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Numerical Modeling of Mid-rise Reinforced Concrete Building Incorporation of Soil-structure-interaction for Different Soil Conditions with AEM

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Abstract

Many types of research have shown that the incorporation of soil-structure-interaction (SSI) effect in the numerical building model will modify its responses with the energy dissipation capacity in the soil and foundation interface. The foundation flexibility in the numerical model lengthens the fundamental period of the building resulting in the increase of the displacement demand. Many practitioners and engineers normally neglect the foundation flexibility in the numerical model for the vulnerability assessment of existing buildings because of its complexity in the calculation process and the limited guidance on the simple modeling procedure. However, in the case of the existing building where the accurate estimation of structural response and behavior is important, neglecting SSI will bring in the questionable structural response values. In this study, SSI models of mid-rise reinforced concrete buildings located on two soil conditions with shear wave velocity (V_s) values of 150 and 250 m/s are examined in comparison with the conventional fixed base case (neglecting SSI). Mid-rise reinforced concrete frame buildings of five, six and eight story buildings (slenderness ratio of 1.96, 2.70, 3.33 respectively) situated in Yangon are selected as the case study buildings. The AEM numerical models for three different cases of foundation (1) conventional fixed base case, (2) elastic SSI case (V_s 150 m/s), and (3) elastic SSI case (V_s 250 m/s) are developed in the commercial software Extreme Loading® for Structures Software (ELS). The difference in the inter-story drift ratio and floor acceleration for each case is checked by running nonlinear time history analysis with selected ground motion record which is relevant for the case study area. From this study, it can be identified that the fundamental period of the SSI considered case is higher than the fixed base case resulting in a slight increase in the inter-story drift ratio (ISD). The effect is more prominent in the case of building with high slenderness ratio; six story and eight story building located on V_s 150 m/s soft soil profile. Roof acceleration of six and eight story building for SSI V_s 150 m/s soft soil profile case is also higher than the fixed base case after a certain period of vibration, after 6 sec. of vibration in this study. Therefore, it can be concluded that the SSI effect is more prominent in the soft soil profile. Neglecting SSI effect for the vulnerability assessment of building located on soft soil profile (V_s 150 m/s in this study) will result in an underestimation of the seismic response of the building.

Keywords: soil-structure-interaction; damage state; building vulnerability; nonlinear dynamic analysis; AEM

1. Introduction

Seismic vulnerability assessment is a necessary process that can identify the damage probability of existing buildings in case of an expected earthquake event. There are many parameters that are normally considered in the assessment process, such as the seismicity of the region, characteristics of the building, and geotechnical condition. Numerical analysis is run based on these parameters. Based on the accuracy of the input parameters, the assessment result will differ accordingly.

In most of the numerical analysis, the geotechnical part; say the foundation part is neglected. The base of the superstructure part is generally considered to be fixed to the ground assuming that the foundation is stiff enough and located on the stiff soil. This kind of fixed based assumption in numerical modeling is mostly accepted in the assessment process because of its simplicity in the analysis procedure.

However, building foundations are not always stiff one located on stiff soil in an actual condition. The fixed base assumption in the numerical model, in the case of a building located on soft soil site, will no longer give the accurate seismic response of the building in the assessment process. The foundation flexibility in the numerical model of building results in the increase of the displacement demand and the reduction in the global force demand [1],[2]. Foundation rocking behavior can affect the response of the superstructure and in some cases, it can affect the retrofitting scheme [3]. Many practitioners and engineers normally neglect the foundation flexibility in the building design process as it will result in an over-conservative estimation of structural responses. In the case of the existing building where the accurate estimation of structural response and behavior is important, neglecting SSI will bring in the questionable structural response values.

