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EFFECTS OF FOUNDATION ISOLATION WITH GEOSYNTHETICS ON SEISMIC PERFORMANCE OF LOW-RISE BUILDINGS

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ABSTRACT

Smooth synthetic liners can be placed underneath the foundation of structures for the dissipation of the seismic energy via sliding. For this purpose, geotextile-geomembrane (GG) couple was horizontally placed underneath the foundation of a 1:10 scaled low-rise building model as foundation isolation material. The suitability of geotextile-geomembrane (GG) couple as foundation isolation material was determined by a series of block tests. In this study, seismic responses of the unisolated and isolated building models were compared by shaking table tests under the 1999 Kocaeli earthquake, 1940 El Centro earthquake and 1995 Kobe earthquake motions. Six performance indicator parameters including the peak and RMS values of horizontal accelerations, Arias intensities at the roof and the foundation as well as the first-floor inter-story drifts, base shear and base moment have been chosen for comparing and evaluating the effectiveness of the geosynthetic couples. In addition, the test results of the isolated model were compared with the identical model without foundation isolation. As a result of the conducted experiments, the use of GG couple which was defined by block tests as foundation isolation material provided substantial reduction in evaluated performance parameters. It is seen that the effectiveness of the proposed foundation isolation system may change under different earthquake motions. More importantly, the proposed GSI-GG system can be used to mitigate the earthquake damages on low-rise buildings.

Keywords: Geotechnical seismic isolation; Geosynthetic liner; Foundation isolation; Seismic performance; Shaking table tests.

1. INTRODUCTION

Nowadays, conventional seismic isolators are generally used. Elastomeric bearing and friction pendulum systems were common types in use. However, these systems are quite expensive in economic aspect. The low-cost alternatives can greatly benefit the developing countries where resources and technology are not adequate for earthquake mitigation. Therefore, the concept of using low-cost mechanisms as seismic isolation as an alternative method is being mentioned in recent studies. This system is called as “Geotechnical Seismic Isolation (GSI) system. Geosynthetics and rubber-soil mixtures (RSM) are proposed as GSI systems. Geosynthetic materials were being used in filtration, separation, drainage, reinforcement etc. In the last years, the utilization of geosynthetic materials as an alternative way of mitigating earthquake effects was studied. Working principle is similar to the Friction Pendulum System (FPS). GSI concept was mentioned with the details in the literature (Tsang, 2008; Tsang et al. 2009; Tsang et al. 2012). Kavazanjian et al. (1991), Yegian and Lahlaf (1992), Yegian et al. (1995), Yegian and Catan (2004), Yegian and Kadakal (2004), and Georgarakos et al. (2005), Edincliler and Sekman (2016), Edincliler and Calikoglu (2017), Calikoglu (2017) conducted several researches on using geosynthetics as a seismic isolation material. GSI with geosynthetics was defined as soil and foundation isolation materials. Utilization of geosynthetics as foundation isolation was mentioned in the study of Yegian et al. (1999). Foundation isolation with geosynthetic liner is based on the principle of the absorption and reduction of transmitted seismic acceleration and energy to overlying structure by geotextile-geomembrane (GG) couple immediately

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underneath the foundation of the building. Yegian et al. (1999) studied this concept on single story building. In another study, this concept was improved and a new model was created by the placement of nonwoven synthetic materials underneath the foundation of the building (Yegian and Kadakal 2004). This feature is distinctive from conventional systems, which are based on isolation at certain discrete supporting points. For this reason, this system was called as "Distributed seismic isolation system". The proposed GSI system with geosynthetics can transmit lower levels of earthquake motion to the superstructure via sliding. Geosynthetics can be used for "soil isolation" and "foundation isolation" systems. This study focused on foundation isolation with geosynthetics. The aim of this study is to determine the effectiveness of the GG couple placed under the foundation of the three story building model. The effects of earthquake motions on seismic response were evaluated.

