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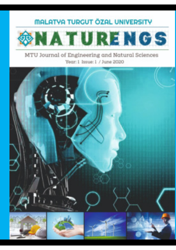

Research Article

Numerical Analysis of Geotechnical Seismic Isolation System for High-Rise Buildings

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ABSTRACT: Seismic isolation is a method of protecting buildings from earthquake-induced deformations by using isolators and devices under the superstructure. The purpose of the seismic isolation method is to reduce the earthquake forces transferred from the ground to the structure by placing energy-absorbing elements between the foundation and superstructure. Especially in developing countries, the "Geotechnical Seismic Isolation (GSI)" system has been proposed as an isolation method to reduce earthquake-induced damages on buildings. This study, it is aimed to reduce the effects of earthquakes in a multi-story building with an isolation layer formed by a rubber-sand mixture (RSM). For this purpose, a 10-story reinforced concrete building was numerically modeled. Beneath the foundation of the building model, a seismic energy absorbent RSM layer was placed and its contact with the natural soil was interrupted by using geosynthetic liners. The model was subjected to the 1992 Erzincan (EW) Earthquake motion and its performance has been evaluated in terms of lateral displacements and accelerations. The numerical studies indicated a substantial improvement due to the use of the RSM layer. The accelerations measured by the superstructure decreased up to 48% by employing the isolation layer. The numerical analysis was carried out using the dynamic module of the PLAXIS 2D finite element analysis program.

Keywords: Geotechnical Seismic Isolation, Rubber Soil Mixture, Dynamic Analysis

1. INTRODUCTION

Since common technology is not sufficient to predict the location, magnitude, and time of earthquakes, the design of earthquake-resistant engineering structures has been inevitable for humanity. Especially the earthquakes with large magnitudes we have experienced in the last century and the resulting loss of life and property have made the design of the earthquake-resistant building one of the most important issues of civil engineering. With the methods and approaches developed in this direction, it is aimed to minimize the damages caused by earthquakes in the buildings, to prevent the loss of life and property, and to be able to fulfill the functions of the buildings after the earthquake. In this context, the design of the architectural and structural systems, structural materials to be used, seismicity of the area, and local soil conditions are the most important factors to be considered in earthquake-resistant building design.

Researchers have developed innovative approaches to ensure that structures display the intended level of resistance against earthquakes. In these approaches, seismic isolation elements are generally used above the foundation level, depending on the principle of separating the

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building from the ground. The basic principle of seismic isolation is to ensure that the ground motion that occurs during an earthquake is transferred to the structure in limited levels and thus the forces that will occur in the structural system are minimized. Isolation elements with low lateral stiffness placed at the level of the foundation enable the structure to oscillate at frequencies lower than the predominant frequency during an earthquake and the superstructure is exposed to lower earthquake forces. The occurrence of higher displacements at the isolation layer compared to the superstructure reduces the relative displacements. With the lengthening of the vibration period of the system, the story accelerations decrease and the structural and non-structural damages are minimized. In an ideal seismic isolation system, the earthquake forces transferred to the building are zero, but it is not possible to achieve this in practice. Successful examples of seismic isolation method in public buildings such as hospitals and transportation facilities were exhibited in our country (Istanbul Sabiha Gökçen International Airport Terminal, 2008; Erzurum Health Campus Buildings, 2012; Marmara University Hospital Buildings, 2013; Başakşehir Çam and Sakura City Hospital, 2020).

Although it has existed as a concept among seismic isolation approaches for a long time, the isolation method suggested by Tsang [1] was first introduced into the literature with the definition of ‘Geotechnical Seismic Isolation (GSI)’. This innovative approach was previously proposed by researchers with the idea of laying a synthetic layer under the building foundations and distributing earthquake energy [2, 3]. Similarly, studies were also carried out on reducing horizontal ground movements by using geotextile between soil layers [4]. However, the GSI method became prominent with the modeling of the RSM layer under the foundation of a 10-story building for seismic isolation (Fig. 1) [1]. It is stated that with the use of the RSM layer, not only the horizontal movement is damped, but also the vertical movements are limited. Regarding the content and applicability of the method; it was also underlined that factors such as nonlinear soil behavior, resonance effects of the soil, liquefaction, ground settlement, and environmental effects should be evaluated. In subsequent studies, comprehensive numerical and experimental studies were carried out on the seismic isolation capacity of RSM layers formed with varying rubber contents [1, 5-10].

