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INFLUENCE OF SSI ON THE SEISMIC RESPONSE OF A FRAMED STRUCTURE WITH GEO-ISOLATION LAYER

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ABSTRACT

Soil structure interaction (SSI) effects can be detrimental or beneficial for a structure depending on the type of structure, earthquake motion and the soil conditions. The current paper evaluates the SSI effects on the seismic response of a low rise framed structure placed on sand-tyre mixture layer (geo-isolation system). A layer of sand-tyre mixture placed beneath the building can serve as an excellent isolation material due to its high damping properties. In the present study, soil structure interaction analyses were carried out for a three-storied framed structure on a raft footing resting on a geo-isolation layer. A two-dimensional model of the structure-foundation-soil system was developed in the finite element based ABAQUS code. The performance of building on static loading analysis is studied considering bearing capacity and settlement aspects. The SSI for dynamic analysis is carried out using direct approach wherein the footing, sand-rubber isolation layer and building are analysed in a single step. The analysis was carried out for Nepal and Myanmar earthquake ground motions. The results are analyzed in terms of PGA, predominate frequency and peak spectral acceleration at different elevations of the building. It is found that the coupled effect of sand rubber mixture-isolator and SSI can reduce the amplitude of peak acceleration and peak spectral acceleration of low rise building by 20-40%.

Keywords: Finite Element; SSI; Geo- isolation; Sand-rubber mixture

1. INTRODUCTION

Many of the developing nations in the world are located in seismically active zones where the construction practices are inadequate for earthquake protection. The impact of earthquake is more severe in the Indian subcontinent due to the vulnerability of structures present. Earthquake vulnerable areas of the Indian subcontinent are mainly located in the Himalayan belt and majority of the earthquakes are due to the subduction of the Indian plate into the Eurasian plate. The traceable earthquakes occurred in these regions majorly cause severe damages to low-rise buildings without any earthquake resistance. Typically, base isolation systems are used as anti-seismic design method which minimize the extend of ground waves reaching the super structure. Base isolators typically bifurcate the foundation and structure by introducing flexibility and high damping which in turn absorbs the seismic waves considerably. Base isolation system commonly uses rubber bearings between foundation and superstructure. The thick rubber layers in the rubber bearing helps in damping of earthquake waves. The conventional seismic isolation techniques are costlier to be implemented for low rise buildings. In the recent years, many researchers (Senetakis et al. 2012; Tsang et. al. 2012; Sheikh et al. 2013; Pitilakis et al. 2015) have emphasized that recycled rubber tyre mixed with sand could act as low-cost seismic base isolation for low rise buildings.

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In the past, Kirzhner et al. (2006) proposed to replace soil by relatively more elastic materials (including rubber or rubber soil mixture) surrounding a tunnel for noise and vibration absorption. Compacted sand layers are often used as an energy dissipating layer (Li et al. 2016). Scrap tyre-sand mixtures placed below the foundation would partially dissipate earthquake energy within the soil itself before the vibrations reach the foundation and the superstructure (Tsang et al. 2012; Pitilakis et al. 2015). There are quite a number of studies reported in the literature on the static and cyclic behaviour of sand-rubber mixtures (Edil and Bosscher 1994; Zornberg et al. 2004; Hazarika et al. 2011; Anastasiadis et al. 2012). Studies on the use of tyre shreds mixed with concrete further confirm the high durability of tyre shreds (Sukontasukkul and Tiamlom 2012) for long term use. Furthermore, sand-tyre mixtures possess low liquefaction potential due to reduction in excess pore water generation (Hyodo et al. 2007). However, limited studies are available on the performance of sand-rubber layer as seismic isolators for low-rise framed structures. The present study aims at exploring the influence of soil-structure interaction (SSI) on the response of low-rise building with shallow footing isolated using sand-rubber tyre mixture (SRM) layer placed below the footing.