2. MATERIALS AND METHODS

In order to evaluate the behavior of geotechnical applications under earthquake excitations, soil containers representing site conditions in a laboratory environment needed. Production and design of the containers are quite important to obtain accurate results from seismic performance tests. After design of the laminar box, a series of performance tests were performed before starting to the tests. Performance tests are composed of inertia, friction, membrane and boundary condition tests. In this study, the developed laminar box in the previous studies (Sekman 2016; Goztepe 2016) was used. The performance tests of laminar box was repeated before starting to shaking table experiments. After successful results were obtained, laminar box was fixed on the shaking table. As sandy soil deposit, Silivri sand having a unit weight of 16.5 kN/m^3 was used and soil classification was determined as SP (poorly graded sand). Sandy soil was added gradually and compacted inside the laminar box. Structural properties of the building model was scaled. A 1/10 scaled building model was created in accordance with the scaling law of Iai (1989). Scaling parameters was illustrated in Table 1. A 1/10 scaled three story building model is shown in Figure 1. The developed shake table test set-up makes possible to evaluate the soil-structure interaction under earthquake motions.

Table 1. Scaling parameters given by Iai (1989) and corresponding values in this study.

Parameter	Scaling Factors	
	Prototype/Model	Scaling Factor for 1/10 Scaled Tests
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

Two different models, unisolated and foundation isolated models, were studied. For unisolated model, the low rise building model was directly placed on the foundation soil. For the foundation isolated model, the first step is to select the suitable G-G couple. The selection of proper geosynthetic couple as GSI material was done via series of block test results (Sekman 2016). GG couple was placed as a straight liner (SL) having a width of 2B. The main principle of the proposed GSI system is to mitigate seismic effects exerted on the building by transformation of earthquake motion to shear displacements via geosynthetic liner underneath the foundation. Geosynthetic layer is composed of two parts that are 190 gr/m^3 nonwoven geotextile (Typar DuPont SF56) on the top and 1 mm thick PTFE geomembrane on the bottom. After placement of GG couple, the building model was placed (Case 1).

Figure 1. A 1/10 scaled 3-story building model.

2.1 Instrumentation

To measure the acceleration response, three accelerometers having a capacity of ±20g were placed at each floor. In order to measure story displacements, three displacement sensors having a range of 1.2m were placed. Sensors were arranged at the middle of each floor in front of the building model. Typical experimental setup scheme is shown in the Figure 2.

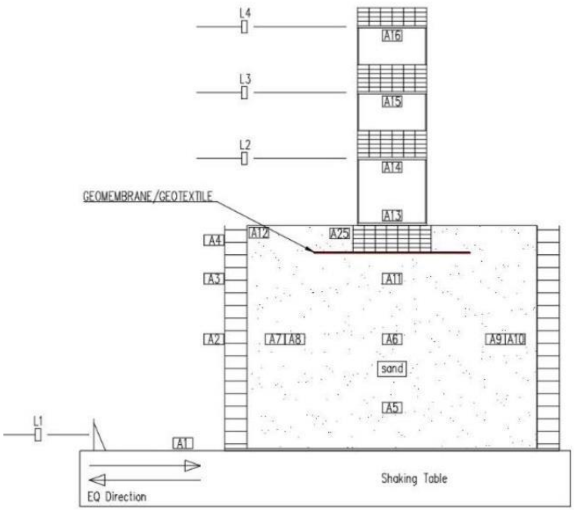

Figure 2. Experimental setup

In this study, the effects of the placement of a geosynthetic liner (geotextile-geomembrane (GG) couple) underneath the foundation of a building were evaluated. As a result of shaking table experiments, seismic response of unisolated and isolated building models were compared for three destructive earthquakes.

2.2 Seismic Input Preparation

As input ground motion, three destructive earthquakes were selected. The 1999 Kocaeli earthquake, the 1940 El Centro earthquake and the 1995 Kobe earthquake records (Table 2). The selected earthquakes were scaled and applied to the shaking table (Figure 3).