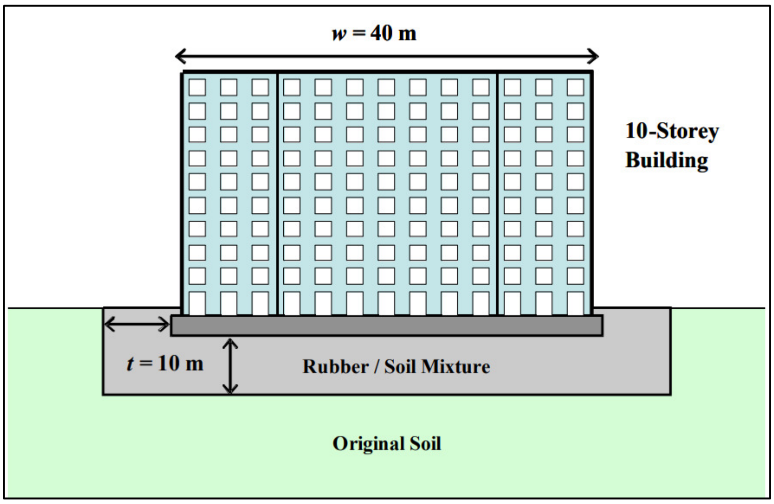

Figure 1. Seismic isolation with rubber-soil mixture [1]

Another example of the GSI method is developing an isolation layer using geosynthetic material with or without an RSM layer. Experimental and numerical studies performed on this method have shown that the seismic performance of low and medium-height buildings improved significantly with geosynthetic layers created in different configurations [11-13]. The method of improving the earthquake performance of soils with geosynthetics has been used not only under the foundation of superstructures but also for strengthening earth retaining structures [12, 14]. Furthermore, researches were carried out on the use of geosynthetics in sloped soils and conducted numerical studies were conducted [15, 16].

In this study, the seismic performance of a high-rise building isolated by a layer of RSM was investigated. In this context, an RSM isolated 10-story building was numerically modeled. The 1992 Erzincan (EW) earthquake motion with varying amplitudes was applied to the developed model. The performance of the RSM-isolated building was evaluated in terms of accelerations and lateral displacements. The dynamic module of the PLAXIS2D finite element analysis program was used for numerical analysis. The applied earthquake records were obtained from the official website of AFAD. The results are graphically presented as acceleration-time and displacement-time histories.

2. NUMERICAL MODELLING

In this study, a high-rise (10-story) building was modeled using the PLAXIS 2D finite element analysis program and its foundation was isolated with the RSM layer. The width of the building foundation is designed as 12 m, story height 2.85 m and foundation depth 90 cm. The thickness of the RSM layer under the foundation is set at 12 m and is equal to the width of the foundation. Two smooth synthetic liners were used to separate the RSM layer from the natural soil, as suggested by the researcher [4]. The synthetic liners were separated by a space of 1 m. The total lengths of both synthetic liners were set as 60 and 64 m, surrounding the RSM layer under the foundation all around. The generic soil conditions are used as a soil profile. Under the foundation of the building, a clay layer with 15 m thickness and a sand layer with 25 m thickness were designed. The groundwater table is set as deep enough below the foundation level. The schematic view of the numerical model is shown in Figure 2.

