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A STUDY ON EFFICIENCY OF PERFECTLY MATCHED LAYER (PML) FOR SEISMIC SOIL-STRUCTURE INTERACTION

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Abstract: The direct method is a finite element approach used in soil-structure interaction (SSI) analysis. The main assumption of this method is the transformation of the infinite soil domain to the truncated soil domain applying different boundary conditions. The objective of this study is to examine the efficiency of The Perfectly Matched Layers (PML) for SSI analysis. For this purpose, the soil-structure problem with different planar-sized truncated soil domains with constrained boundary (CB) and non-reflecting boundary (NRB) were analyzed using 3 different soil stiffness. The results obtained from these analyses were compared with PML and fixed-base reference model results. According to the findings, if the truncated soil domain planar sizes are larger than 10 times the foundation widths for traditional boundary conditions, the effect of the soil domain size is negligible. When the foundation soil stiffness is assumed to be medium and hard, it was observed that PML results are very close to other boundary condition model results, but greater differences were observed in results between PML and other models for soft foundation soil conditions. From the parametrical study, it was concluded that PML provides superiority in terms of computational cost and practical application.

Keywords: Soil-structure Interaction, Boundary Condition, Perfectly Matched Layer, Non-reflecting Boundary, Soil Stiffness

Sismik Yapı-Zemin Etkileşimi İçin Mükemmel Eşleşen Katmanların Etkinliği Üzerine Bir Çalışma

Öz: Direkt yöntem, zemin-yapı etkileşimi (SSI) analizlerinde kullanılan bir sonlu eleman yaklaşımıdır. Bu yöntemin temel varsayımı, sonsuz zemin ortamının, farklı sınır koşulları uygulanarak sınırlandırılmış zemin ortamına dönüştürülmesidir. Bu çalışmanın amacı, SSI analizi için Mükemmel Eşleşen Katmanların (PML) etkinliğini incelemektir. Bu amaçla, zemin-yapı etkileşim problemi geleneksel rijit sınırlar (CB) ve yansıtmayan sınırlar (NRB) ile sınırlandırılan 3 farklı rijitliğe sahip kırpılmış zemin ortamı ile analiz edilmiştir. Bu analizlerden elde edilen sonuçlar referans ankastre tabanlı model ve PML modelleri ile karşılaştırılmıştır. Elde edilen bulgulara göre kırpılmış zemin hacminin plandaki boyutları temel genişliğinin 10 katını aşması durumunda zemin ortamının yapı davranışı üzerindeki etkisinin olmadığı görülmüştür. Temel zemini orta ve sert olması varsayımında PML ve diğer sınır koşullarından elde edilen sonuçların birbirine oldukça yakın olduğu ancak yumuşak zemin koşullarında aralarında daha büyük farklılıkların oluştuğu gözlemlenmiştir. Parametrik çalışmalar sonucunda PML'nin çözüm süresi ve uygulama kolaylığı açısından oldukça üstünlük sağladığı çıkarımı yapılmıştır.

Anahtar Kelimeler: Yapı-zemin Etkileşimi, Sınır Şartı, Mükemmel Eşleşen Katman, Yansıtmayan Sınır, Zemin Rijitliği

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1. INTRODUCTION

In the last decades, soil-structure interaction (SSI) analysis has been a very popular scientific research field that has attracted the attention of researchers dealing with structural and geotechnical engineering. It is well known that the seismic response of structures is influenced by the interaction between the foundation of the structure and the supporting soil, which is called soil-structure interaction. This interaction between soil and structure significantly affects the structural behavior, as well as the behavior of the soil around the structure.

In the analyses of structural systems, it is generally assumed that the superstructure is fixed to the soil medium through the foundation system, and SSI is neglected. This assumption is reasonable for flexible structures resting on stiff soil or bedrock. However, scientific research shows that this is not a suitable approach and the periods of structures resting on soft soil are increased by permitting movement to some extent due to deformability of soft soil (Mylonakis and Gazetas, 2000; Jeremić et al., 2009; Torabi and Rayhani, 2014).

Soil is a semi-infinite and non-homogeneous medium, which has quite complex material behavior. Therefore, the realistic modeling of semi-infinite soil medium is highly complicated compared to modeling of the superstructure. Selection of proper numerical modeling or computation methods according to the nature of the problem is an important stage for soil-structure interaction.

The most common numerical methods used in SSI analyses are substructure and direct methods. In the substructure method, the whole system is divided into different sub-structures, and the response of each sub-structure is calculated separately. The responses of all sub-structures are finally superposed to calculate the behavior of the whole system (Wolf 1985). Although limited for linear analyses, nonlinearity is very difficult to take into account for unbounded soil media (Bolisetti, 2014 and Fathi et al., 2020).

In the direct method, a more realistic simulation of the nonlinear response of the soil-structure system can be acquired in a single step. Commercial finite element software using the direct method is often adopted for this analysis. Simulation of semi-infinite soil domain is a major challenge in the direct method. To overcome the challenge, soil-medium is truncated or bounded with different assumptions.

The truncated soil medium needs to satisfy the radiation damping and wave propagation in the infinite domain. The waves radiating away from the structure to the soil domain must not be reflected back. In addition, the stress equilibrium at the lateral boundaries of the truncated or finite domain should represent the rest of the soil environment.

These requirements can be achieved by implementing absorbing boundary conditions in finite element programs. In recent years, the most commons of these boundary conditions are Viscous Boundaries (first proposed by Lysmer and Kuhlemeyer, 1969), Non-reflecting Boundaries (first proposed by Smith, 1974), Infinite Elements (first proposed by Bettess, 1977) and Perfectly Matched Layers (first proposed by Berenger, 1994).

Perfectly Matched Layers (PML) were firstly developed for absorbing electromagnetic waves by Belenger and converted to various elasto-dynamic problems by some researchers (Basu and Chopra, 2003; Basu and Chopra 2004 and Basu, 2009). PML is an absorbing layer placed around a truncated part of an unbounded domain for absorption and attenuation of outgoing waves of all non-tangential angles incidence and of all non-zero frequencies. PML has widespread application diversity such as free-space simulation problems, radiation and scattering problems, soil-structure interaction, seismic survey problems, computational fluid dynamics, geophysical subsurface sensing, waveguides, non-destructive evaluation applications, etc. (Kucukcoban and Kallivokas, 2010; Jayalekshimi and Chinmayi, 2016).

Recently, PML including complex formulation has been implemented in commercial finite element software (Basu, 2009; Ates et al, 2013; LSTC, 2017; Poul and Zerva, 2018; Zhang et al.

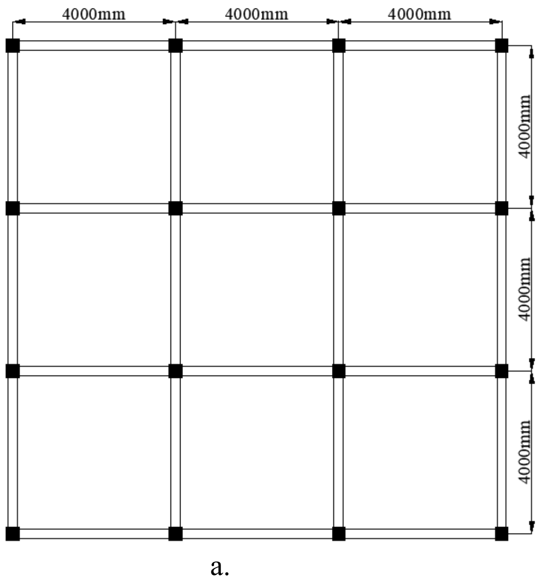
and 2019). According to the literature, there are very few studies on soil-structure interaction that take into account PML as a boundary condition.

In this study, the dynamic behavior of a model structure was investigated depending on the direct method approach which has different boundary conditions (non-reflecting and constrained boundaries) and truncated soil domain in order to demonstrate the effectiveness of PML on soil-structure interaction analysis depending on different soil stiffness. The results obtained from these numerical models were compared with fixed base model results to exhibit the effect of soil-structure interaction on the seismic behavior of the model structure. The values of roof deflections, inter-story drift, peak acceleration value at roof level, and base shear of structure for all models were compared.