2. SOIL-STRUCTURE INTERACTION ANALYSIS

Kinematic interaction effects of SSI are generally neglected in the fixed base assumption studies which assume that free-field motions and foundation input motion are the same. However, when a structure is subjected to an earthquake excitation, it interacts with the foundation and the soil. Hence foundation motion will be different from free-field motion due to incoherent ground motion, embedment of foundation and wave scattering effect (Stewart et al. 1999). SSI analysis plays a vital role in the study of the response of base isolator structures depending on the types of soil (Alavi and Alidoost 2012). SSI studies are widely popular in the dynamic response of structures in nuclear power plants and bridges due to the massive size of foundations involved (Jaya et al. 2009; Tongaonkar and Jangid 2003). Studies carried out by Novak and Henderson (1989), Kelly (1991) and Dicleli & Buddaram (2006) shows that the SSI effect has a considerable influence on the dynamic characteristics of base isolated structures, which in turn affect its seismic response and efficiency of the isolation layers.

Shallow foundations are often approximated with lumped springs with an assumption that the foundation is supported by a homogeneous, elastic, semi-infinite medium (Gazetas 1991; Wolf 1997). The application of these methods to the seismic analysis of a building structure requires determination of equivalent elastic properties and the fundamental frequency of the structure. However, the above methods may not accurately model the structure-foundation soil-system. Therefore, the most comprehensive approach to solve the SSI problem is through an FE analysis in which complex structural configurations and soil layers can be explicitly modelled. SSI problems are generally solved by direct approach or substructure approach. The direct method of soil-structure interaction is used for the present study in which the soil, foundation, and structure are modelled as one system considering the continuity of the soil medium and the entire analysis is carried out in one step. The direct approach requires infinite boundary to the soil medium, the damping of the material and proper mesh size to ensure transmission of seismic waves.

3. NUMERICAL STUDY

The present study focuses on the static and dynamic performance of building placed on geo isolation layer subjected to earthquake input motions with different frequency content. A conventional low-rise moment resisting 2 storied framed structure with 3 bays was selected for the analysis. The frames are rigidly connected to a raft footing as shown in Figure 1. A layer of geo isolator is placed below the footing and its sides followed by a homogeneous half space. The efficiency of the geo isolator system is analyzed using direct approach of SSI.

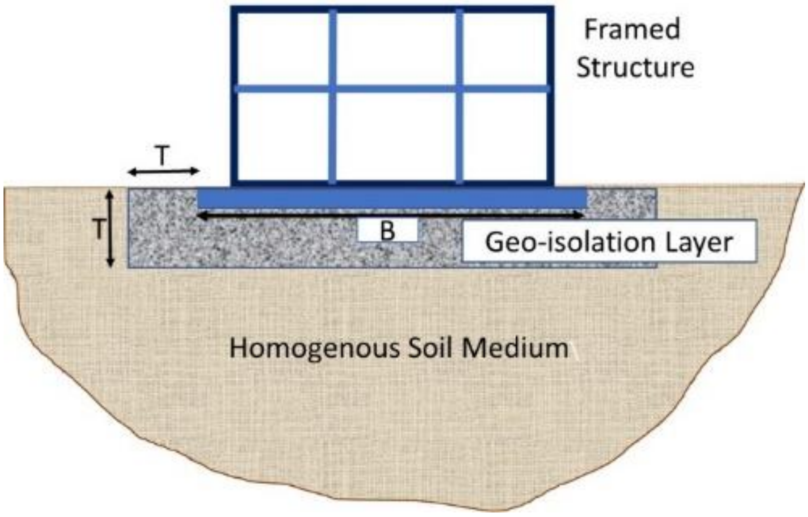

Figure 1. SRM- isolation system used for earthquake protection of building

The numerical modelling of soil- structure system based on the direct approach is carried out using the finite element code ABAQUS 6.14. The two storied 3 bayed framed building with rigid footing as considered in Pitilakis et al. (2015) resting on the soil medium is modelled in the time-domain assuming plane strain conditions as shown in Figure 2. The width (B) and depth of the footing (D_f) are 20m and 1m respectively. The foundation and superstructure are placed on the geo-isolation system with thickness (T) of 0.1B. The entire structure and geo-isolation system is placed on a 30m thick homogeneous soil medium. The length of soil medium is considered as 200m (10B) to ensure free-field conditions and infinite boundaries are provided at the far field to ensure absorption of outgoing waves thereby preventing wave reflection.