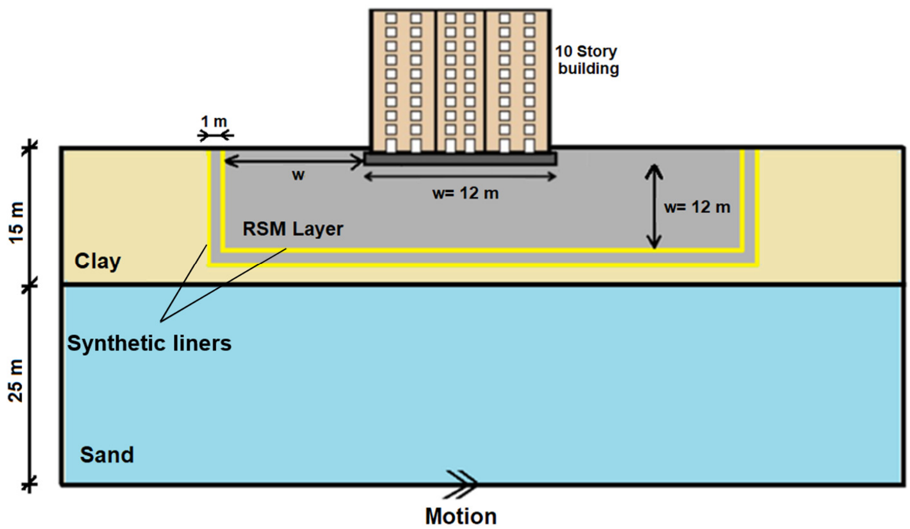

Figure 2. The schematic view of the numerical model

The geometry was simulated using an axisymmetric model in which the building model was positioned along the axis of symmetry. Both the soil and building were modeled with 15-noded elements. Interface elements were placed around the foundation and geosynthetics to model the interaction between separated elements. The boundaries of the model were taken sufficiently far away (200*50 m) to avoid the direct influence of the boundary conditions. Standard fixities were considered and standard absorbent boundaries were used to avoid spurious reflections. Static load was applied to the building model at the top ceiling level. The strength reduction factor was taken as unity (R_{inter} = 1) for all soil layers. After defining the geometry of the model and assigning the material properties, a two-dimensional mesh was generated to perform the finite element calculations. The mesh generation is performed through 15-noded triangular elements. Since the model includes edges of used geosynthetic liners, the local coarseness factor is set to 1.0 which corresponds to medium size element distributions for all geometry points. Initial effective stresses were generated by the K_o procedure. The meshed view of the RSM isolated building model with two layers of smooth geosynthetic liners is shown in Figure 3.

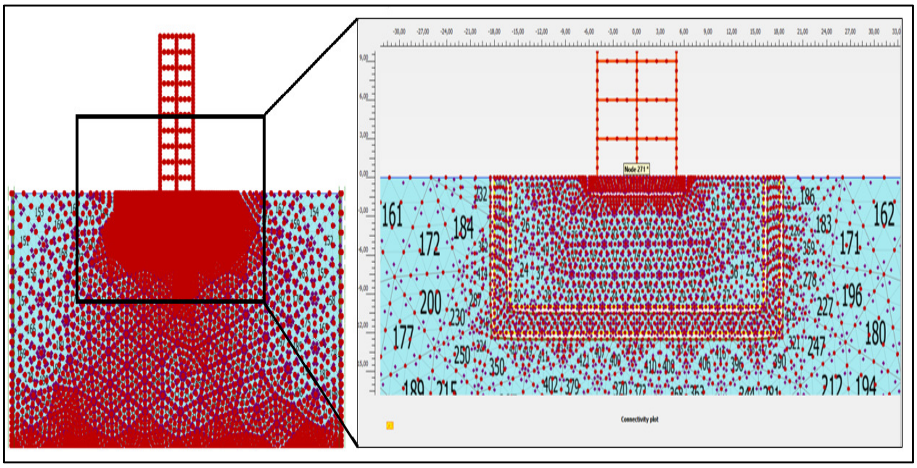

Figure 3. The meshed view of the model with RSM isolation layer

2.1. Material Properties

The RSM layer placed beneath the foundation consists of a mixture of scrap tires and sand materials. The soil material was modeled using the hardening soil model which is an advanced model for the simulation of soil behavior under dynamic loading. The properties and used parameters of the RSM layer, sand, and clay materials are presented in Table 1. Structural elements of the model are selected as plate elements in PLAXIS2D. The parameters of the footing, building and geosynthetic liner are given in Table 2.

