Shaking table experiments on soil isolation with using geosynthetics for medium rise buildings

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ABSTRACT: In this study, the results of the preliminary study on a proposed soil isolation method by using geosynthetics for mitigating the seismic hazards of medium-rise buildings are presented. Geotechnical seismic isolation (GSI) system is comprised of a geotextile laid over a geomembrane located within a soil profile beneath the structure with a cylindrical shape. This system stands on the concept of the dissipation of the seismic energy via sliding. Geosynthetics placed within a soil profile can absorb seismic energy and transmit smaller ground motions to an overlying structure. To obtain the more reliable results and to observe soil-structure behavior during the earthquake excitations, an experimental setup was developed. The effectiveness of the proposed GSI system was assessed by comparing the response of performed shaking table experiments with and without GSI material. The comparative results of experiments revealed that GSI system can affect the horizontal accelerations, horizontal drifts, Arias intensity, base shear, and base moment of the building model. By using the proposed GSI isolation system, seismic energy transmitted from ground to structure is dissipated through slip displacement between geotextile and geomembrane. Noticeable improvements were obtained on the seismic performance of the building model against strong ground motion. More importantly, it is revealed that soil isolation with geosynthetics can be used to mitigate the earthquake hazards for medium-rise buildings in developing countries.

Keywords: Geotechnical seismic isolation, Geosynthetics, Soil isolation, Earthquake hazards, Shaking table tests.

1 INTRODUCTION

Geosynthetics have been used in many different construction areas for decades. In the past years, geosynthetics have been proposed to utilize as a Geotechnical Seismic Isolation (GSI) material. Geosynthetics are proposed to use as “soil isolation” and “foundation isolation” materials. Proposed classification of the seismic isolation systems is defined by Tsang et al. 2012. Edincliler and Sekman (2016) studied on the foundation isolation with geosynthetics by considering soil-structure interaction effects. The effects of geosynthetic linear beneath the mid-rise building model are investigated by shake table tests. They mentioned that using foundation isolation with geosynthetics had a beneficial effect on the seismic performance of the mid-rise building model. Yegian and Catan (2004) mentioned that a smooth synthetic liner placed within a soil deposit can dissipate earthquake energy through slip deformations along the liner interface, thus reducing the intensity of the propagating shear waves. Such a system is referred to as soil isolation with geosynthetics because the soil layer above the liner is isolated from the underlying soil deposit that is experiencing the seismic shaking. The system is the placement of geosynthetics within the soil profile at some depth below the foundation of a structure. Yegian and Catan (2004), Georgarakos et al. (2005) and Tsatsis et al. (2013) have studied the soil isolation approach with different geometries and depths. The geometry of the low friction interface is a key factor controlling the magnitude of the transmitted accelerations and resulting slip displacements of the isolated soil mass relative to the free field. Yegian and Catan (2004), Georgarakos et al. (2005), and Tsatsis et al. (2013) were investigated the importance of the geometry of the GSI. It is seen that cylindrically shaped geosynthetics geometry generates the restoring gravitational force that would bring the isolated sand deposit back to its horizontal position. Thus, cylindrical shaped liner can decrease the permanent slip of the both structure and isolated soil region after experiencing seismic excitations. Considering gravity restoring effect and the results of the mentioned studies, it can be deduced that cylindrically shaped geometry is the most efficient one among the others.

The aim of this study is to determine the effectiveness of soil isolation with geosynthetics on seismic behavior of mid-rise buildings through shaking table experiments. This study is the first experimental study in the literature that makes possible to evaluate the validity of the proposed GSI system together with the soil-structure interaction by considering fundamental base isolation principles. While determining the effectiveness of the GSI system for the structures, it can be important to observe the seismic behavior of the foundation soil and structure together. Previous experimental researches on the similar subject did not cover the effects of GSI system on the foundation soil and superstructure in the same experimental model. This study aims to obtain preliminary results by considering the needs in the literature. By using the experiences from both experimental and numerical studies in the literature, a new shaking table test setup was developed to check the validity of proposed GSI system by taking into account the seismic behavior of soil and structure. It is aimed to be a guidance study for further detailed investigations.