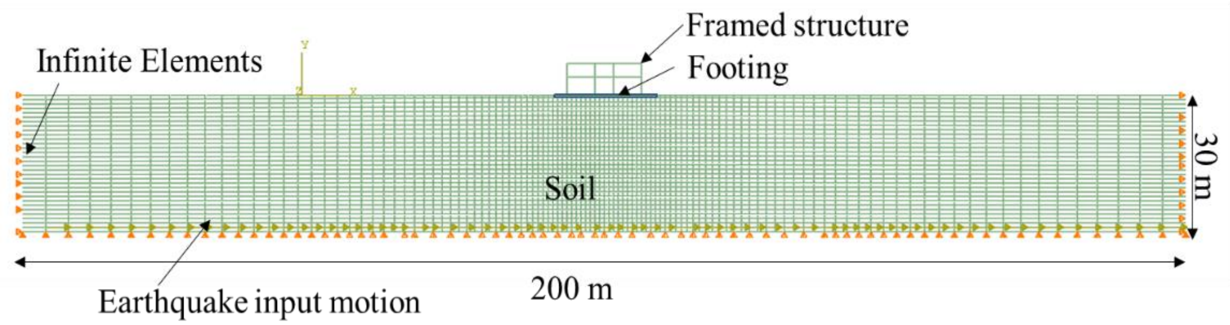

Figure 2. Finite element model of geo isolated structure

3.1 Geometry and Material Characteristics of the Model

Elastic beam-column elements are employed for the simulation of the 2D frame elements with three degrees of freedom. Rectangular sections are used for the simulation of the column and beam sections. Based on the lumped-mass approach, the total mass of the elements is distributed to the nodes of the corresponding frame elements. The size of the FE mesh is adopted considering the frequency content of the input motion and the shear wave velocity of the soil medium. The soil medium is discretized using isoperimetric four-node plain strain continuum elements. The mesh size of the soil medium is varied from 1m x 1m to 5m x 1m. To minimize the wave refraction effects infinite elements were considered in the lateral direction. The frame is modelled using wire elements. Beam profile of cross section 0.35m x 0.35m is assigned to the wire elements.

Zornberg et al. (2004) and Rao and Dutta (2006) reported that the maximum shear strength and shear modulus increment for sand-rubber mixture occurs when SRM with tire chip content of 20-35% (gravimetric) was used. In the present study, dynamic properties of SRM corresponding to 30% rubber content (Dhanya et al. 2017) is used for geo-isolation layer as shown in Table 1. Soil and geo-isolator are modeled as elastio-plastic materials. The angle of internal friction obtained from consolidated drained test for sand and 30% tyre content are 420 and 350 respectively.

The damping nature of soil and SRM is incorporated in the SSI model using Rayleigh damping coefficient α and β based on the concept of damping matrix (C) which is proportional to mass (M) and stiffness (K) matrices (Ryan and Polanco 2008) as below:

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

Strain dependent modulus and damping curves of sand-tyre mixtures obtained from the cyclic triaxial tests (Dhanya et al. 2017) were used in the equivalent-linear procedure to account for non-linear soil behavior. Damping ratio of 10% and 16% were considered for calculating Rayleigh damping coefficient of soil and geo-isolation layer. The concrete footing and frame are modelled with linear elastic properties considering 5% structural damping as listed in Table 1.