Table 1. Material properties

Parameter	Clay	Sand	RSM
E_{50}^{ref}(kPa)	10.000	15.000	6300
E_{oed}^{ref}(kPa)	10.000	15000	6300
E_{ur}^{ref}(kPa)	30.000	45000	20000
c^{ref}(kPa)	5	5	5
ϕ'(°)	26	21	60
Ψ (°)	0	0	35
γ_{sat} (kN/m³)	17,5	17	13.3
γ_{unsat} (kN/m³)	17,5	17	13.3
K_o	0,3	0,4	0.4
ν	0,3	0,2	0.2
e_{init}	0,5	0,5	0.4

E_{50}^{ref}: secant stiffness, E_{oed}^{ref}: oedometer loading stiffness, E_{ur}^{ref}: unloading–reloading stiffness, c_{ref}: effective shear strength, ϕ': effective friction angle, Ψ: dilatancy angle, γ_{sat}: saturated unit weight, γ_{unsat}: unsaturated unit weight, K_o: pressure coefficients, ν: Poisson's ratio, e_{init}: initial void ratio.

Table 2. Parameters of footing, building and geosynthetic

Parameter	Footing	Building	Geosynthetic
EA (kN/m)	$12E^6$	$9E^6$	$500E^3$
EI (kN/m)	$400E^3$	$67.5E^3$	-

EA: normal stiffness, EI: flexural rigidity

2.2. Dynamic Motion

The 1992 Erzincan (EW) Earthquake (Ms:6.8, PGA: 0.50g) motion record was used for the dynamic analysis. The acceleration-time history of the earthquake motion can be seen in Figure 4. To investigate the effect of the varying amplitudes, the earthquake motion with 1A, 0.5A, and 2A were applied both to non-isolated and isolated building models.

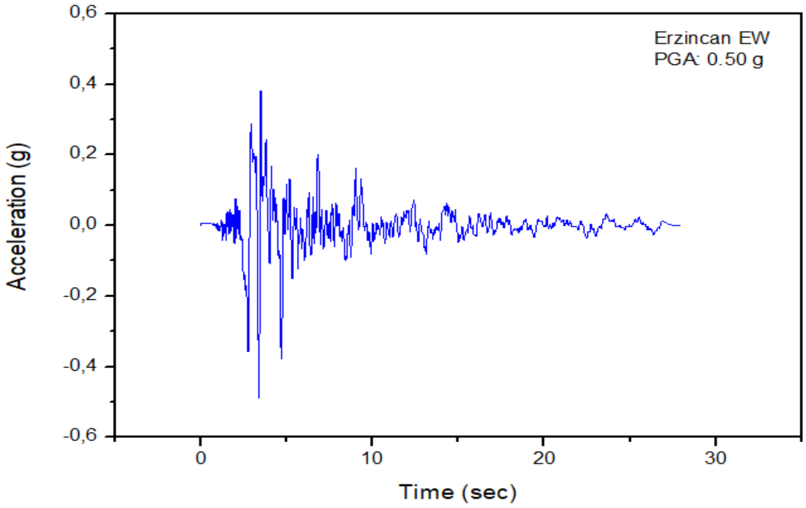

Figure 4. Acceleration time history of 1992 Erzincan EW earthquake motion

3. RESULTS AND DISCUSSION

Numerical results are presented in terms of transmitted accelerations and lateral displacements for a controlling node selected at the mid-top of the building model. Results are given both for non-isolated and isolated cases.

The acceleration-time history of the model subjected to 2A amplitude earthquake motion is shown in Figure 5a. The maximum acceleration value of the non-isolated model is measured as 0.81g at 3.5 sec. The maximum lateral acceleration for the isolated case is measured as 0.42g at 3.8 sec. The reduction of the lateral acceleration with the use of the RSM layer is calculated as 48 %. The maximum lateral displacements are measured as 13 cm and 18 cm for non-isolated and isolated models, respectively (Fig. 5b). The use of the RSM layer leads to deamplification of lateral acceleration whereas it causes a 38% increase in lateral displacement. Soft soils can potentially act as a natural mechanism for passive isolation, especially for near-field earthquakes that are rich in high-frequency wave components. Similarly, the use of the RSM layer, which represents soft soil conditions, leads reduction in accelerations, especially at higher frequencies. The reduction in measured acceleration is also apparent in amplitude spectra of the isolated case (Fig. 6).