2. MODELING

2.1. Properties of Moment-Resisting Frame System

A four-storey moment-frame system which has storey height and bay length as 3 and 4m, respectively was analyzed by finite element method for determination of the effect of dynamic soil-structure interaction. The plan and the 3-dimensional FEM model of the building considered in the analysis are given in Figure 1. The symmetric structural system has 16 column elements with 320mm x 320mm section dimensions and 24 beam elements with 230mm x 230mm section dimensions on every floor. At each node of the element, there are three translational and three rotational degrees of freedom. The floor and raft slabs having a thickness of 150mm and 300mm, respectively were modeled using a four-node shell element (Belytschko–Tsay). Belytschko–Tsay having bending and membrane capabilities is a default element option in Ls-Dyna and then it possesses six degrees of freedom at each node. In the modeling, beam and columns are formed using beam elements and all dimensions have been assigned as section parameters (shell and beam elements). Element mesh sizes were chosen as 1 m for all components of the structure. The dimensions of structural elements were taken from the study by Jayalekshimi and Chinmayi (2016) with the intent of verification of parametrical studies. The material behavior of structural members has been considered as linear elastic (using *MAT_ELASTIC_001 options). The mass density, Poisson’s ratio, and elasticity modulus of all members are selected as $24*10^3$ N/m^3, 0.25, and $2.70*10^{10}$ Pa, respectively (Table 1).



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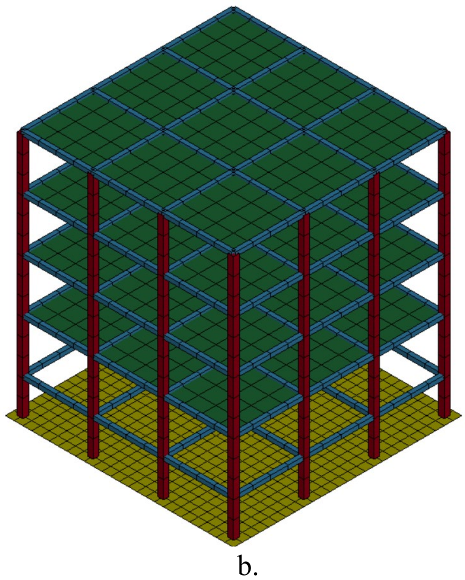


b.

Figure 1:
Plan view and 3-D FEM model of building

2.2. Properties of Soil Medium

3-dimensional solid elements were used in the modeling of soil medium. These elements are fully integrated with three translational degrees of freedom at each node. In the analyses, soil medium was assumed as linear-elastic, isotropic, and homogeneous. *MAT_ELASTIC_001 option which is founded in Ls-Dyna material library was used in the analyses. The input parameters of this option are Mass density, Elastic modulus, and Poisson's ratio. These parameters were assumed as $15*10^3$ N/m^3, $1*10^7$ Pa, and 0.3, respectively for soil type S-1. While the Poisson's ratio was kept constant, unit weight and modulus of elasticity were taken as $18*10^3$ N/m^3 and $3*10^7$ Pa for S-2, $20*10^3$ N/m^3, and $10*10^7$ Pa for S-3 (Table 1).

Table 1. Elastic material properties of structure and soil

Type	Unit weight (N/m^3)	Modulus of Elasticity (N/m^2)	Poisson's ratio
Concrete	24x10^3	2.7x10^{10}	0.25
S-1 Soil	15x10^3	1x10^7	0.3
S-2 Soil	18x10^3	3x10^7	0.3
S-3 Soil	20x10^3	10x10^7	0.3

3. SOIL-STRUCTURE INTERACTION ANALYSIS

In the conventional seismic design guides, structures have been assumed that they are fixed to foundation level and soil deposit is not considered under fixed supports. This assumption can be acceptable for foundations resting on very stiff soils or rock. However, many researchers have stated that the dynamic behaviors of flexible and tall buildings founded on soft soils are quite different from the fixed base conditions (Bolisetti, 2014; Tabatabaiefar et al., 2010). This effect called soil-structure interaction has been taken into account in ASCE Standart 7 (ASCE, 2010) and FEMA 440 (FEMA, 2005). The simulation of an infinite soil medium with a finite domain is one of the most important steps in SSI problems. Generally, sub-structure and direct methods have been developed for SSI analysis. In the direct method, soil medium and structure were represented in a model and analyzed in a single step. However, the selection of sufficient truncated soil domain and appropriate boundary conditions are very prominent for simulation of infinite soil domain in the direct method. In this study, a series of seismic SSI analyses which are given in Table 2 have been performed depending on the above-mentioned parameters.

3.1. Soil-Structure Interaction Modeling with Non-reflecting Boundaries

The soil-structure interaction problem can be defined as the determination of structural behavior when a structure is subjected to the earthquake which propagates from bedrock to soil layers. The finite element method is the most common analysis approach to solve soil-structure interaction problems. In this approach, it has been used many idealizations for nonlinearity, wave propagation, layer boundaries, continuity, etc. to represent infinite soil media. For modeling the infinite soil media, a radiation condition between far-field and near field has to be satisfied (Sesli and Akköse, 2013: Sesli, 2022).

One popular of various boundary conditions which were developed by researchers for soil-structure interaction systems is non-reflecting boundaries (NRBCs). This boundary has been used to prevent artificial stress wave reflections generated at the model boundaries from reentering the model and contaminating the results. Especially, NRBCs are important for limiting the spatial extent of the finite element mesh and the number of solid elements for geomechanical problems

(LSTC, 2012). In Ls-Dyna, NRBCs are defined as a collection of segments, which are equivalent to element faces on the boundary. Internally, impedance matching functions are determined for all non-reflecting boundary segments based on an assumption of linear material behavior. Thus, the discrete model of the geomechanical problem may be contained all significant nonlinear behavior using NRBCs which are limited for 3-dimensional solid elements in Ls-Dyna.

In this part of the study, in order to determine the seismic behavior of the structure seen in Figure 1, considering the soil-structure interaction, time history analysis was performed according to the direct method for different boundary conditions and truncated soil domains. 3 different soil domains were selected as 59m, 149m, and 299m square plan dimensions (Figure 2) according to raft width proposed by Bolisetti (2014) and Jayalekshmi and Chinmayi (2016). The depth of soil domain for all models was selected as a constant value of 25m. Material properties, structural elements, and boundary conditions are considered as similar in all finite element models.

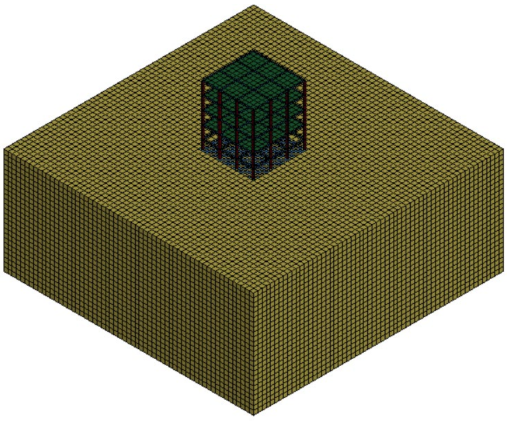
A soil-foundation interface was created with * INTERFACE_SSI option which doesn't allow separation between basemat and soil surface.

In constrained boundary conditions (CBs), the nodes on the lateral boundaries were constrained in the normal direction (to only move in shear) using the *SPC_SET options. However, the nodes at the base of the soil domain are constrained in all directions.

In non-reflecting boundary models, the nodes on the lateral boundaries are free to move in each direction while the ones at the bottom are fully constrained as in constrained boundary models.