2 MATERIALS AND METHODS

In this study, by the help of experiences, guidance and knowledge taken from the literature, the laminar box was designed, constructed and verified the performance criteria to simulate the field conditions in the laboratory. These performance tests investigate the effect of inertia, friction, membrane, and boundary on laminar box performance (Prasad et al. 2004, Jafarzadeh 2004, Ecemis and Kahraman 2012).

The soil material used in the experiments is named as “Silivri Sand" which is locally found around Istanbul region. The grain-size distribution of the sand was determined according to the American Standard Test Method of D422 as shown in Figure 1. According to the Unified Soil Classification System, the sand material is classified as poorly graded sand (SP) with the coefficient of curvature as C_u = 2.29 and the coefficient of uniformity as C_c = 1.1. The triaxial test conducted by Cagatay (2008) gives the internal friction angle as ϕ = 41.5°. Specific gravity of sand was obtained as G_s = 2.67 and the unit weight of sand is 16.5 kN/m^3. The maximum and minimum void ratios of the sand were obtained as 0.73 and 0.37, respectively.

The experimental parameters of the shaking table experiments involve geosynthetic types, the number of building story and GSI depths (H/D ratio). The simple idea of the proposed GSI system is transforming ground motion to slip displacement via creating an additional geosynthetics layer beneath the structure. The geosynthetics layer consists of two geosynthetics in the way that one on the top of the other. Moreover, Yegian and Kadakal (2004) summarized the requirements to select geosynthetics for an alternative seismic isolation (SI) material. Considering all given requirements and reviewing the literature, commercially available 1.0 mm thick PTFE sheet and 150 gr/m^2 nonwoven geotextile (Typar DuPont SF 44) were decided to utilize as GSI material. The selection of proper geosynthetic couple as GSI material was done via series of block test results (Sekman 2016).

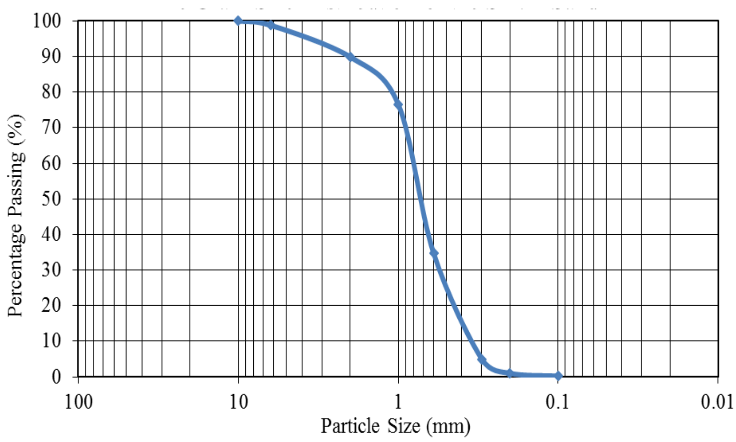

Figure 1. Grain-size distribution of the Silivri sand.

The model prototype was selected as 5-story building. The dimensions of laminar box do not allow the full-scale building models. Thereby, considering maximum allowable dimensions for the building model a 1:10 scale factor was determined. Similitude requirements of the building model was taken from Harris and Sabnis (1999). The most important issue during the design and scaling of the building was soil structure behavior that occurs during the experiments. By taking into consideration this subject, the prototype was scaled with base pressure and soil structure behavior. The scaling factors for required parameters are given in Table 1.

Table 1. Scaling parameters used in this study (Iai 1989).

Parameter	1:10 Scale Model/ Prototype	
Length	L	1/10
Time	$\sqrt{L}$	$1/\sqrt{10}$
Mass	L^2	1/100
Displacement	L	1/10
Acceleration	1	1/1
Stress	1	1/1
Strain	1	1/1
Force	L^2	1/100

Yegian and Catan (2004) plotted the graph displaying the transmitted acceleration versus H/D ratio. This figure helped to decide an ideal GSI depth (H/D ratio) according to the width of the covered geosynthetics as seen in the Figure 2. In the current research, GSI width toward the shaking direction was established as one meter due to the dimensions of the laminar box. Thereby, the depth of the GSI became directly proportional to transmitted acceleration. This means that if the GSI depth is increased, transmitted acceleration to the building increases for this condition. Transmitted acceleration becomes quite stable after H/D ratio exceeds 6.0. Therefore, the depth of the GSI was distinguished as 10 cm (H/D = 10).

