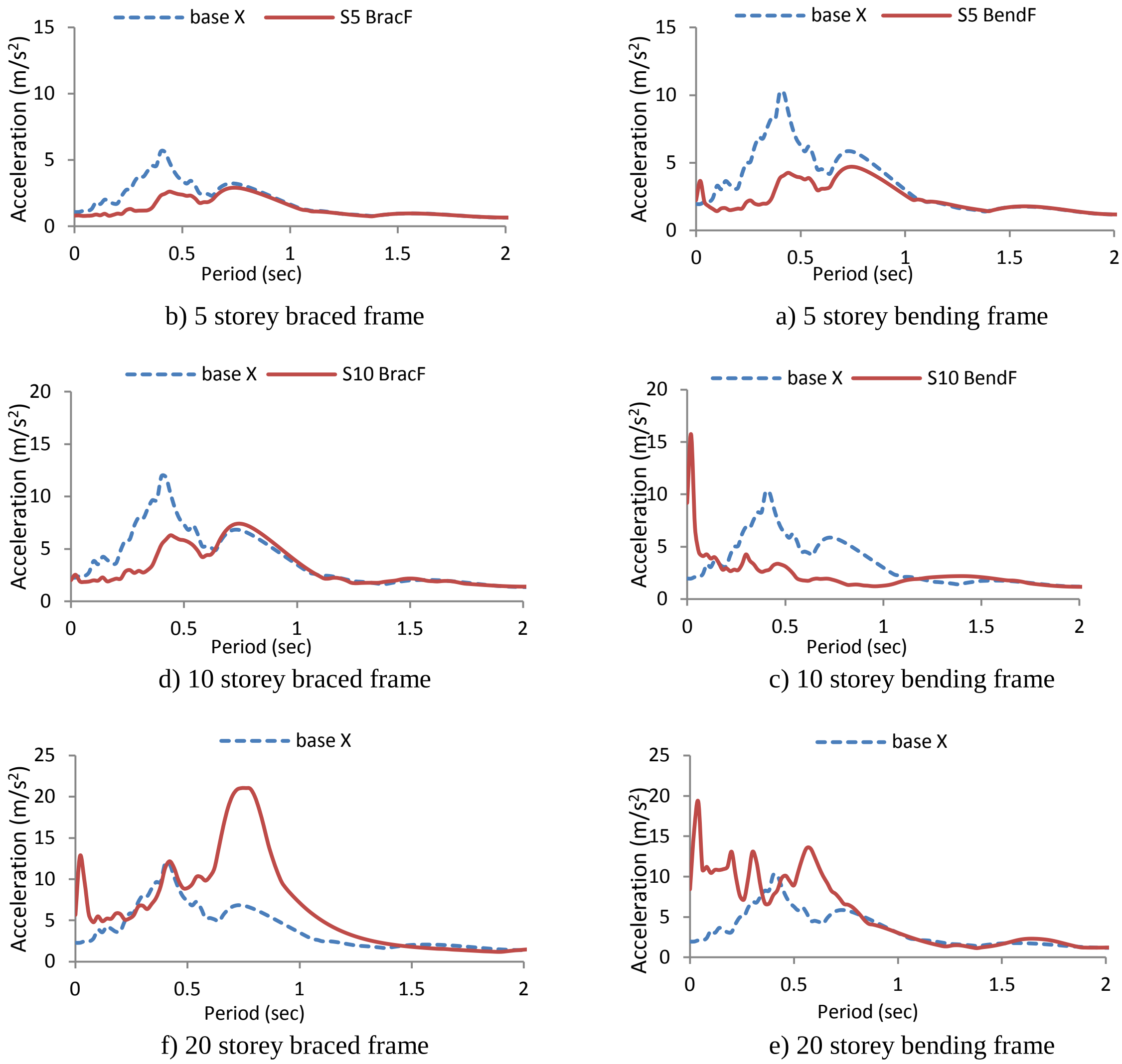

Figure 4: Horizontal acceleration response spectrum for a soil point near to the structure (for models with or without structure) under Duzce earthquake (tied boundary conditions)

6.2. The effect of soil domain size

Here the effect of the size of the soil domain on the interaction response and the sensitivity of the results to this value are evaluated. The response is considered in terms of maximum base shear and interstorey drifts, which are compared to each other in different models as well as the model without soil structure interaction. For this purpose two moment resisting (bending) and braced frames with 20 stories are considered on the FE model of soil with free, tied and transmitting boundaries. Also two alternatives of massless and mass-included soil are considered. It is noted that due to the fact that the boundary condition has no effect on the response of the massless soil, for this model only free boundary is considered. The soil domain is considered in three sizes so that the width of the soil domain to be 5, 10 and 15 times the width of the structure (F=5B, 10B and 15B) and the structure is located symmetrically in the middle of the soil domain. Figure 5 shows the maximum base shear for all models and earthquakes and Figure 6 shows a sample of maximum interstorey drift results for the Cape earthquake. Note that the “No SSI” models represent the frame structures’ modelling with fixed base assumption and the corresponding results are independent from soil domain size. Mass and No Mass indicate soil domain models with and without mass, respectively. The other abbreviations used on the figures specify the type of the boundary and are self explanatory.