The boundary conditions in the FE model is established through fixed support at the base of the soil model by restraining rotation and displacement to ensure the stability of the model to simulate rigid boundary condition equivalent to bedrock. The far-field response was ensured by infinite elements which are placed at the lateral boundaries of the model to minimize reflection of shear wave energy back to the model during dynamic excitations. The footing is considered at the center of the model to avoid boundary effects. Lumped masses are applied at the nodes of the frame. The dynamic analysis was carried by considering dynamic explicit method.

3.2 Input Motion

In the present study, two horizontal input motions from recent occurred earthquakes Nepal earthquake (2015) and Myanmar earthquake (2016) was used. The Nepal earthquake (2015) recorded in the Himalayan belt represents a medium frequency earthquake (Mw=7.8; PHA=0.14g and predominant frequency=3.5Hz) and the Myanmar earthquake (2016) represents a high frequency earthquake (Mw=6.8; PHA=0.11g and predominant frequency=8Hz) as shown in Figure 3. The horizontal input motions were applied at the base of the soil medium.

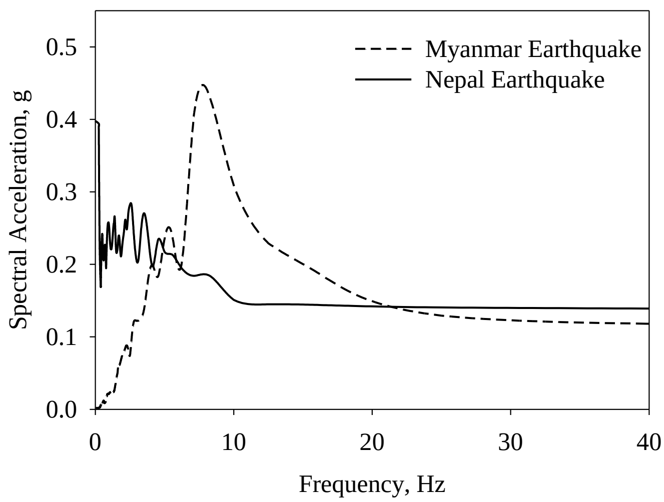

Figure 3. Response spectra of input motions

Table 1. Material Properties used in numerical model

Properties		Soil	Sand-tyre	Concrete
Young's modulus (MPa)		85	60	30000
Poisson's ratio		0.32	0.35	0.2
Density (kg/m^3)		1600	1500	2400
Damping	α	0.132	1.854	0.97
coefficient	β	0.006	0.183	0.0004

4. RESULTS AND DISCUSSION

The results of SSI analysis carried out on 2-storied structure considering the effects of geo isolation under static and seismic loading conditions are discussed in this section. The results are presented in terms of bearing pressure and settlement for static loading condition and time histories of acceleration and displacement time histories for dynamic loading conditions.

4.1 Bearing Capacity and Settlement of Footing

Numerical study is carried out to ensure that shallow footing resting on geo-isolation layer is be able to meet adequate bearing capacity and settlement demands. Vertical pressure is applied on the footing at equal increments of 20 kPa until failure occurs. Figure 4 shows the bearing pressure-settlement ratio (s/B) curves for geo-isolated and non-isolated systems. In this case, the settlement ratio is the normalized value of footing settlement (s) to the width of the footing (B). It can be clearly seen that there is a small reduction in bearing capacity for geo-isolated system compared to the non-isolated system. However, at a higher s/B ratio of 0.14%, the ultimate load carrying capacity of geo-isolated system and non-isolated systems are almost the same. This ensures that the performance of footing in terms of bearing capacity is not affected much due to the presence of SRM layer.