Many types of research have shown that the incorporation of soil-structure-interaction (SSI) effect in the building numerical model will modify its responses with the energy dissipation capacity in the soil and foundation interface [4]-[8]. SSI has a detrimental effect on the shape of the fragility curve of the building subjected to the nature of the building. It was studied by Rajeev and Tesfamariam for three, five and nine story mid-rise non-ductile RC buildings using nonlinear dynamic analysis [9]. It was concluded that the overall variations, in terms of median spectral acceleration, between fixed base and SSI considered case are about 40%, 16% and 25% for three, five and nine story building respectively. Zeris et al. also explored the SSI effect on seismic performance of seven story RC building and concluded that SSI deteriorated the structural performance in case of an earthquake event [10]. Nakhaei and Ghannad investigated the SSI effect on the seismic vulnerability by using a generalized system of single-degree-of-freedom (SDOF) with three degrees of freedom at the base. They enumerated that the damage index of short period or slender buildings gets higher on softer soils before the predominant period of the ground motion [11]. Because of period lengthening effects from SSI, many practitioners mistakenly believe that SSI would be more prominent in the tall buildings. However, SSI effects are known to be significant on stiff, squat and shorter-period buildings [12]. All these literatures stated that SSI has a significant effect on the structural vulnerability and performance.

In this study, the seismic vulnerability of typical mid-rise buildings in Yangon city is evaluated with the consideration of soil-structure-interaction. Nonlinear time history analysis is carried out to check the seismic responses. Numerical analysis is performed on AEM-applied commercial software Extreme Loading® for Structures Software (ELS). The most vulnerable scenario in terms of story height, and shear wave velocity profile, which will be useful for decision-makers in prioritizing the mitigation measures, is identified. Details on the selection of typical buildings and soil conditions, modeling and analysis procedures are described in the following section.

2. Selection of Case Study Buildings and Soil Properties

Three types of RC mid-rise buildings located in Yangon city, Myanmar are chosen as the case study buildings. Many mid-rise buildings were constructed in Yangon city during the 1990s and the seismic-resistant practices were not fully applied during that time. Therefore, the seismic-resistant capacity of those mid-rise buildings is questionable. Moreover, the new construction rate of mid-rise buildings is still increasing as per construction completion statistics from Yangon City Development Committee website [13]. The construction completion rate for selected months is shown in Fig. 1. In the mid-rise building category (from four to twelve story), five, six and eight story building types are mostly constructed according to the statistics. Therefore, five, six and eight story RC mid-rise buildings are chosen as the case study building. It is intended to identify the seismic-resistant capacity of those mid-rise buildings through this current research not only for the safety of existing buildings but also for the mitigation measures of new construction.

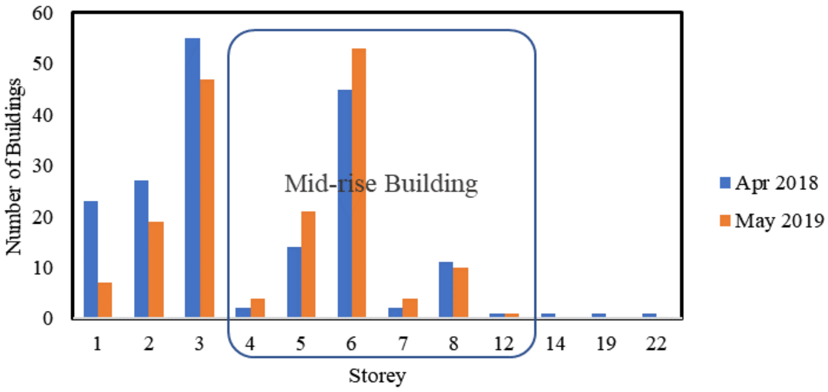
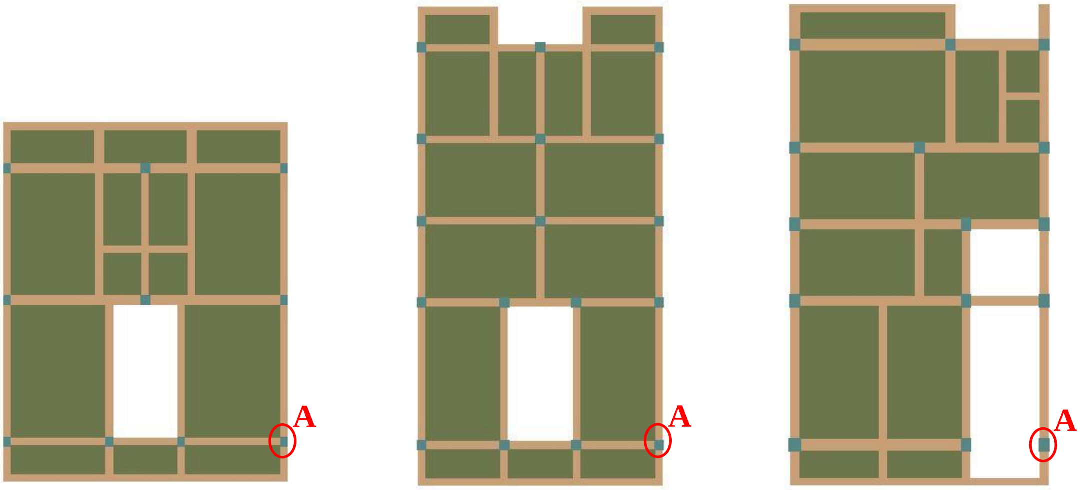