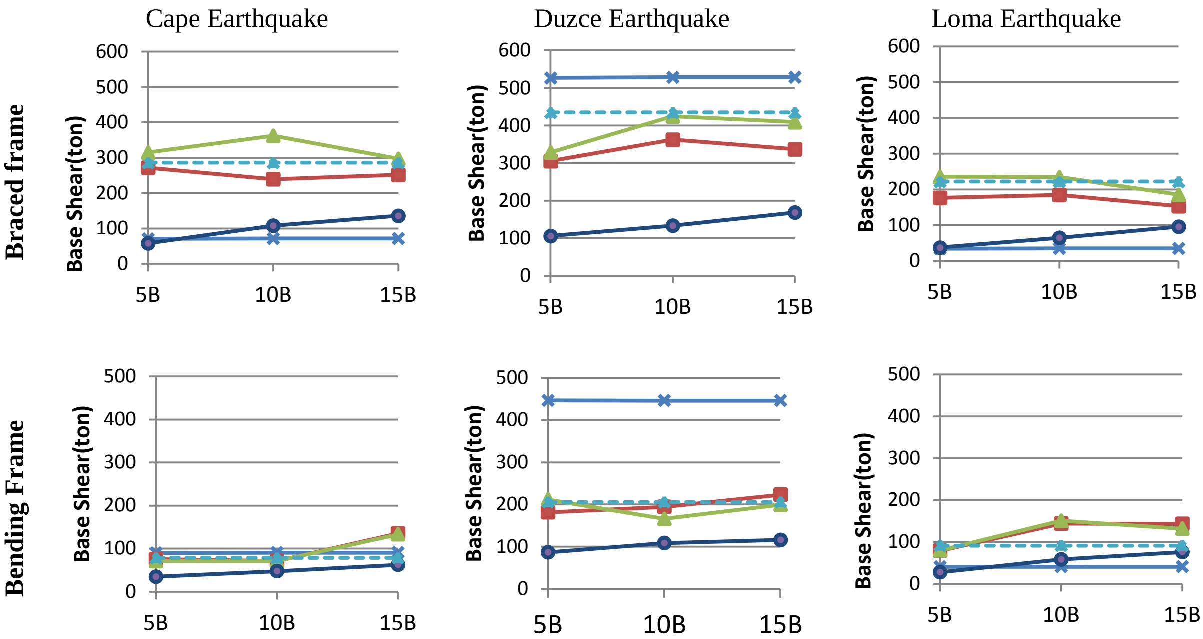

Figure 5: Maximum base shear for 20 storey frames (different size of the soil domain & earthquakes)

From these results it can be seen that in the massless models maximum base shear is not affected by the soil domain size but it is sensitive to the type of the earthquake. In both types of the structures and under all earthquakes the base shear in the model with transmitting boundaries increases with increase in the size of the soil domain size. Among the models including soil mass the minimum base shear corresponds to the model with transmitting boundaries, irrespective of the type of the structure or earthquake. In the models including the soil domain mass and having free or tied boundaries it is seen that with the increase of the soil domain size there are changes in the value of the base shear but the variations do not follow any specific trend.

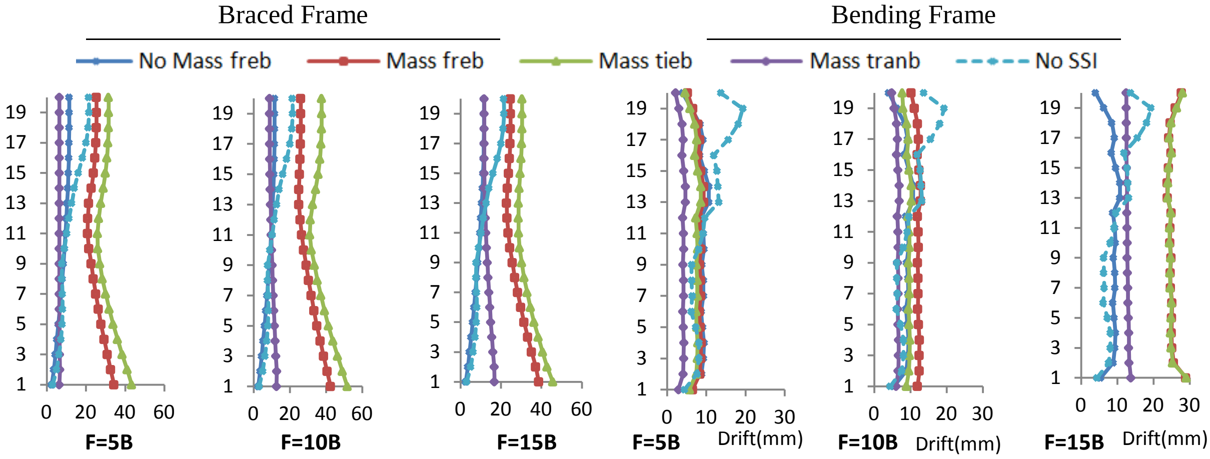

Figure 6: Maximum interstorey drift for 20 storey buildings with different soil size under Cape earthquakes