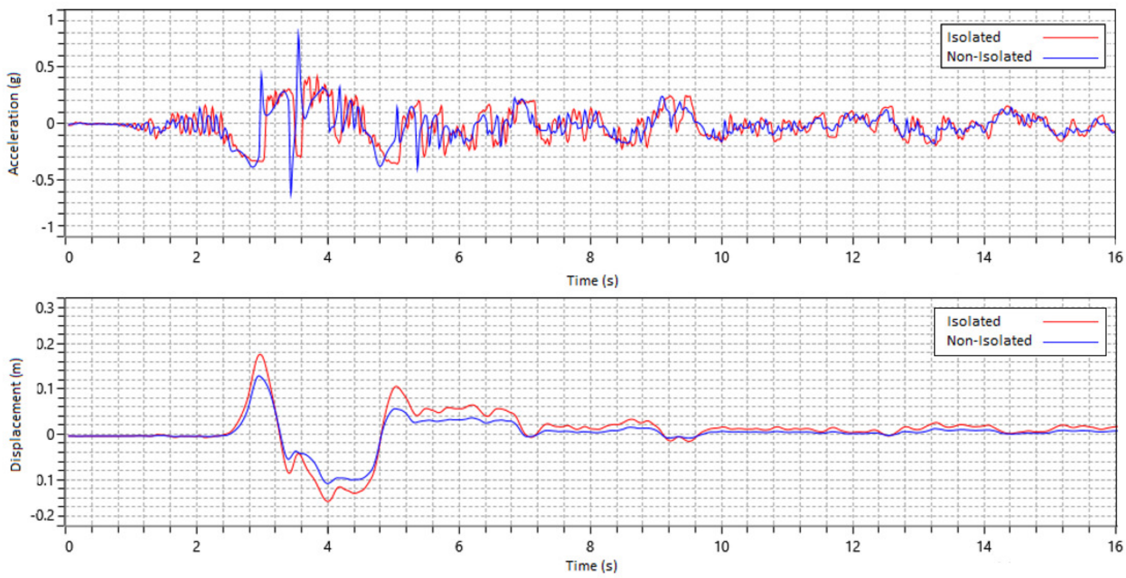

Figure 5. a. Acceleration-time history and **b.** displacement-time history of the models subjected to 2A amplitude of earthquake motion

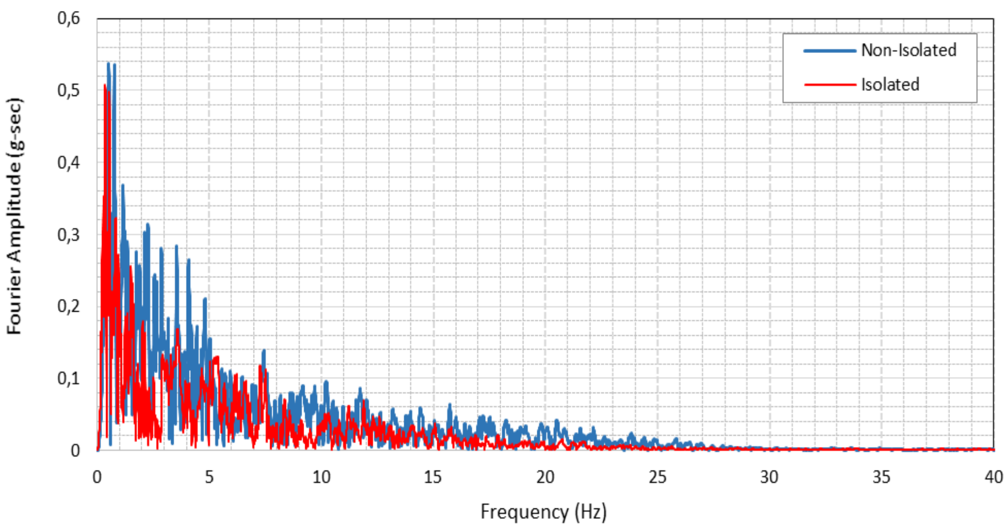

Figure 6. Fourier amplitude spectra of the acceleration time history of the models subjected to 2A amplitude of earthquake motion