Fig. 1 – Number of buildings completed as per YCDC statistics for selected months

2.1 Building characteristics

Five, six and eight story RC buildings which are typical mid-rise buildings in the case study area are modeled as per their existing building information shown in Table 1. The structural plan and 3D view for three buildings are shown in Fig. 2 and 3.



(a) (b) (c)

Fig. 2 – Structural plan view (a) five, (b) six, and (c) eight story building (not to scale)

Table 1 – Building information

Building	Dimension (L×B)	Total height (H)	Typical story height	Type of foundation and depth	Slenderness ratio (H/L)	Note
5 story	27 ft × 35.5 ft	53 ft	9 ft	Strip footing (7 ft)	1.96	*Ground floor includes two levels of 9 ft and 8 ft each.*
6 story	23 ft × 47 ft	62 ft	9 ft	Strip footing (8.5 ft)	2.70	
8 story	24 ft × 47 ft	80 ft	9 ft	Pile foundation (40 ft)	3.33	

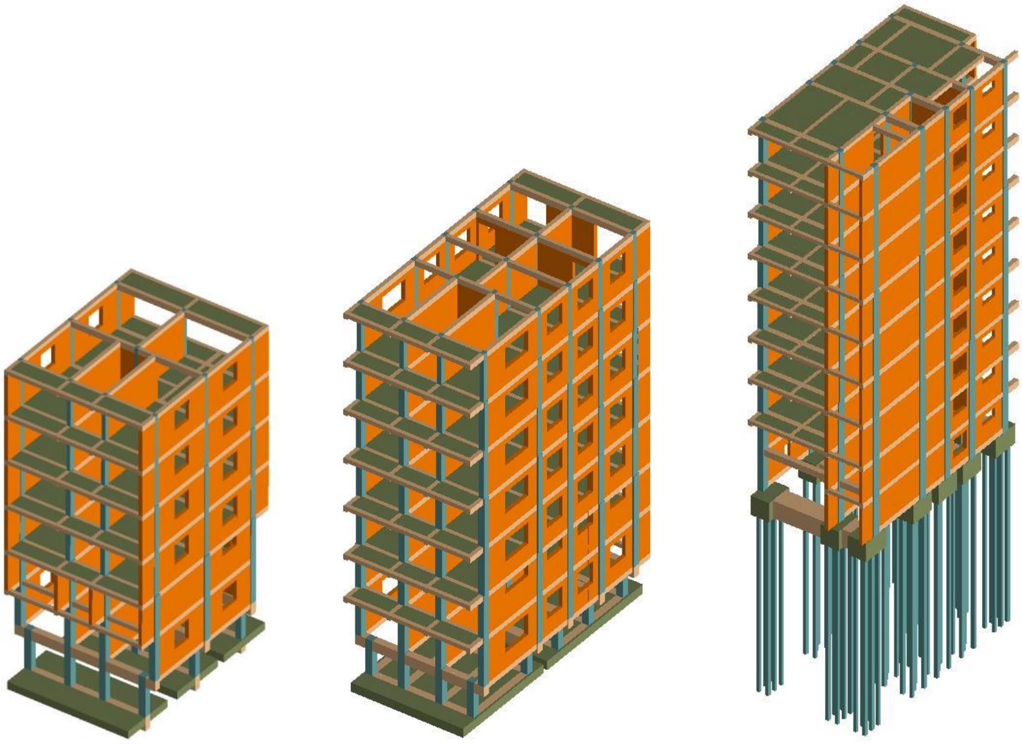
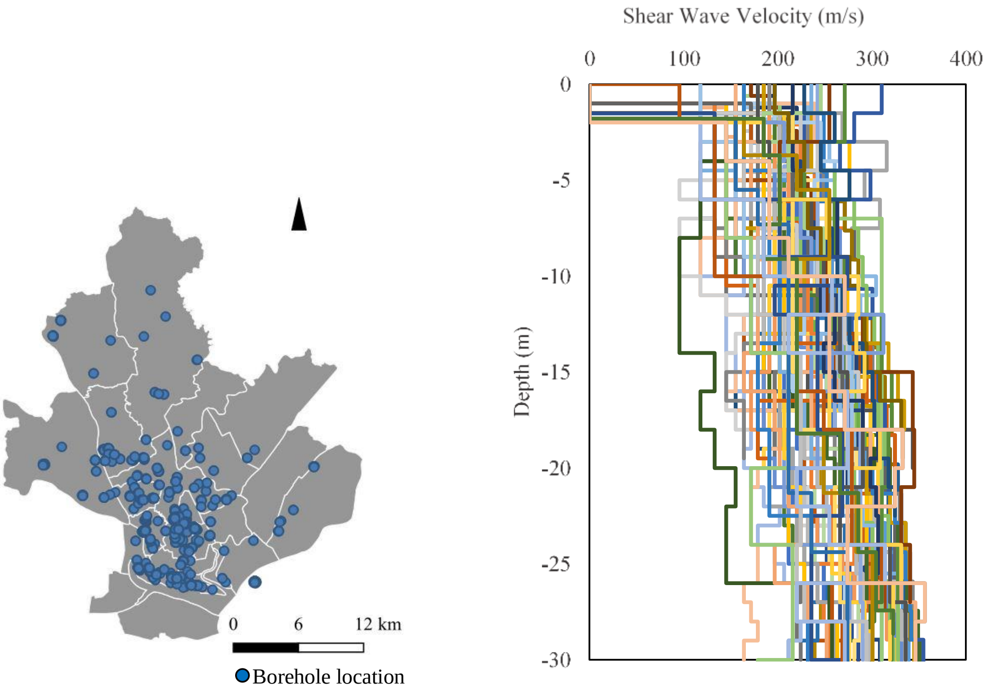