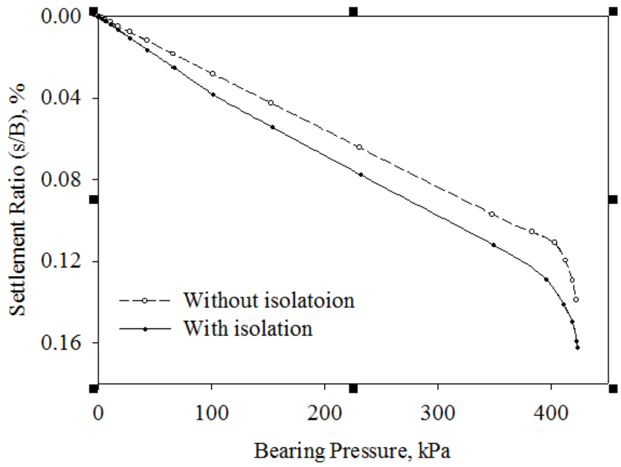

Figure 4. Bearing pressure- settlement response under static loading

4.2 Peak Acceleration at Footing and Floor levels

The earthquake input motion is applied at the bottom of the soil model at a depth of 30m below ground level and the corresponding acceleration-time histories are obtained at the top of the footing and first floor of the building. The computed time history of acceleration at the footing level of building with and without isolation layers is shown in Figure 5 and 6 for Nepal (2015) and Myanmar (2015) earthquake respectively. It is clearly visible from Figures 5 and 6 that the presence of geo isolator reduces the acceleration when compared without isolation system for both input motions. However, the reduction is more predominant for Myanmar earthquake in comparison to Nepal earthquake. The computed peak acceleration at the top of the footing and the first floor is presented in

Table 2. It can be easily noticed from Table 2 that an average reduction of peak acceleration by 40-50% occurs for building with geo-isolation layer in comparison to the building without isolation

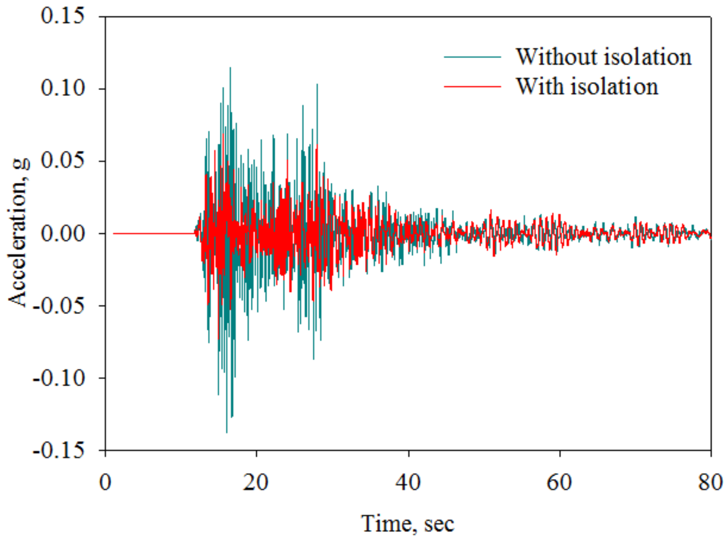

Figure 5. Acceleration-time history at the footing level for Myanmar earthquake

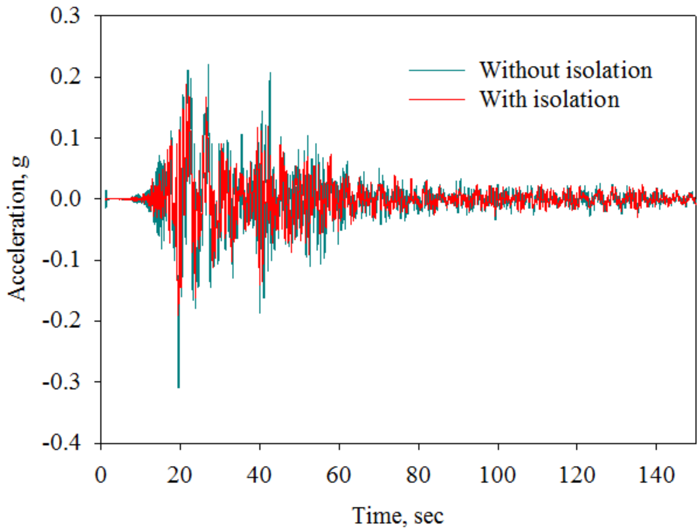

Figure 6. Acceleration-time history at the footing level for Nepal earthquake

Table 2. Peak acceleration at different levels of the building.