The analysis results of the numerical model subjected to 1A amplitude earthquake motion are shown in Figure 7. The maximum acceleration value of the non-isolated model is measured as 0.41g at 3.6 sec. The isolated model reduced the lateral acceleration measured in 4. Second to 0.27 g (Fig.7a). The reduction in acceleration is calculated as 34%. The lateral displacements at the top of the building are measured as 7 cm and 5 cm for isolated and non-isolated models, respectively (Fig.7b). The final lateral distance of the isolated model concerning its original position is about 1 cm which reveals a recentring problem. There is a significant decrease in amplitudes at frequencies greater than 2 Hz. This is attributed to the implementation of a less stiff layer beneath the foundation lengthening the period of shaking (Fig. 8).

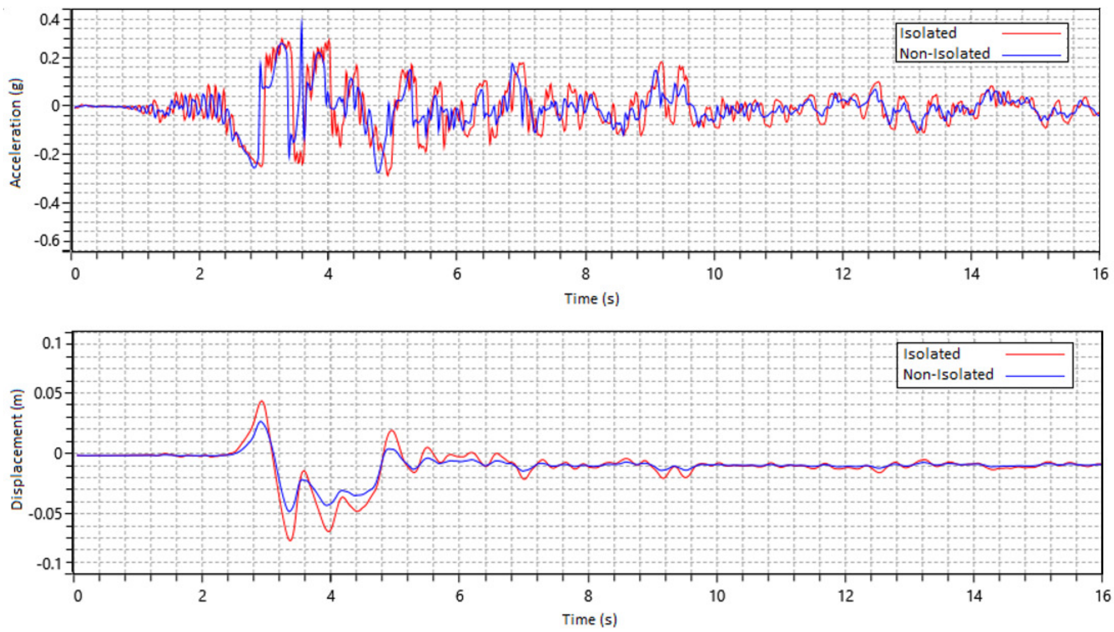

Figure 7. a. Acceleration-time history and **b.** displacement-time history of the models subjected to 1A amplitude of earthquake motion.