(a) (b) (c)

Fig. 3 – Structural 3D view (a) five, (b) six, and (c) eight story building (not to scale)

2.2 Collection of soil properties

The important parameters of soil property such as density and SPT-N values, are obtained through borehole drilling. More than 300 borehole data were collected from different sources [14], [15], to get the overall soil property of Yangon city. The location of collected borehole data is illustrated in Fig. 4 (a). Foundation of mid-rise buildings ranges from 7 ft (in case of strip footing) to 40 ft (in case of pile foundation) as per the existing building information. Shear wave velocity values are noted at a depth between foundation depth and the foundation depth plus the effective profile depth ($\sqrt{A}/4$) [16]. According to the foundation depth and effective profile depth of the selected case study buildings, shear wave velocity values ranges from 150 m/s to 250 m/s confirming to the recorded borehole data as shown in Fig. 4 (b). Two types of shear wave velocity value; 150 m/s and 250 m/s are considered in this study.



(a) (b)

Fig. 4 – Location of the borehole in the case study area, (b) Shear wave velocity profile

3. Modeling of Structures and Ground Motion Selection

3.1 Numerical modeling

The software program Extreme Loading® for Structures (www.appliedscienceint.com) - ELS is used in numerical modeling. The AEM approach in which the elements are connected by one normal and two shear springs along their edges, are adopted in the ELS program. Each spring represents the stresses and deformations of a certain volume of material and the elements can separate and re-contact each other based on the matrix springs generated in each element. There are three types of element contacts in the program; corner to ground contact, edge to edge, corner to corner; as shown in Fig. 6 to Fig. 8. In the ELS program, the soil-structure-interaction can be considered without the need to model a large number of soil elements [17]. Relevant material properties that are used in numerical modeling are shown in Table 2. Gravity load values as mentioned in Table 3 are applied to the numerical model considering the typical loads for residential building.