Table 2. Details of SSI models

Model no	Boundary Conditions	Soil domain size (mxmxm)
FB	---	----
NRB1	Non-reflecting	59x59x25
NRB2	Non-reflecting	149x149x25
NRB3	Non-reflecting	299x299x25
CB1	Constrained	59x59x25
CB2	Constrained	149x149x25
CB3	Constrained	299x299x25
PML	Perfectly Matched Layers	25x25x6



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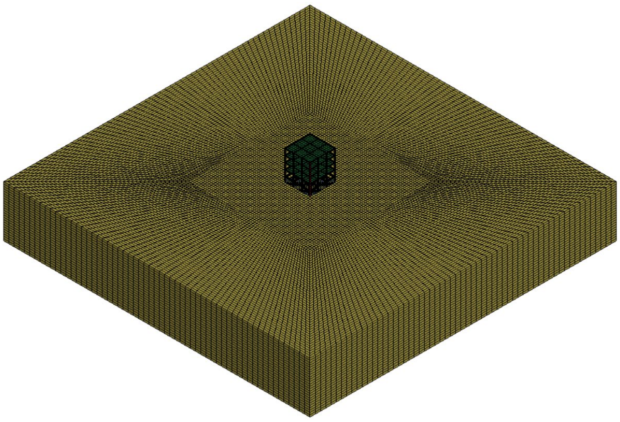

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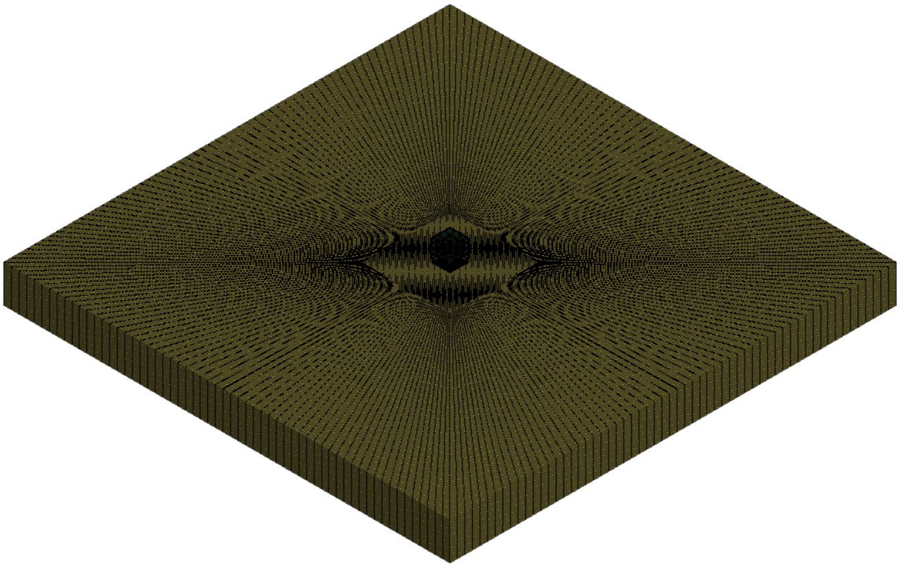


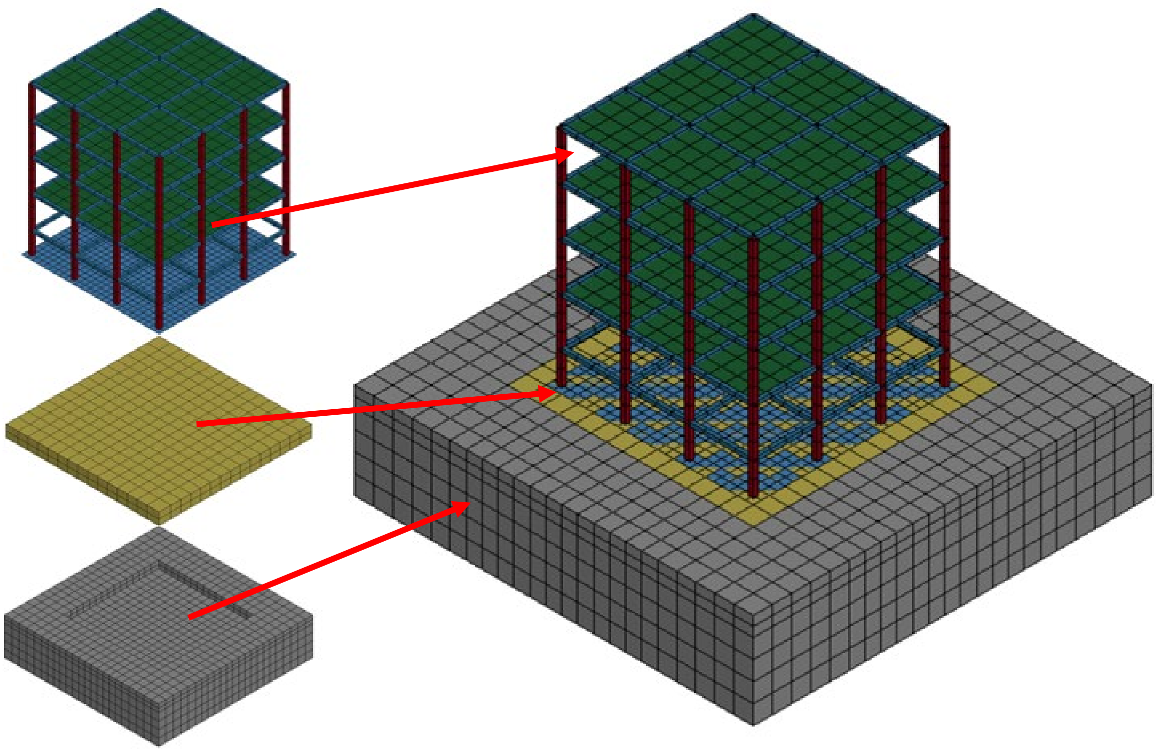
c.

***Figure 2*:**
SSI model with soil domain of;
***a.** 59m*59m plan dimensions* ***b.** 149m*149m plan dimensions* ***c.** 299m*299m plan dimensions*

3.2. Soil-Structure Interaction Modeling with Perfect Matched Layers (PML)

Perfectly matched layer (PML) is an effective solution method for the simulation of infinite soil domain in terms of absorbing and attenuation of seismic waves. These layers were applied adjacent to the truncated part of the infinite soil domain. The main advantage of PML is the capability of absorption of seismic waves propagating in PML with any angle and frequency. Thus, the PML is called 'perfectly matched' for the truncated domain. The PML attenuates the wave inside the layer using an attenuation function. Attenuated waves which have low amplitude re-entered into the truncated domain after being reflected from outer sides of PML. Another superior property of PML is the low computational cost compared with traditional boundaries (CBs and NRBCs etc.).

The width and height of the truncated soil domain (shown in yellow in Figure 3) were accepted as 0.2 and 1.2 times the raft width (B), respectively. The PML's thickness around the truncated soil domain (internal soil domain) was chosen as 0.4 times the raft width (B). These values were proposed by Basu (2009).



a. b.

***Figure 3*:**
Finite Element Model with PML in;
***a.** Separate form **b.** Combined form*

The perfectly matched layer surrounding the truncated soil domain was accepted as a PML elastic material (using *PML_ELASTIC option). Material properties of PML elastic were accepted to be the same as the soil properties given in Table 1. The nodes on the outer surface of the PML layer were constrained in all directions.

A soil-foundation interface was created by *INTERFACE_SSI option which provides a tied-contact soil-structure interface in a transient analysis. If this option is chosen, ground motions recorded on the interface in an earlier analysis are read (LSTC, 2012). In the PML models, the interface was defined between the segments which are selected in raft base and soil top surface.

3.3. Seismic Input

For the soil-structure interaction evaluation, the seismic time history analysis was carried out by Ls-Dyna, which is a commercial finite element software. Input ground motion was selected from the longitudinal component of the Imperial Valley earthquake at El Centro in 1940. The magnitude and peak ground acceleration of the earthquake are 6.95 and 0.28g, respectively. In this study, acceleration time history was scaled down to 0.1g, and the duration of motion was limited with the first 35 seconds (given in Figure 4).