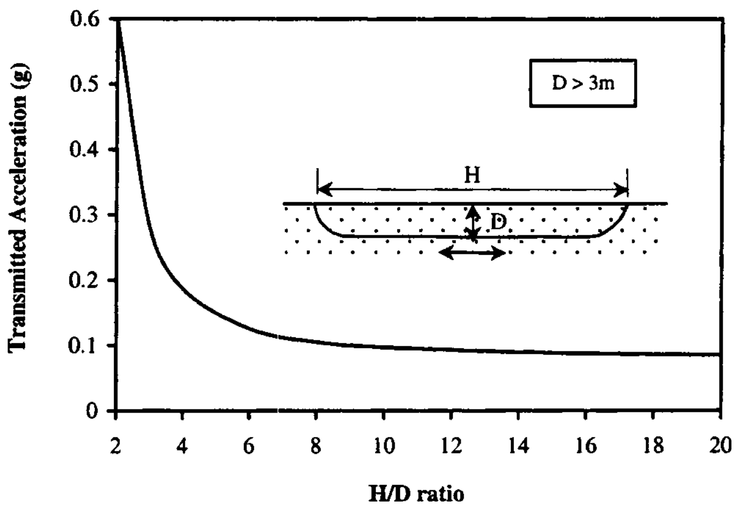

Figure 2. Transmitted acceleration as a function of H/D ratio (Yegian and Catan 2004).

Experiment setup with five story building model is shown in Figure 3. Four accelerometers with ±3 g capacity were placed in-soil and accelerometers with ±20g capacity were mounted on the building to measure accelerations. Six ODS were utilized for measuring story displacements. ODS were placed on the frame toward the each floor of the building model. Likewise, 20g capacity accelerometers were mounted on midpoint of every floor and 3g accelerometers were placed in soil. In order to understand the influence of the GSI locations of the in-soil accelerometers were determined carefully. Firstly, in-soil accelerometer was located midpoint of the laminar box under the GSI. Second one was placed just under the GSI. Third one was positioned between the foundation and GSI. Last accelerometer was placed outside of the GSI system near the surface.

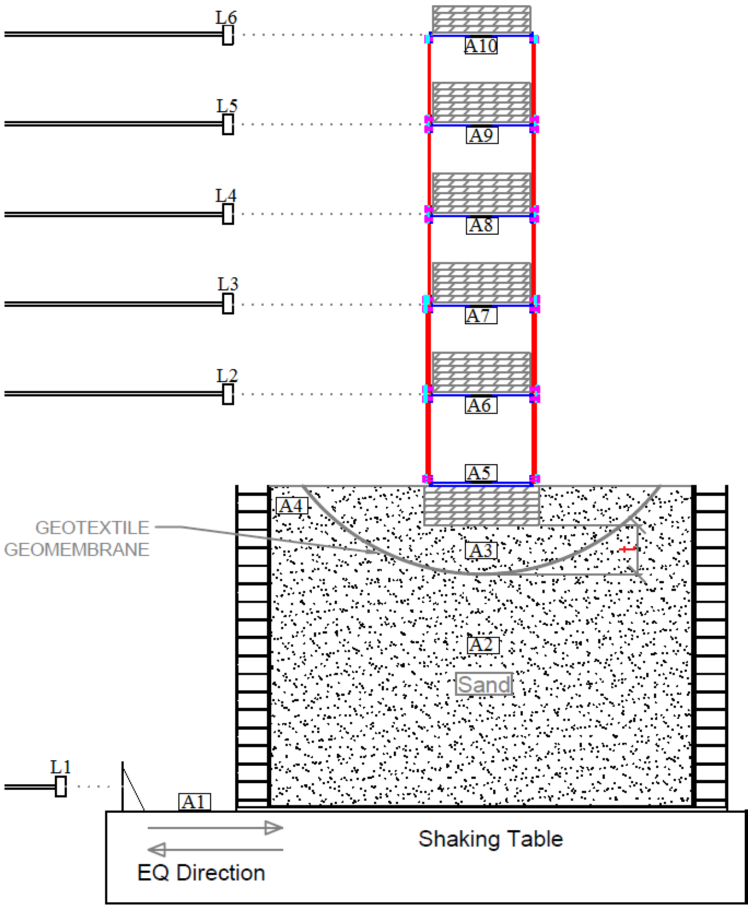

Figure 3. Experiment setup with five story building model.