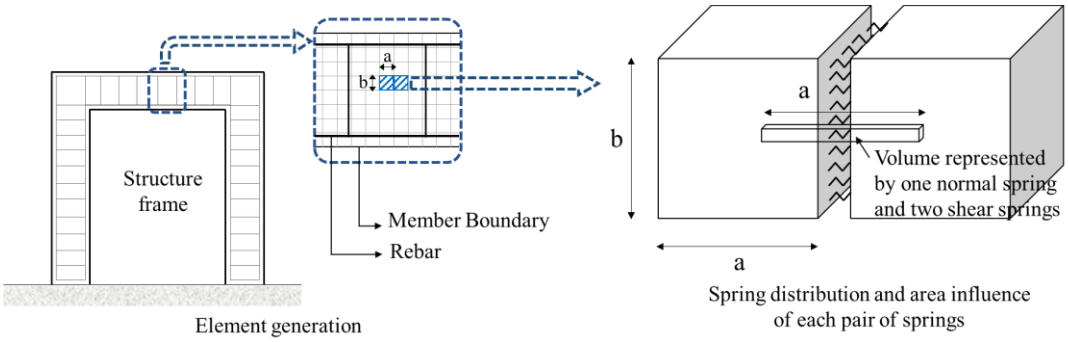


Fig. 5 – Modeling of structure to AEM

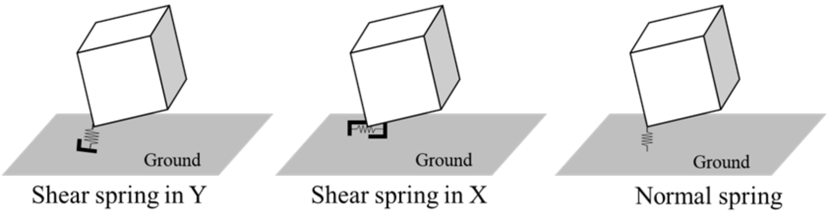


Fig. 6 – Corner to ground contact [17]

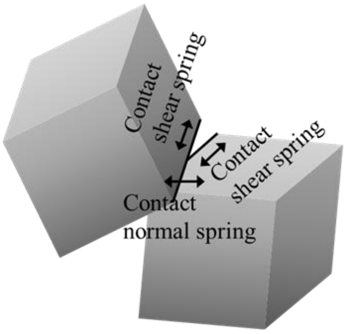


Fig. 7 – Edge to edge contact [17]

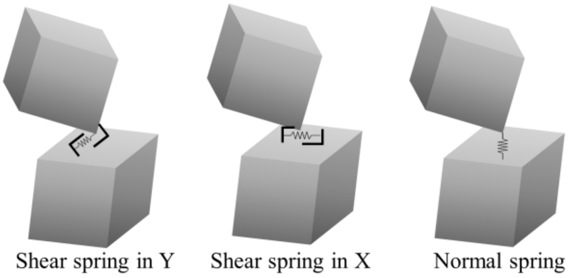


Fig. 8 – Corner to corner contact [17]

Table 2 – Properties of materials for numerical modeling

Unit (psi)	Concrete	Steel	Soil 1 (V_s 150 m/s)	Soil 2 (V_s 250 m/s)
Compressive strength	2500	40000	-	-
Tensile Strength	250	40000	-	-
Young’s modulus	2.85e+006	2.9e+007	610	2440
Shear Modulus	1.14e+006	1.16e+007	230	900

Table 3 – Gravity load used in the numerical model

Gravity load	Story	Roof
Dead load (lb/ft^2)	40	40
Live load (lb/ft^2)	40	20

3.2 Ground motion selection

In and around Yangon city, most of the earthquakes happened are shallow focus earthquakes, especially within about 250 km in radius, mostly related to strike-slip Sagaing Fault, which is the most active fault in Myanmar that has the potential of generating devastating earthquake in the future [14]. Ground motion is selected and scaled to match the expected target spectrum for Yangon city, considering the mechanisms of the strike-slip fault and expected magnitude. The expected target spectrum, scaled spectrum, and the time history record of selected ground motion are shown in Fig. 9 and 10.