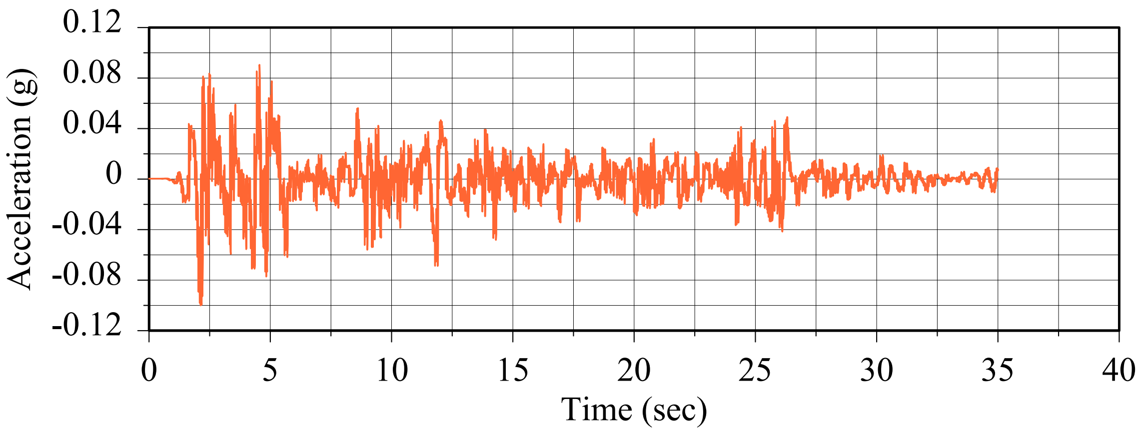


Figure 4:
Time history of Imperial Valley Earthquake

4. RESULTS AND DISCUSSION

A study regarding seismic SSI analysis was realized under transient loading on a 4-storey building and the raft foundation system. The foundation is resting on soil domains having various soil material properties, dimensions, and boundary conditions as implemented in Table 1 and Table 2. Both soil and structure were assumed to behave in a linear elastic manner. The analyses were conducted under the effect of El Centro ground motion, acceleration values of which were scaled corresponding to PGA of 0.1g. Dynamic response of the structure with the effect of soil-structure interaction is presented in Table 3 and Table 4 in terms of the maximum of base shear, roof deflection, peak acceleration, and story drift. Fixed base model is independent of soil material properties since no soil is added on the system. The results of FB are yet specified for S-1, S-2, and S-3 to make a comparison with the other models. To compare the computational cost of various analyses, element numbers and analysis times are provided in (Table 5).

For the purpose of observing seismic behavior of the building under earthquake excitation, base shear, roof deflection, and roof acceleration are plotted with respect to time (Figure 5) for two representative models of S-2: NRB2 and CB2. The seismic behaviors of the building appear to be consistent with the ground motion recording presented in Figure 4.

Table 3. Base shear, roof deflection and acceleration comparison for different models and soil types

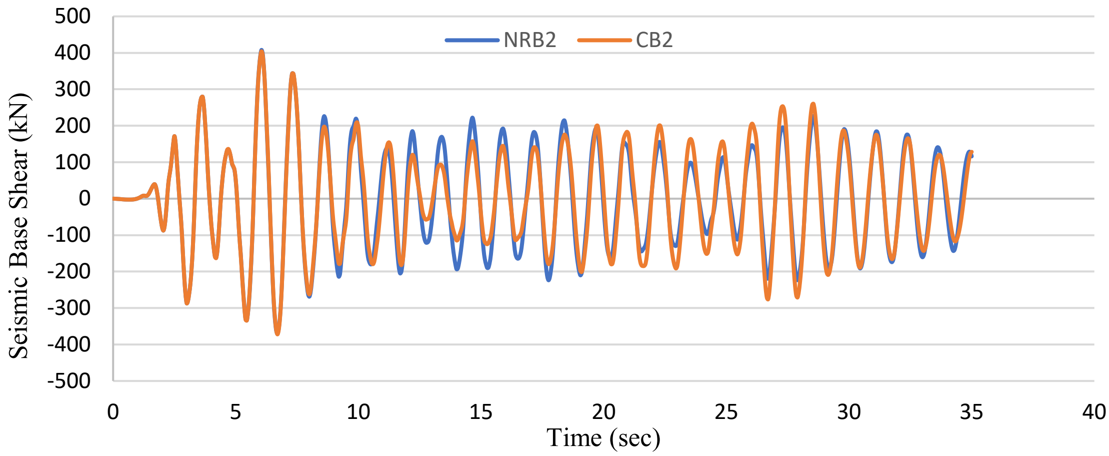
Model No	Base Shear (kN)			Roof Deflection (cm)			Acceleration (g)		
	S-1	*S-2*	*S-3*	*S-1*	*S-2*	*S-3*	*S-1*	*S-2*	*S-3*
FB	517	517	517	7.98	7.98	7.98	0.20	0.20	0.20
NRB1	423	529	516	6.31	7.76	7.93	0.15	0.19	0.19
NRB2	408	527	520	6.15	7.72	7.96	0.14	0.19	0.19
NRB3	405	526	520	6.14	7.72	7.96	0.14	0.19	0.19
CB1	376	547	520	5.84	7.92	7.96	0.13	0.19	0.19
CB2	404	519	520	6.16	7.66	7.96	0.14	0.18	0.19
CB3	405	526	520	6.14	7.72	7.96	0.14	0.19	0.19
PML	356	503	535	5.33	6.75	7.11	0.11	0.16	0.17

Table 4. Story drifts comparison for different models and soil types (in cm)

Model No	S-1				S-2				S-3			
	1st Floor	*2nd Floor*	*3rd Floor*	*4th Floor*	*1st Floor*	*2nd Floor*	*3rd Floor*	*4th Floor*	*1st Floor*	*2nd Floor*	*3rd Floor*	*4th Floor*
FB	3.37	4.42	5.12	5.51	3.37	4.42	5.12	5.51	3.37	4.42	5.12	5.51
NRB1	3.07	4.11	4.86	5.37	3.54	4.67	5.44	5.91	3.35	4.37	5.03	5.40
NRB2	2.98	4.00	4.73	5.24	3.53	4.65	5.42	5.88	3.38	4.40	5.07	5.44
NRB3	2.96	3.97	4.70	5.21	3.52	4.64	5.41	5.87	3.38	4.40	5.07	5.44
CB1	2.78	3.74	4.44	4.94	3.66	4.82	5.62	6.10	3.37	4.40	5.06	5.43
CB2	2.96	3.96	4.70	5.20	3.47	4.58	5.33	5.79	3.37	4.40	5.07	5.44
CB3	2.96	3.97	4.70	5.20	3.52	4.64	5.41	5.88	3.37	4.40	5.07	5.43
PML	2.58	3.43	4.05	4.46	3.37	4.45	5.19	5.63	3.49	4.57	5.30	5.71

Table 5. Element numbers and analysis times of all models

Model No	Element Numbers			Analysis Time (hour)
	Beam	*Shell*	*Solid*	
FB	704	1252	-	0.03
CB1	704	1252	87025	4
CB2	704	1252	352525	17
CB3	704	1252	795025	41
NRB1	704	1252	87025	6
NRB2	704	1252	352525	24
NRB3	704	1252	795025	51
PML	704	1252	3174	0.5