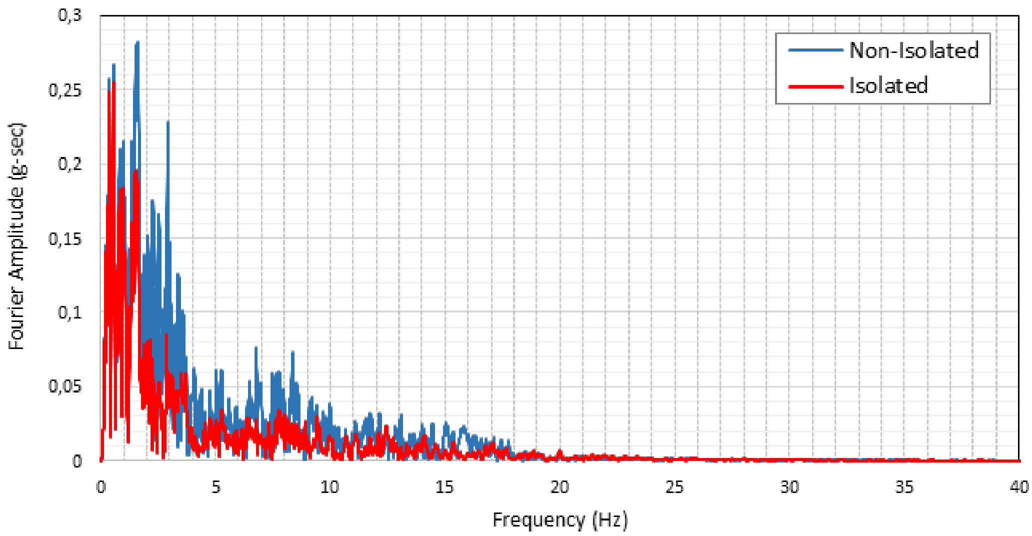

Figure 8. Fourier amplitude spectra of the acceleration time history of the models subjected to 1A amplitude of earthquake motion

The horizontal accelerations measured by isolated and non-isolated models are 0.18 g and 0.22g, at 3.5 and 3.6 seconds, respectively (Fig. 9a). The amount of reduction in lateral displacement is calculated as 18%. The lateral displacement for the non-isolated model is measured as 20 cm. However, as those obtained by models analyzed under higher amplitudes, the lateral displacement measured by the non-isolated model is lower than of isolated model as 12 cm (Fig. 9b). It is observed that the use of an isolation layer decreases the accelerations whereas it leads to an increase in lateral displacements. The amplitude spectra of acceleration for the isolated model are lower than the non-isolated one especially at higher frequencies (Fig.10). The use of the RSM layer under all three amplitudes leads to deamplification of accelerations. However, it was observed that in cases where the amplitude of the input motion is higher, the deamplification effect becomes more pronounced (Table 3).

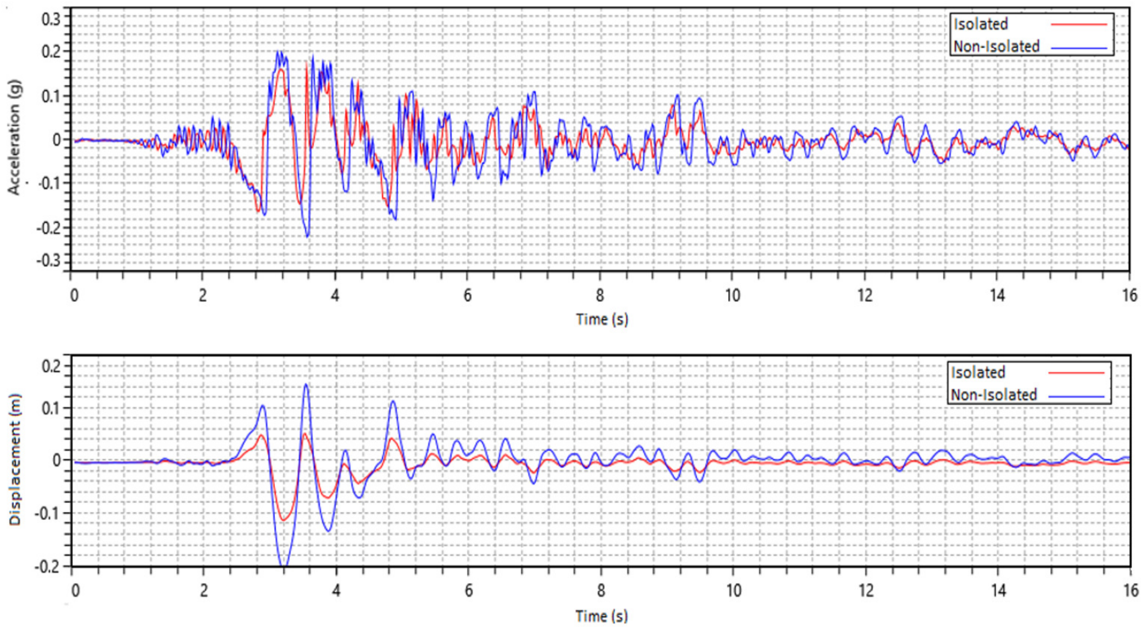

Figure 9. a. Acceleration-time history and **b.** displacement-time history of the models subjected to 0.5A amplitude of earthquake motion.