The 1995 Kobe (KJMA station) earthquake (M_w=6.7; PGA=0.82g) has been selected for the shaking table tests as input motion. Because of having the uniaxial shaking table in the laboratory, the horizontal component of the earthquakes was selected. During the selection of earthquake, frequency content and applicability to the shaking table were considered. The earthquake data was obtained from the PEER Ground Motion Database – PEER Center. To apply the earthquake records to the proposed GSI system and building models, duration of the earthquake input data was scaled as 1:10 by multiplying duration with a scaling factor of $\sqrt{10}$ in the light of similitude rules taken from Harris and Sabnis (1999). In other words, to maintain dynamic similitude, earthquake record was compressed in time by a factor of $\sqrt{10}$. Time history of the scaled earthquake motion is shown in Figure 4.

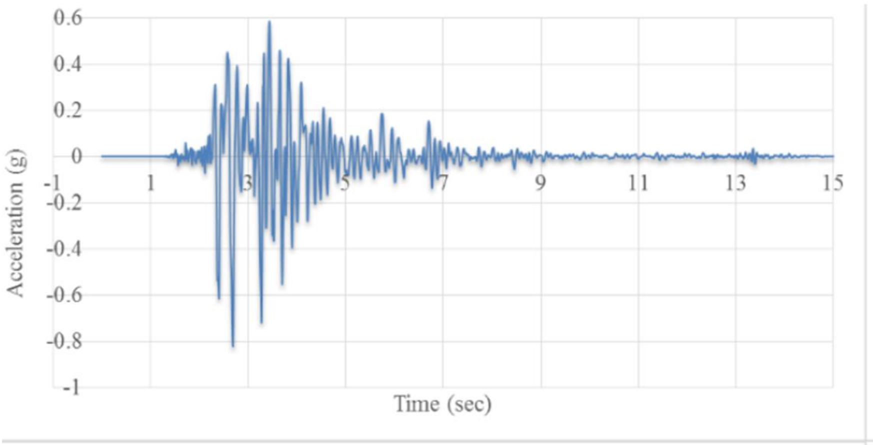

Figure 4. Acceleration-time history of the scaled 1995 Kobe Earthquake motion.

3 SHAKE TABLE TESTS

In order to investigate the effectiveness and robustness of the proposed GSI system, Cases were established to evaluate the effects of the depth of GSI (H/D ratio) and ground motion characteristics for proposed GSI system (Sekman, 2016). Control model (CM) was created to observe the behavior of the unisolated system including 5-story building model under the same input motion. The results of the experiments would be presented as comparisons that were made based on control model. Coherent with the literature (Tsang et al., 2012 and Adir, 2013), three main performance indicators that were foundation horizontal acceleration response, top floor horizontal acceleration response and first-floor drift and their peak and root-mean square (RMS) parameters were selected. Furthermore, the "percentage (%) reduction" parameter was computed to exemplify better the effectiveness of the proposed GSI system regarding its ability to reduce the acceleration and drift demand in a structure. This parameter was computed as 100% minus the response quantity gathered from the proposed GSI system expressed as a percentage (%) of the respective response quantity as obtained from the control model. Beside of these performance indicator parameters used in the literature, five additional performance indicator parameters were chosen. Arias intensity parameter was selected to observe the earthquake energy dissipation and strength of earthquake as a comparison between isolated and unisolated systems. Both Arias intensity and % reduction of Arias intensity were computed for each floor. Peak spectral acceleration was chosen as performance indicator parameter. Peak spectral acceleration values for each floor and % reduction of them are illustrated to clarify the reduction in the spectral acceleration. The shifting of the natural period of the structure is a feature of the conventional seismic isolation system. To determine whether this feature was valid or not for proposed GSI system, natural period and period shifting ratio were presented. Base shear and base moment were chosen as performance indicator parameters to see effects of proposed GSI system on total lateral seismic forces and its relevance to building height. The effects of the soil isolation with geosynthetics are given for H/D=10 under the 1995 Kobe Earthquake motion as Case 1.