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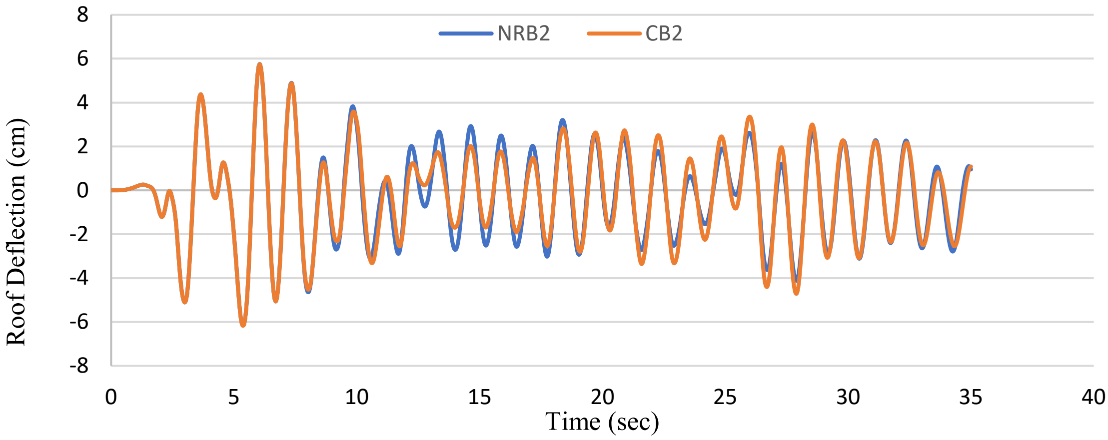

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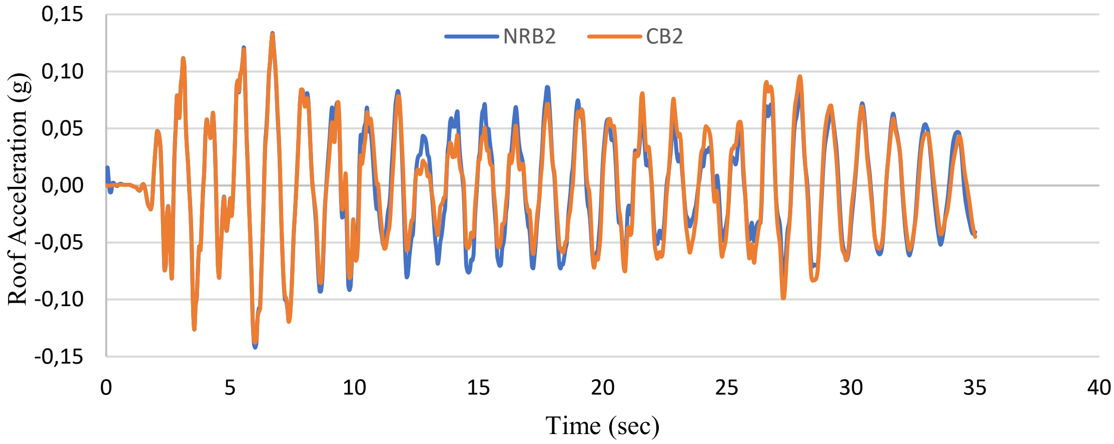


c.

Figure 5:

Seismic response of the building in NRB2 and CB2 models of S-2 soil type in terms of; ***a.*** *Base shear* ***b.*** *Roof deflection in x-direction* ***c.*** *Roof acceleration in x-direction*

4.1. Roof Deflection

Roof deflection can be decided as the resultant displacement obtained at one of the top nodes of the building. The ground motion was applied to the system in x-direction. Thus, the contribution of y and z components of displacement to the resultant is so limited that displacement can be presented in the x-direction. By doing so, the similarity of seismic response of the building with the applied seismic loading can be observed (Figure 5).

Roof deflections belonging to various soil domains, boundary conditions, and soil types under transient seismic loading are presented in Table 3. The results are obtained at the top corner node, which theoretically exhibits the highest deformation, and presented schematically in Figure 6.

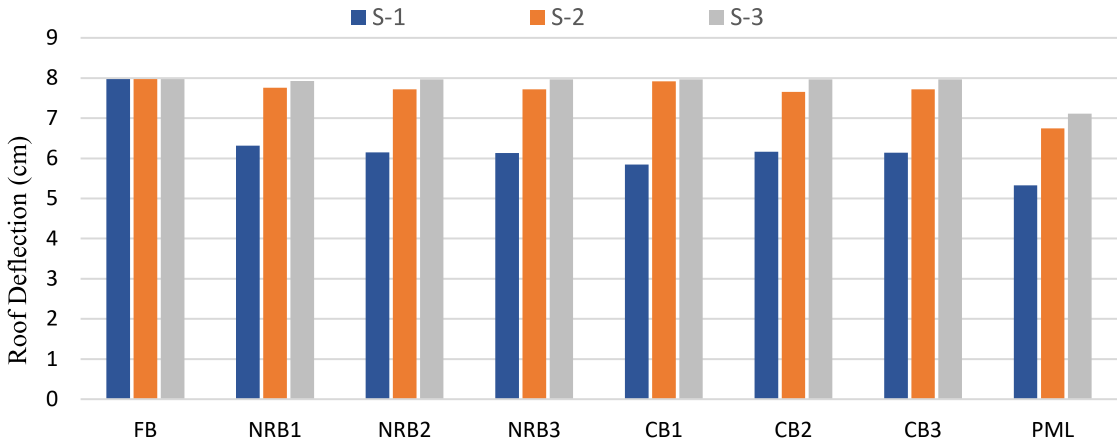


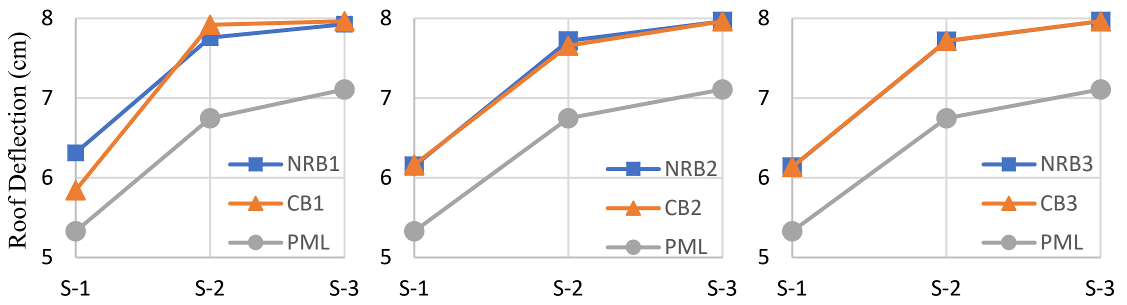
Figure 6:
Roof deflection of the models with different sizes, boundary conditions and soil types.

Fixed base model, the base of which is fully constrained against both translation and rotation is expected to give the highest seismic response when exposed to seismic ground shaking. As seen in Figure 6, dynamic response of the building in roof deflection manner is greatest in FB. The effect of the interaction between soil and structure can be distinctly observed by comparing the seismic responses with changing stiffness. Among the 3 soil types, S-1 has the least stiffness while S-3 is the stiffest one (Table 1). No matter what the soil domain size and boundary condition are, it can clearly be seen that roof deflection tends to be increasing and approaching that of FB with increasing stiffness of the soil (from S-1 to S-3).

For the soil type S-1, models with constrained soil boundaries exhibit an increasing trend with enlarging soil domain. The variation between the maximum and minimum responses in the soil type S-1 is 5.2% while it is 3.4% in S-2. The results obtained in the stiffest soil (S-3), on the other hand, are the same for each soil domain giving a variation of less than 0.1%.

Unlike constrained boundaries, the models with non-reflecting soil boundaries exhibit lower structural responses as the soil domain's plan dimensions increase. The variations in roof deflection responses of NRB models with changing soil domain are limited compared to CBs. The maximum deviations between different soil domains of NRBs with the soil types S-1, S-2, and S-3 are 2.8%, 0.6%, and 0.5%, respectively.