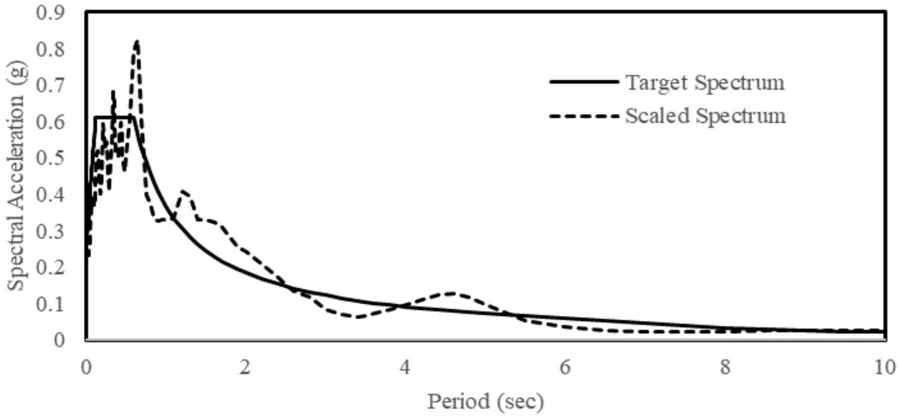


Fig. 9 – Acceleration response spectrum of target and selected ground motion

Earthquake Name	Victoria-Mexico
Year	1980
Station Name	Chihuahua
Magnitude	6.33
Mechanism	Strike Slip
Rjb (km)	18.53
Rrup (km)	18.96

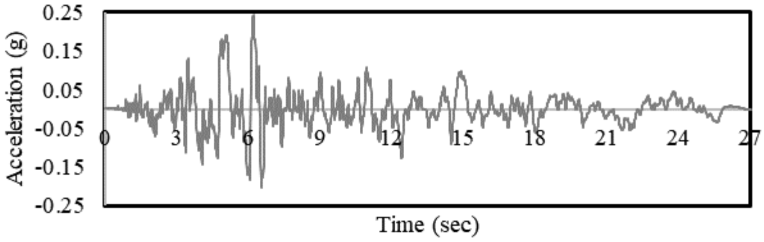


Fig. 10 – Time history record of selected ground motion

4. Results and Discussion

4.1 Eigen analysis

Firstly, eigen analysis is ran for all numerical models of the case study buildings to understand the effects of foundation flexibility. It can be seen from Table 4 that the fundamental period of the SSI considered case is higher than the conventional fixed-base case. Period elongation of nearly 10% is found out in 9 story building due to SSI effects.

Table 4 – Fundamental period from eigen analysis (unit - sec)

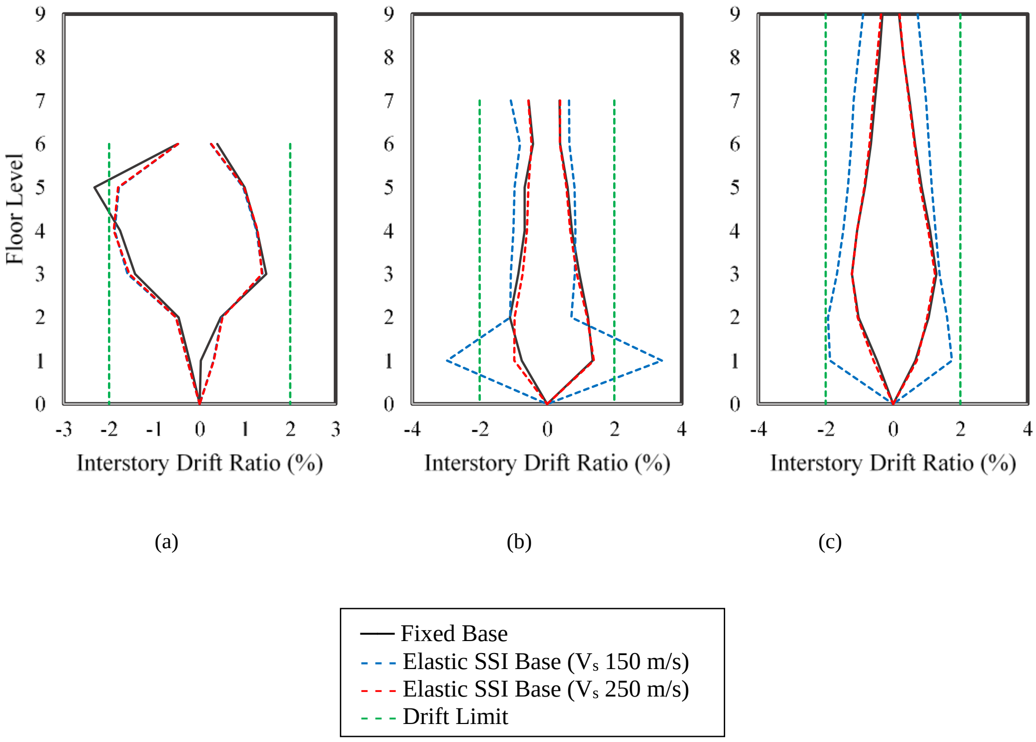
Building	Fixed base	SSI Linear base (V_s 150 m/s)	SSI Linear base (V_s 250 m/s)
5 story	0.63	0.64	0.64
6 story	0.64	0.66	0.66
8 story	0.82	0.89	0.89