6.3 The effect of boundary modelling on the response of the structures

To investigate the effect of the type of boundary modelling the same 5, 10 and 20 storey bending and braced frames are considered with a constant size of the soil domain (300m×80m) and two alternatives for the soil mass (with and without). The models are subjected to concurrent horizontal and vertical ground motions. Extensive results for various cases have been extracted and discussed elsewhere (Moradi, 2011). In Figure 7 maximum base shear and interstorey drifts from all 3 earthquakes are depicted. Wherever the SSI is considered in most cases the maximum interstorey drift of the different structures corresponds to the massless soil models. However it is noted that in the case of 10 storey braced frame under all three earthquakes the maximum response corresponds to models with soil mass included. This means that even if we ignore the results of the massless soil, considering SSI can result in a significant increase of drift value up to twice the models that do not consider SSI. More over this shows that the results of the massless foundation are not necessarily conservative in all cases.

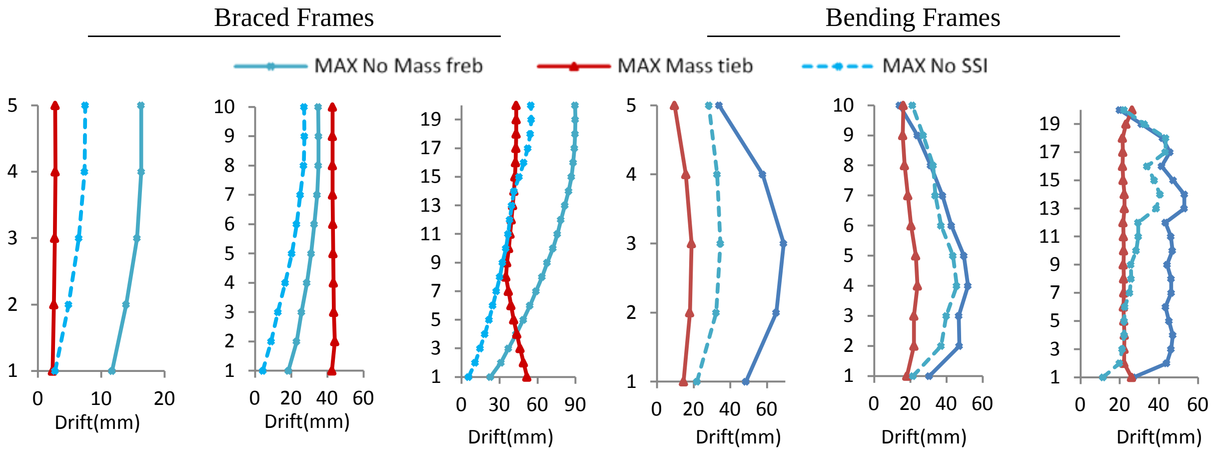

Figure 7: Maximum interstorey drift for bending and braced frames under 3 different earthquakes

7. CONCLUSIONS

In this study soil structure problem was tackled using some simple modelling choices available in most standard finite element programs. Several parameters that deemed to be important were investigated such as: soil mass, soil domain size, boundary type, structural type and aspect ratio. In all analyses both horizontal and vertical component of the earthquake were considered. The following are the main conclusions from this study:

- Considering the assessment of free field response it is concluded that the model with tied boundary conditions performs well in simulating the free field motion both at near and far point of the soil system and under both horizontal and vertical component of the earthquake.
- Adding the structure on the soil layer alters the ground motion characteristics near to the structure and the extent of the modifications depends on the structural height (or period), type of the structure and earthquake. For small structures the effect of the structure is independent of the structural type and the applied earthquake, where it reduces the spectral acceleration around the structure while for larger structures clearly a significant increase is observed.
- When the structure is present on the soil layer seismic responses in the models with soil mass for all three boundary types may considerably vary as a result of change in soil domain size. However in this investigation no specific trend was found to be governing on the changes in the base shear value for different structures due to variations in soil domain size.
- The seismic response of different structural models is greatly affected by the type of boundary modelling. However it is noticed that for smaller structures, having different boundary types, the response values for the models are quite close to each other while with the increase of the height of the structure the differences in the response are also increasing.
- The results also show that considering dynamic SSI may increase or reduce the seismic response depending on the characteristics of the soil and the structure. However with regard to interstorey drifts it can be said that in most cases considering SSI will increase the drift values, more specifically in taller structures.

Overall it appears that tied boundary modelling has clearly performed better than free and transmitting (viscous) boundaries, for both horizontal and vertical component of the earthquake.

Despite considerable efforts to take into account some important parameters for simplified finite element modelling of the soil-structure system, it is imperative to point out that this research study attempted to provide a comparative assessment of various parameters. Comprehensive assessment of the models discussed in this study would require more accurate modelling of system using available more advance analytical tools.

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