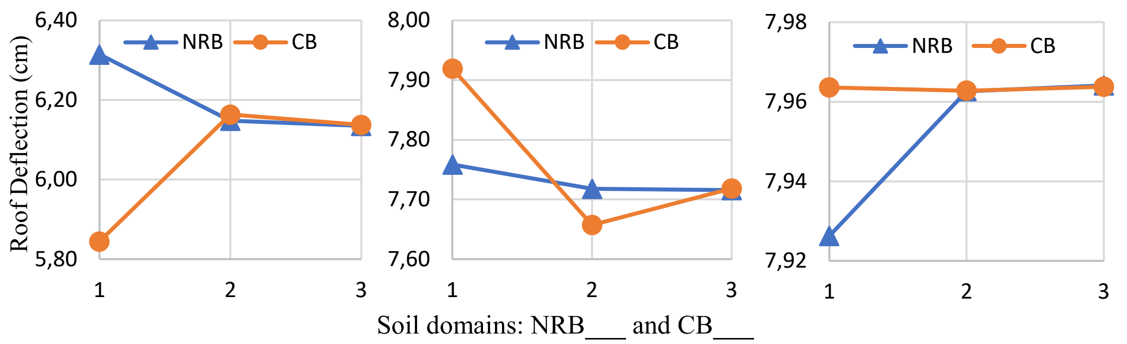
As the soil's stiffness increases, soil domains with non-reflecting and constrained lateral boundaries start responding to the seismic loading in the same way. It can clearly be seen from Figure 6 and Figure 7 that all NRB and CB models with soil type S-3 delivered the same result which is very close to that of FB.



a. b. c.

Figure 7:
Roof deflection magnitudes of NRB and CB models against soil types for;
***a.** smallest **b**. medium **c.** biggest soil domain sizes.*

Moreover, roof deflection obtained from NRB3 and CB3 are the same in all three types of soil. This observation can be followed by the deduction that the effect of lateral soil boundaries on the dynamic response of the structure reduces when the soil domain is large enough. From Figure 8, the deviation between NRBs and CBs can clearly be seen to be decreasing with enlarging soil domain size (from NRB1 and CB1 to NRB3 and CB3).



a. b. c.

Figure 8:
Roof deflection magnitudes of NRB and CB models with soil types;
***a.** S-1 **b.** S-2 **c.** S-3*

Perfectly matched layer seems to be underestimating lateral displacement compared to NRBs and CBs (Figure 7). Roof deflections in x-direction obtained from transient analyses of PML models are smaller than the models with largest soil domain (NRB3 and CB3) by amounts of 13.2%, 12.6% and 10.7% for the soil types S-1, S-2 and S-3, respectively.

4.2. Acceleration

Response of the building was studied in acceleration manner due to adjusted El Centro ground motion. Peak acceleration is obtained at the top corner node of the building in the direction of seismic loading. As explained in the preceding section, y and z components are ignored due to their insignificant contributions. Figure 9 shows the peak acceleration responses of various models and soil types in terms of g.

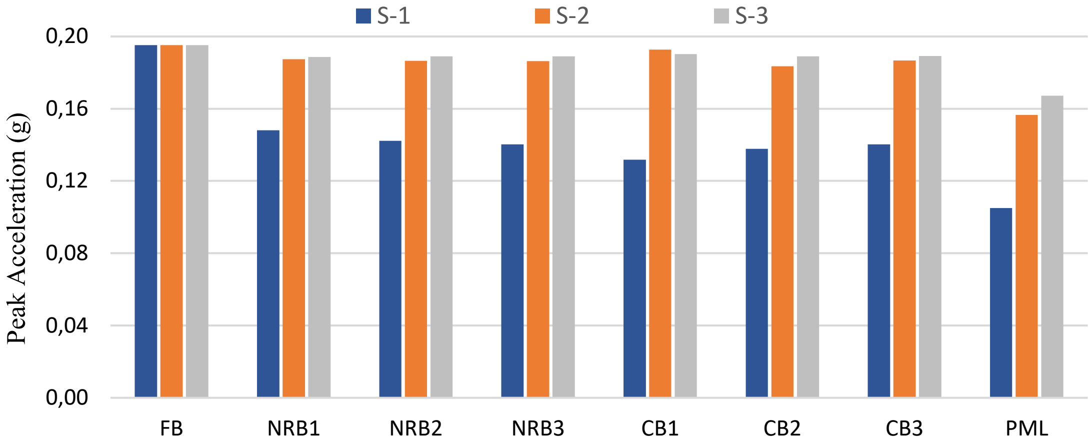


Figure 9:
Peak acceleration of the models with different sizes, boundary conditions and soil types.

The highest acceleration is observed in the fixed base model as expected, since there is no soil domain to decrease the stiffness. The effect of the interaction between soil and structure is investigated based on soil's material properties and surface area with various lateral boundary conditions. For the same soil domain and boundary conditions, soft soil (S-1) is observed to produce the minimum peak acceleration. As in the case of roof deflection, acceleration responses of NRBs, CBs, and PML magnify and approach that of FB as the stiffness of the soil increases (Figure 10).

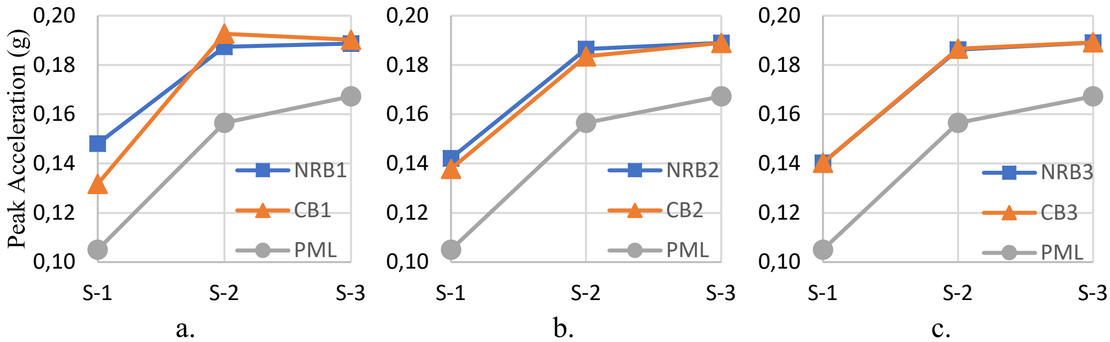


Figure 10:
Peak acceleration magnitudes of NRB and CB models against soil types for;
a. *smallest* ***b****. medium* ***c.*** *biggest soil domain sizes.*

Figure 11 displays the convergence of NRB and CB models with enlarging soil domain. This observation can be explained by the theory that the effect of lateral soil boundary conditions on the seismic response of the structure reduces as the soil domain expands. This is expected because truncated soil starts representing the infinite soil medium when it is large enough.

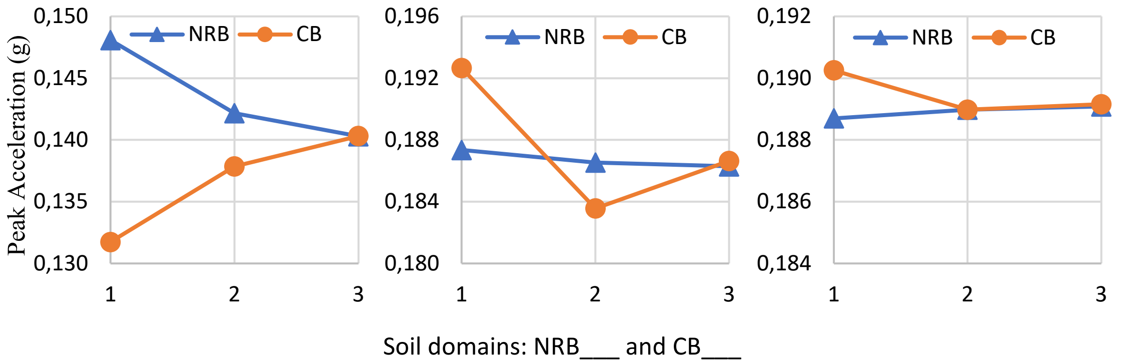


Figure 11:
Peak acceleration magnitudes of NRB and CB models with soil types;
a. *S-1* ***b.*** *S-2* ***c.*** *S-3*

Similar to roof deflection responses, PML appears to underestimate acceleration magnitudes compared to NRBs and CBs (Figure 10). Peak acceleration magnitudes obtained from transient analyses of PML, NRB3 and CB3 for soil type S-1 are 0.11g, 0.14g and 0.14g, respectively. Soil domain modelled with perfectly matched layer, thus, exhibits a deviation 25.1% from both NRB3 and CB3. These deviations drop to 16.0% and 16.1% for S-2, 11.5% and 11.6% for S-3. The divergence of the results obtained from perfectly matched layers from non-reflecting and conventionally constrained boundary diminishes from S-1 to S-3.