3.1 *Seismic performance of 5-story building model constructed on unisolated soil*

CM was established to observe the behavior of the unisolated system including 5-story building model under chosen earthquake motion. Figure 5 illustrates the foundation horizontal acceleration response, top floor horizontal acceleration response and first-floor drift of CM under the Kobe earthquake motion. In order to clarify the effectiveness of the proposed GSI system, the experimental results of the Case 1 are presented as a comparison with control model (Figure 6 and Table 6).

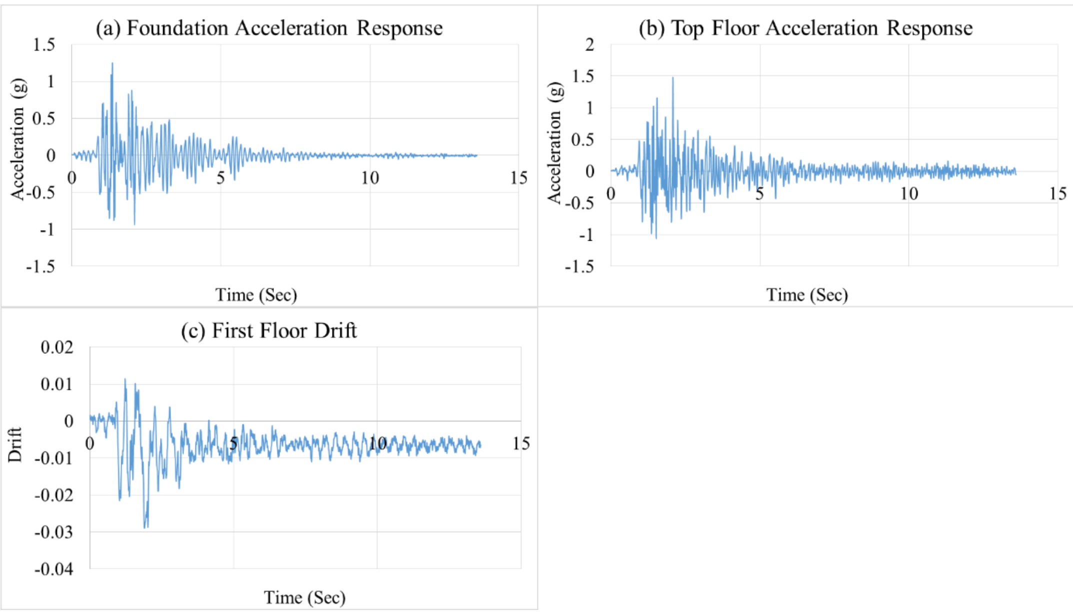

Figure 5. (a) Foundation, (b) Top floor horizontal acceleration response and (c) First floor drift of the CM under Kobe Earthquake motion.

3.2 *Seismic performance of 5-story building model constructed on isolated soil*

For the Case 1, PTFE 1 mm geomembrane with Typar DuPont SF56 nonwoven geotextile were placed with cylindrical shaped (H/D =10) under the foundation. 5-story building model excited with the selected earthquake motion. Besides, the results of Case 1 comparing with an unisolated case that is given below, belong to Kobe earthquake motion.

The reduction of foundation acceleration, top floor acceleration, and first-floor drift comparing CM are shown in Figure 6a, Figure 6b, and Figure 6c. The foundation acceleration is reduced approximately 18% in RMS and 16% in peak as seen in Figure 6a. The acceleration values are taken from the accelerometer that was placed midpoint of the isolated soil region is decreased 11% in RMS but magnified in peak value (Table 2). However, reduction of acceleration values become up to 18% in RMS and 28% in peak at the upper stories. The first-floor drift is decreased approximately 10% in RMS. There is no the top floor drift reduction in contrast with first-floor drift. Figure 6e illustrates the base shear and base moment that are diminished roughly 11% and 5% in RMS, respectively. It can be observed from Figure 6f that Arias intensity values computed for the floors are decreased up to 33%. In brief, nearly all performance indicator parameters indicate that proposed GSI system decreases performance indicator parameters like the transmitted acceleration and story drifts generally. Detailed information relative to the performance indicator parameters as respectively; horizontal acceleration response, horizontal story drift, Arias intensity, peak spectral acceleration, period lengthening ratio of the floors and base shear and base moment of 5-story building model is summarized in Table 2. On the other side, period lengthening ratio of the first floor, third floor, and top floor are altered. Moreover, peak spectral accelerations are reduced up to 25% as seen in Table 2.