4.2 Nonlinear time history analysis

Time history analysis is carried out using the scaled ground motion that matched the target spectrum of the case study location. In order to identify the effects of SSI, responses of the conventional fixed-base case and the SSI elastic base cases are compared. For SSI considered case, two value of soil condition; V_s 150 m/s and 250 m/s are considered representing the stiff soil and soft soil deposit.

Inter-story drift ratio (ISD) of three base conditions; (1) fixed base, (2) elastic SSI base (V_s 150 m/s), and (3) elastic SSI base (V_s 250 m/s) are compared for five, six and eight story building as shown in Fig. 11. ISD of a fixed base and elastic SSI base (V_s 250 m/s) case are nearly the same in all five, six and eight story buildings indicating that the effect of SSI can be neglected in case of an V_s 250 m/s soil profile.

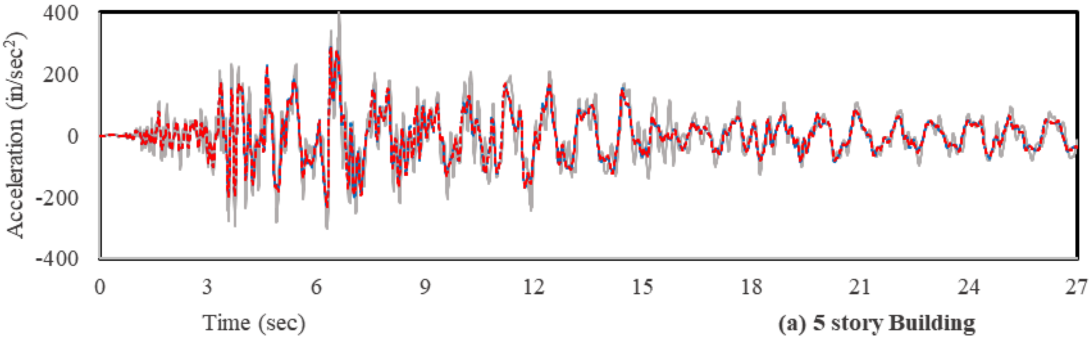
However, in SSI (V_s 150 m/s) case, ISD is significantly different from the fixed base case except five story building. Slenderness ratios of five, six and eight story buildings are 1.96, 2.70, and 3.33, respectively. From the ISD comparison, it can be said that the SSI effect correlates with the slenderness ratio of the building. The higher the slenderness ratio, the greater the effect of SSI for V_s 150 m/s soft soil profile.



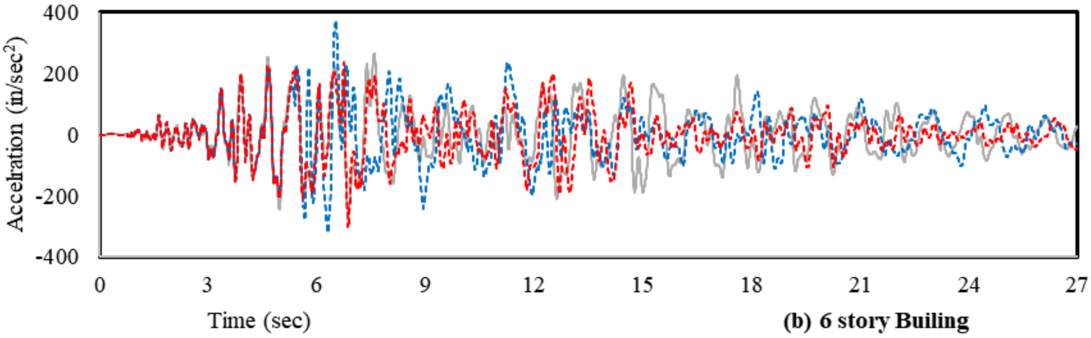
(a) (b) (c)