4.3. Base Shear

Base shear is the maximum lateral force that is expected to be exerted at the base of a building due to seismic ground motion. Figure 12 provides base shear of the building with the aforementioned soil domains, boundary conditions, and soil types under the effect of El Centro ground motion.

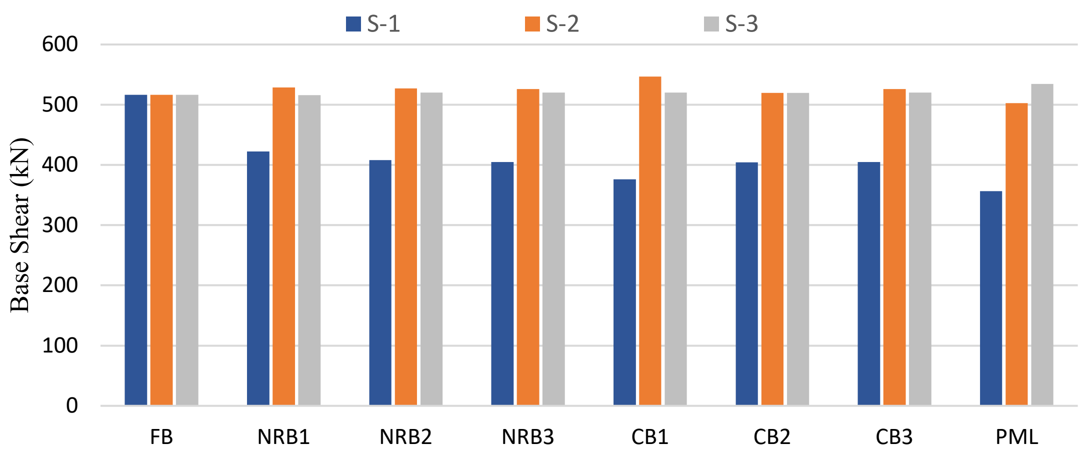


Figure 12:
Base shear of the models with different sizes, boundary conditions and soil types.

Base shear is observed to be more stable in non-reflecting boundaries than traditionally constrained boundaries. The maximum variations among NRB and CB models having the same soil type are 4.2% and 7.1% for S-1. The variations are 0.5% and 4.0% for S-2, 0.9% and 0% for

S-3. Fixed base model presented considerably higher responses than NRBs, CBs and PML when they are modelled with the soft soil domain (S-1). Figure 12 reveals the similarity of base shear responses of fixed base model and the models with the hard soil domain (S-3), no matter what the lateral boundary conditions are. The divergence of maximum lateral forces obtained from NRB3, CB3 and PML from FB when the soil is modelled in the hard form (S-3) are 0.7%, 0.7% and 3.5%, respectively.

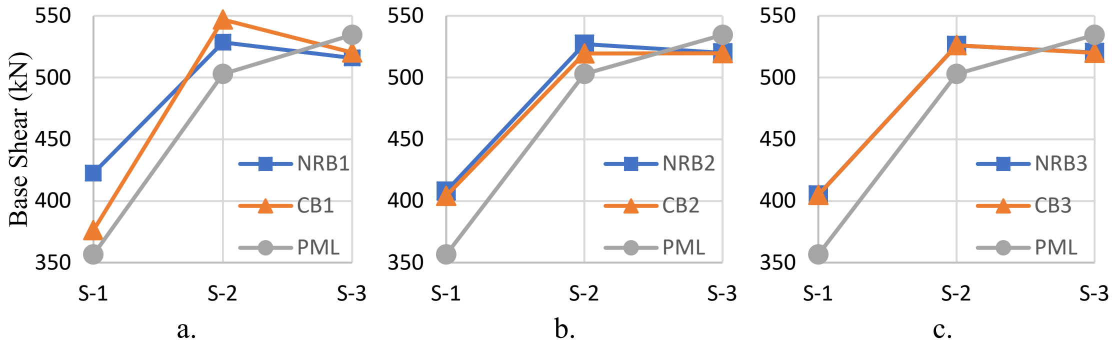


Figure 13:
Base shear magnitudes of NRB and CB models against soil types for;
a. *smallest* ***b****. medium* ***c.*** *biggest soil domain sizes.*

Seismic response of the structures modelled above a soft soil domain remains lower compared to relatively hard models. From S-1 to S-3, not only the seismic base shear responses magnify but also the gap between various boundary conditions closes (Figure 13).

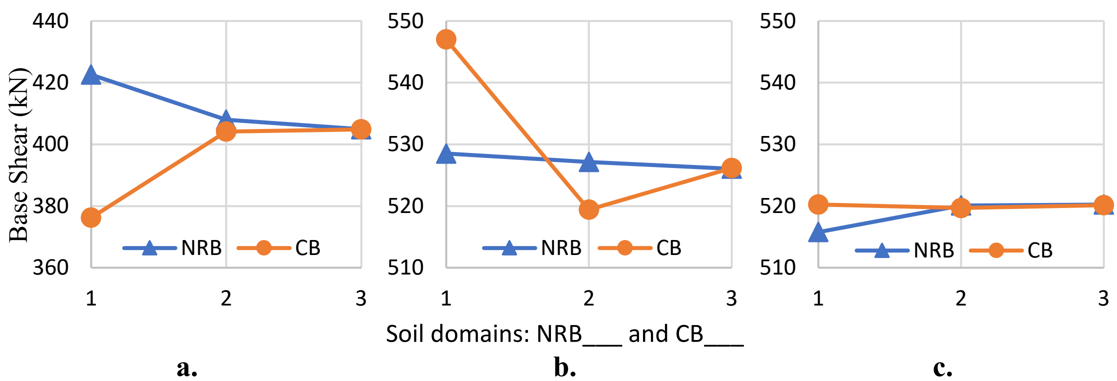


Figure 14:
Base shear magnitudes of NRB and CB models with soil types;
a. *S-1* ***b.*** *S-2* ***c.*** *S-3*

As the truncated soil domain expands, the response to seismic loading converges to that of infinite soil medium. The impact of expanding soil domain on the seismic response can be seen in Figure 14. Base shear magnitudes obtained from seismic analyses of NRB and CB models approach each other as soil's plan dimensions increase.

When the soil type S-1 is considered, PML results in lower base shear magnitudes relative to other models (Figure 13). It was realized that NRB3 and CB3 produced the same base shear for each soil type. The variation of PML (356 kN) from NRB3 (405 kN) and CB3 (405 kN) is 11.9%. This divergence drops to 4.4% in S-2 and 2.8 in S-3. As in the case of roof deflection and acceleration, the base shear response of perfectly matched layers seems to match better with those of non-reflecting and conventionally constrained boundaries as the stiffness of the soil increases. Unlike roof deflection and peak acceleration, the base shear response of PML exceeds NRBs and CBs when the structure is modelled above the hard soil (S-3).