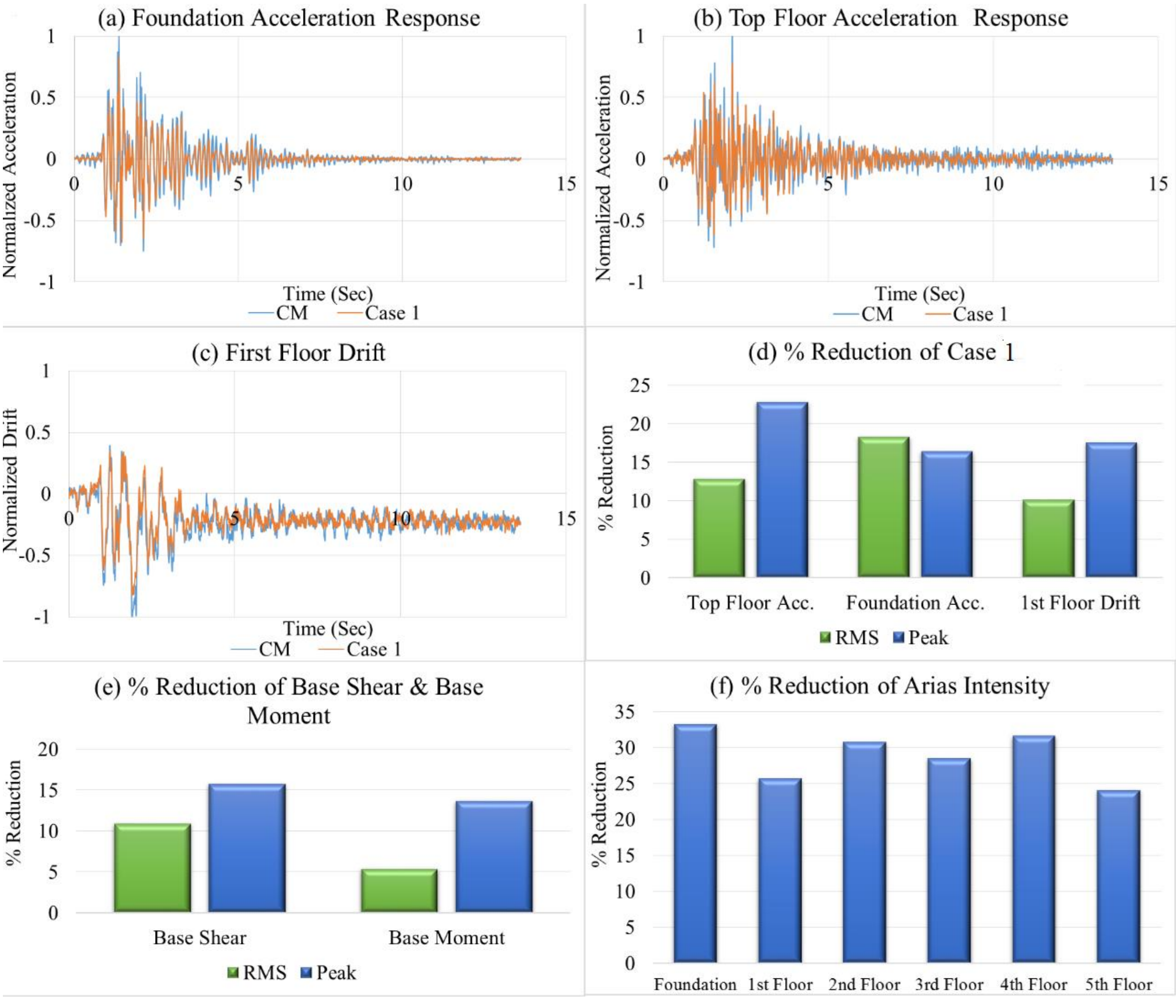

Figure 6. (a) Foundation, (b) Top floor horizontal acceleration response, (c) First floor drift, (d) % Reduction of Case 1, (e) % Reduction of base shear and base moment and (f) % Reduction of Arias intensity of Case 1 compared with CM under Kobe Earthquake motion.

Table 2. Comparison of Case 1 with the CM under Kobe Earthquake.