Fig. 11 – ISD of a fixed base and elastic SSI bases (a) five, (b) six, and (c) eight story building

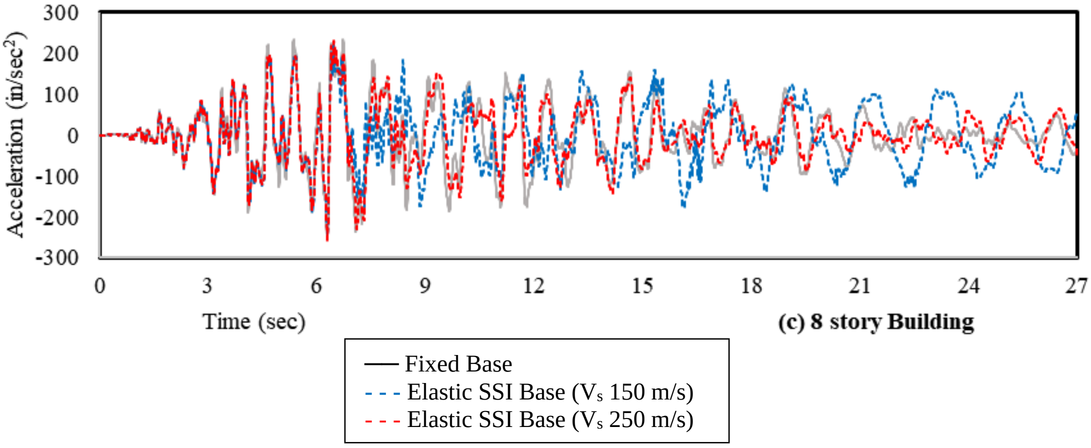
Comparisons of roof acceleration at column “A” location for all three types of buildings for three different base conditions are shown in the following Fig. 12. For five story building, roof acceleration for both V_s 150 m/s and 250 m/s elastic SSI cases are nearly the same, and is smaller than the fixed base case. In reverse to this, roof floor acceleration of both SSI cases for six story and eight story buildings are slightly higher than the fixed base case after a certain period of vibration, after 6 sec. of vibration in this study.



(a) 5 story Building



(b) 6 story Builing



(c) 8 story Building

Fig. 12 – Roof acceleration at column “A” location

5. Conclusion

The effect of soil-structure-interaction in the seismic response for mid-rise buildings of the different story (different slenderness ratios) has been identified in this study. Nonlinear time history analysis for three types of buildings (1) five, (2) six, and (3) eight story buildings with three different base conditions (1) fixed, (2) elastic SSI (V_s 150 m/s), and (3) elastic SSI (V_s 250 m/s) were performed. It can be identified that the fundamental period of the SSI considered case is higher than the fixed base case resulting in a slight increase in the inter-story drift ratio (ISD). The effect is more prominent in the case of six story and eight story building located on V_s 150 m/s soft soil profile.

For six and eight story building, roof acceleration considering SSI V_s 150 m/s soft soil profile case is higher than the fixed base case after a certain period of vibration, after 6 sec. of vibration in this study. Therefore, it can be concluded that the SSI effect is more prominent in the soft soil profile. Neglecting the SSI effect for the vulnerability assessment of building located on soft soil profile (V_s 150 m/s in this study) results in an underestimation of the seismic response of the building. Structural mitigation measures should be prioritized for the six story and eight story building located on soft soil profile of V_s 150 m/s in the case study area.

This study is an initial research for building vulnerability assessment of typical mide rise buildings in Yangon considering soil-structure-interaction effect for expected earthquake event. Conclusion is limited to the building configurations, material properties and building slenderness ratio considered in this study. Further study with different building configurations and material properties is recommended considering the nonlinearlity of soil condition with different ground motion patterns.

6. Copyrights

7. References

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