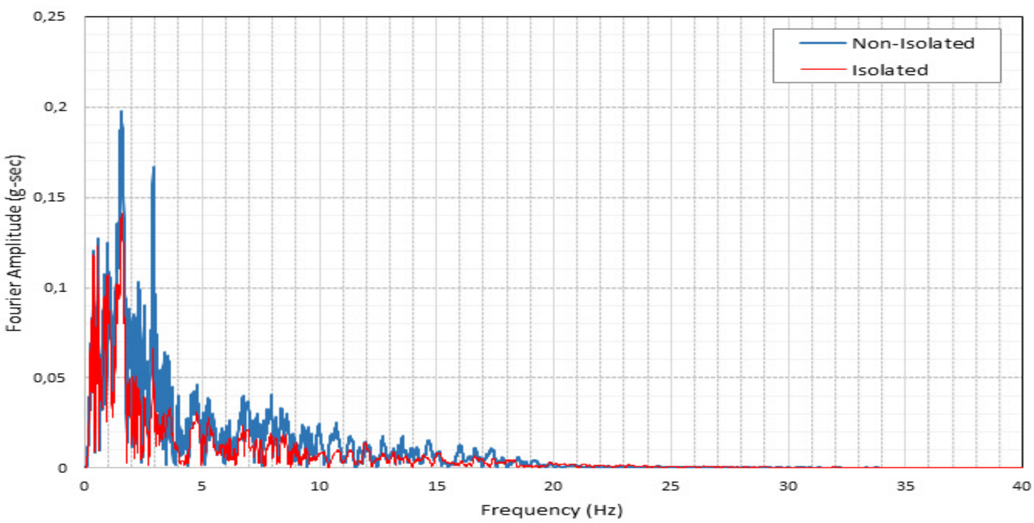

Figure 10. Fourier amplitude spectra of the acceleration time history of the models subjected to 0.5A amplitude of earthquake motion

Table 3. Measured acceleration values and calculated the percentage of reductions.

Model	**Acceleration**		
	2A	**1A**	**0.5A**
Non-Isolated	0.81g	0.41g	0.22g
Isolated	0.42g	0.27g	0.18g
Reduction (%)	48	34	18

5. CONCLUSIONS

In this study, the effectiveness of the Geotechnical Seismic Isolation system was investigated by developed numerical models. In this context, an isolation layer formed by rubber-soil mixture (RSM) was placed under a high-rise building model with two separated smooth synthetic liners. The performance of the model under real earthquake excitation with different amplitudes was examined. Based on the results of numerical analyses the following main conclusions can be drawn:

- The measured acceleration values are reduced between 18 and 48 % with the use of the RSM layer.
- A deamplification is observed in the acceleration values measured at the top of the isolated building model, while an increase in the displacements is observed.
- The recent problem that occurred by isolated models is attributed to the high friction angle of the RSM layer.
- As the amplitude of the applied input motion decreases, the reduction in accelerations measured by the use of the isolation layer decreased.

The GSI method examined in this study is not an alternative to the conventional seismic isolation method. However, it is a promising method since it is a low-cost application and can contribute to environmental problems caused by waste tire stockpiles. Numerical models regarding the use of the GSI method have been developed widely in the literature but it has no known real application. Since the material used in this method has high compressibility, it should be verified to what extent the behavior of the material under heavy structural loads will be compatible with numerical models. Additionally, numerical and low-scale models show that the performance of the proposed method in the laboratory environment under short-term loading conditions is satisfactory. However, the behavior of the RSM layer that will be subjected to high structural loads and environmental influences is still a virgin issue. To clarify these issues with larger-scale model tests is likely to expand the field of the practical application of the GSI method.

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