Results of Case 1 Comparing CM under Kobe Earthquake														
	In-soil		Foundation		1st Floor		2nd Floor		3rd Floor		4th Floor		5th Floor	
	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak
Horizontal Acceleration (g)														
CM	0.164	0.949	0.168	1.250	0.189	1.615	0.153	1.248	0.140	1.042	0.147	1.010	0.189	1.478
Case 1	0.147	1.001	0.137	1.044	0.163	1.265	0.127	0.948	0.119	0.892	0.122	0.727	0.165	1.140
% Reduction (%)	10.6	-5.5	18.3	16.4	13.8	21.7	16.8	24.0	15.4	14.4	17.3	28.0	12.9	22.8
Horizontal Story Drift														
CM	-	-	-	-	0.216	0.798	0.204	0.799	0.180	0.754	0.161	0.786	0.153	0.665
Case 1	-	-	-	-	0.194	0.658	0.339	0.917	0.090	0.546	0.133	0.759	0.208	0.828
% Reduction (%)	-	-	-	-	10.1	17.6	-65.9	-14.8	49.9	27.7	17.5	3.5	-36.1	-24.5
Arias Intensity (m/sec)														
CM	5.673		5.911		7.486		4.916		4.126		4.542		7.491	
Case 1	4.538		3.946		5.563		3.404		2.952		3.106		5.689	
% Reduction (%)	20.0		33.2		25.7		30.8		28.5		31.6		24.1	
Peak Spectral Acceleration (g)														
CM	-		3.989		4.556		3.965		4.582		4.521		4.826	
Case 1	-		3.549		4.546		2.965		4.642		3.432		3.913	
% Reduction (%)	-		11.0		0.2		25.2		-1.3		24.1		18.9	
Period Lengthening Ratio														
CM			0.155		0.040		0.040		0.060		0.040		0.040	
Case 1			0.155		0.055		0.040		0.055		0.040		0.055	
Period Length. Ratio			1.000		1.375		1.000		0.917		1.000		1.375	

	Base Shear (kN)		Base Moment (kN.m)	
	RMS	Peak	RMS	Peak
CM	1.023	7.418	0.412	2.802
Case 1	0.911	6.251	0.390	2.419
% Reduction (%)	10.9	15.7	5.4	13.6

4 DISCUSSION OF THE TEST RESULTS

Reduction of selected performance indicator parameters (%) is summarized in Table 3. It is observed that the soil isolated model (Case 1) showed the mitigation of the seismic effects under Kobe earthquake motion. Case 1 having 10 cm GSI depth (H/D =10) was feasible when comparing with unisolated case (Control Model).

Table 3. % Reduction of selected performance indicator parameters

Performance Indicator Parameters	RMS	Peak
Top Floor Acceleration	13	23
Foundation Acceleration	18	16
Top Floor Drift	-36	-25
First Floor Drift	10	18
Base Shear	11	16
Base Moment	5	14
Top Floor Arias Intensity	24	
Foundation Arias Intensity	33	

5 CONCLUSIONS

The effectiveness of soil isolation with geosynthetics on medium rise building was determined by a series of shake table tests. A preliminary shake table experimental setup has been developed for modeling seismic responses of soil–foundation–structure system by which the effectiveness and robustness of the proposed method have been evaluated. Comparison of the soil isolated model with the unisolated model revealed the following results.

- An isolation liner can significantly reduce the accelerations at the surface of the isolated soil mass.
- The spectral accelerations were reduced in general when the proposed GSI system was utilized. In other words, damping of the system was increased. Unlike for the conventional seismic isolation systems, the spectral accelerations obtained using the proposed GSI system drop significantly at the natural period of the 5-story building model whereas the natural periods of the same building model was not shifted.
- The transmitted top, foundation and in-soil accelerations of the building model and the top and first-floor story drifts can be substantially decreased due to the inclusion of GSI material within soil profile. The rest of the performance indicator parameters that are base shear, base moment, top floor Arias intensity, and foundation Arias intensity were reduced.

As a conclusion, experimental studies showed that the proposed GSI system works efficiently under the considered seismic motion. Mitigation of seismic effects on mid-rise buildings for developing countries can be obtained by using the GSI with geosynthetics. As further studies, detailed experimental study with changing the type of foundation soil and size of structures should be performed. The seismic performance of the scaled model should be validated with the prototype models in the field.

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