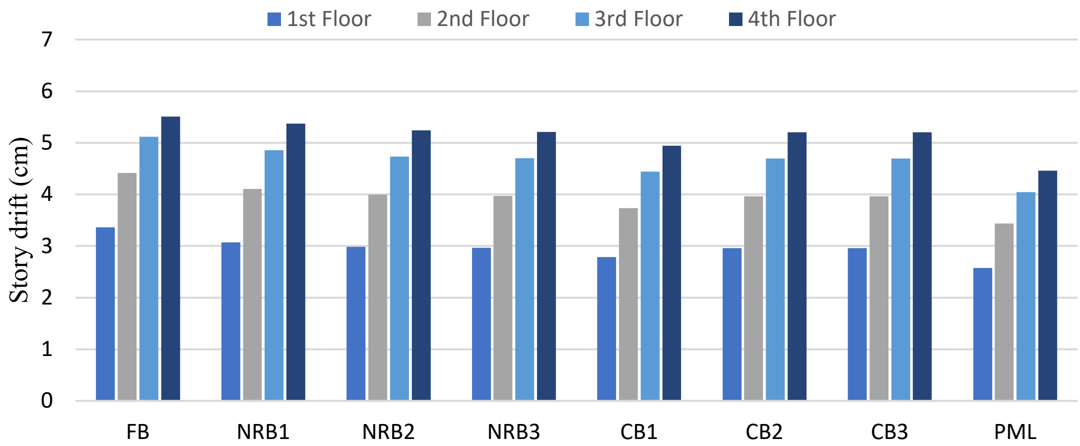
4.4. Story Drift

Story drift can be defined as the movement of a particular storey relative to a reference storey. In this case, ground floor is taken as reference. Displacement of each storey from the ground to the roof, due to the seismic loading of El Centro ground motion is obtained. Table 4 includes story drifts in x-direction rather than the resultant.

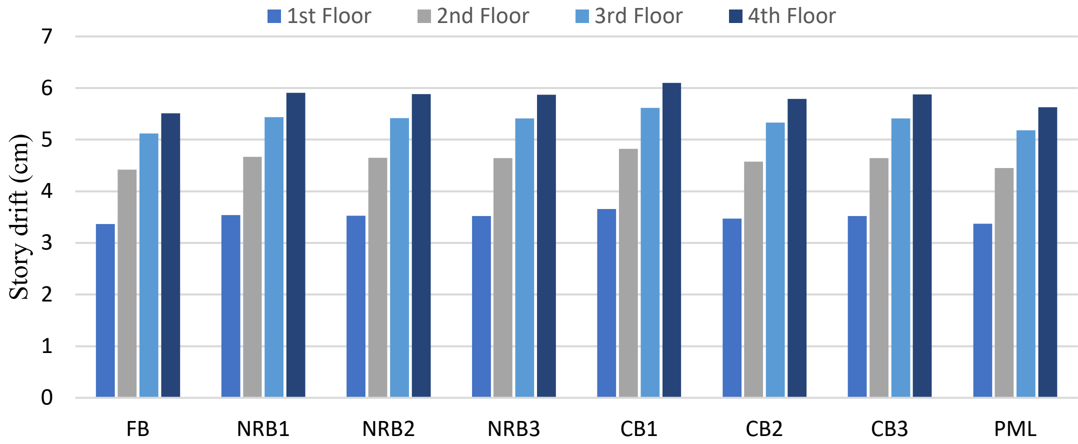
Story drifts assessed at the corner node of each storey relative to that of ground floor are shown graphically in Figure 15. It was noticed that story drifts increase and then taper downward as the soil domain's stiffness increases independently of lateral soil boundary conditions.

Story drift assessed from seismic analysis of non-reflecting boundary models due to the scaled El Centro ground motion is observed to be decreasing with increasing size of the soil domain. Relative displacement of 1st storey in NRB1 shows a deviation of 3.7% from NRB3 when the structure is modelled with underlying soil type of S-1. This difference between NRB1 and NRB3 is 3.5% for 2nd, 3.4% for 3rd, and 3.2% for 4th storeys. The differences fall into a narrow range of 0.5%. As the soil type changes from S-1 to S-3, this deviation becomes almost zero. A reverse trend can be monitored in constrained boundary models. Relative displacements of 1st, 2nd, 3rd, and 4th stories of CB1 are 6.0%, 5.8%, 5.4%, and 5.0% smaller than those of CB3 for soil type S-3, respectively. The magnitudes of story drift converge and becomes almost identical towards the higher stiffness so that the deviations are less than 1% for S-3 for both NRBs and CBs.

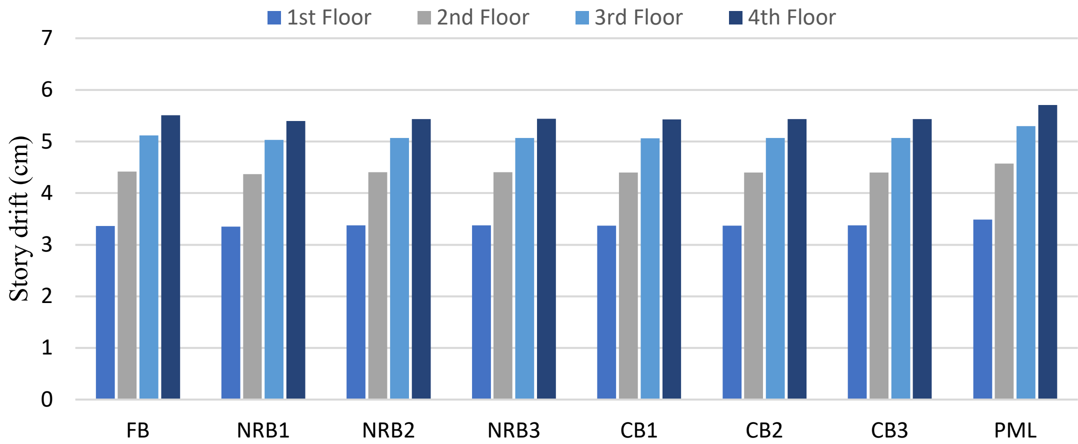
PML produced lesser relative floor displacement values for soil types S-1 and S-2, higher values for S-3 compared to NRBs and CBs. The deviations of the 4th floor's story drifts of PML from NRB3 and CB3 are 14.4%, 4.2%, and 4.9% for S-1, S-2, and S-3, respectively.



a.



b.



c.

Figure 15:
Story drifts of the models with different sizes and boundary for
***a.** S-1 **b.** S-2 **c.** S-3*

5. CONCLUSION

In this study, a soil-structure interaction model was analyzed in the Ls-Dyna finite element software according to the direct method. In the analysis, the effect of the truncated soil domain's size, soil boundary conditions, and soil stiffness on the structural behavior was parametrically investigated. The results obtained from SSI models were compared with the fixed-base model results in terms of roof deflections, interstory drift, peak acceleration value at roof level, and base shear. The material behavior is assumed to be linear elastic for SSI systems and the following conclusions can be made:

- Regardless of the soil boundary conditions and soil domain's size, soil-structure interaction effects disappeared, and the model structure behaved as a fixed-base structure depending on the increment of soil stiffness.
- For the non-reflecting boundary conditions, if the foundation soil is soft, the increasing planar soil domain dimensions result in a decrease in base shear, roof deflection, and story drift values. However, for the constrained boundaries, the results were obtained vice versa.
- If the plan size of the truncated soil domain exceeds ten times the foundation width, the effect of boundary conditions on the structural behavior is then negligible.

- When the analyses were compared in terms of computational cost and number of elements, the cheaper and faster solution was ensured with PML.
- In this study, internal soil domain and PML sizes suggested by Basu (2009) were considered. When the results obtained from these analyses with PML were compared with the results obtained from other boundary conditions, it was observed that the results were very close for medium and hard soils, while the difference between the results increased in soft soil conditions.

In future studies, parametric analyses considered different internal soil domain and PML size combinations should be conducted to show the effectiveness of PML. In addition, the effectiveness of the PML method will be investigated with further analyses that takes into account the type of structure, the idealization of the interface between the soil and structure, and the nonlinear behavior of the materials.

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CONFLICT OF INTEREST

Author(s) approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

AUTHOR CONTRIBUTION

Abdulkadir Genç: determining the concept and and design process of the research, data collection and analysis, data analysis and interpretation of results, critical analysis of the intellectual content, final approval and full responsibility. Ahmet Kuvat: determining the concept and design process of the research, research management, data analysis and interpretation of results, preparation of the manuscript, critical analysis of the intellectual content, final approval and full responsibility. Hasan SESLİ, determining the concept and design process of the research, research management, data analysis and interpretation of results, preparation of the manuscript, critical analysis of the intellectual content, final approval and full responsibility.

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