Type of Building System	**Level**	**Peak acceleration, g**	
		Myanmar (2015)	**Nepal (2015)**
without isolation	Footing (top)	0.137	0.31
	First floor	0.15	0.39
With isolation	Footing (top)	0.072	0.116
	First floor	0.09	1.19

4.3 Response Spectra

The response spectra for 5% damping ratio at the footing level of the building with and without geo isolation is plotted in Figure 7 (a) and (b) for Myanmar and Nepal earthquakes respectively. It can be noticed from Figure 7 that a slight period shift occurs for the isolated building for both input motion considered. But a significant reduction in spectral acceleration at the footing level due to the presence of geo isolator is evident in both the cases of earthquake motions. However, for Myanmar earthquake input motion, the reduction of peak spectral acceleration is significant in comparison to the Nepal earthquake input motion. The shift in natural period is evident in both cases especially for Nepal earthquake. It is also found from Figure 7 that the reduction of peak spectral acceleration at the footing level for geo isolated system is about 20% for Nepal earthquake input motion and 40% for Myanmar earthquake input motion in comparison to the non-isolated system.

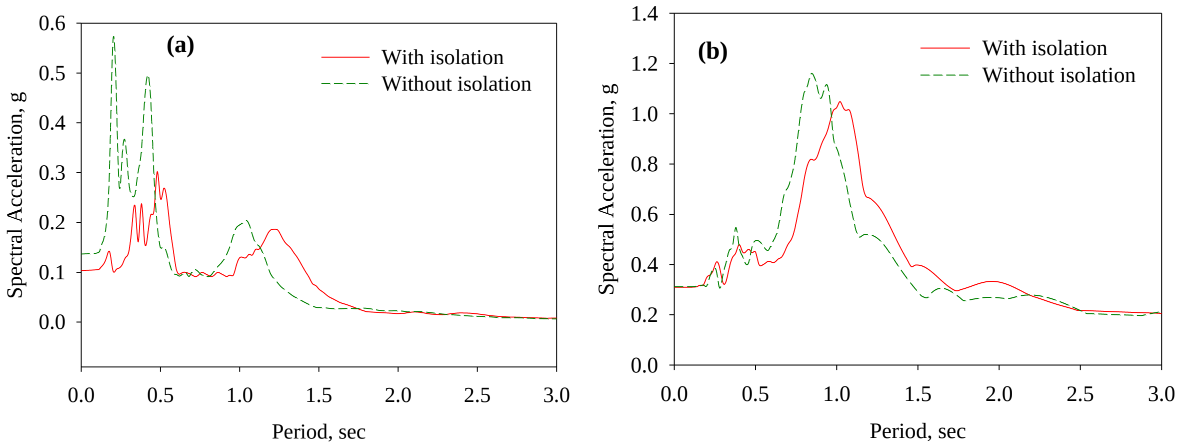

Figure 7. Response spectra at the footing level for (a) Myanmar and (b) Nepal earthquakes

5. CONCLUSIONS

The static and seismic SSI analysis of low-rise building with base isolation using sand-rubber tyre mixture (SRM) layer placed below the footing was carried using finite element code ABAQUS. It is found out from the static analysis that the bearing capacity and settlement aspect of the building is not much affected by the introduction of SRM layer below the footing. The results of seismic SSI analysis show that SRM layer causes a slight period shift and a significant reduction in peak horizontal acceleration and peak spectral acceleration of the building due to the occurrence of a high amount of damping. The beneficial effects of SRM layer are highly influenced by the frequency content of earthquake input motion. The reduction of peak spectral acceleration at the footing level for Geo isolated system is about 20% for Nepal earthquake input motion and 40% for Myanmar earthquake input motion in comparison to the non-isolated system.

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