Table 2. Information about the input motions (PEER).

Name	Date	Station	Magnitude	PGA (g)	PGV (cm/sec)	PGD (cm)
Kocaeli	17.08.1999	Izmit	7.51	0.22	27.02	14.51
El Centro	19.08.1940	Imperial Valley	6.95	0.31	31.74	18.01
Kobe	15.01.1995	KJMA	6.90	0.82	77.83	18.87

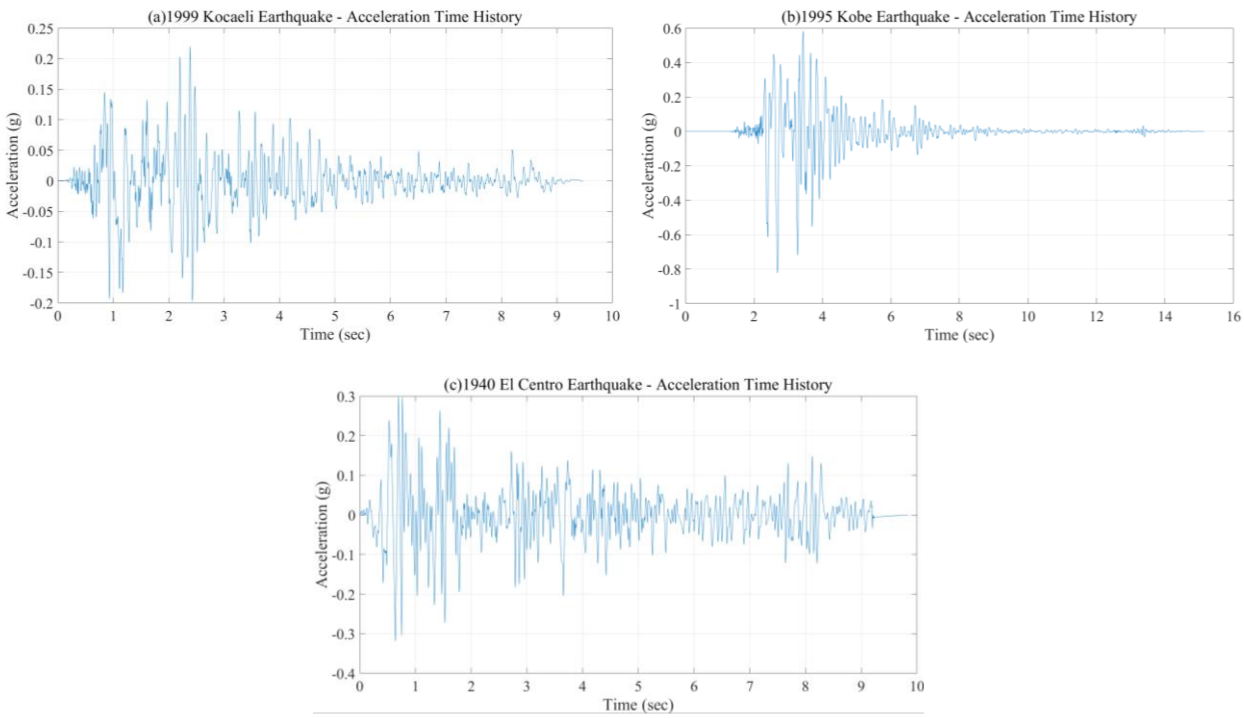

Figure 3. Scaled input motions (a) Kocaeli earthquake, (b) Kobe earthquake, (c) El Centro earthquake

3. SHAKING TABLE EXPERIMENTS

Six performance indicator parameters including the peak and RMS values of horizontal accelerations, Arias intensities at the roof and the foundation as well as the first-floor inter-story drifts, base shear and base moment have been chosen for comparing and evaluating the effectiveness of the geosynthetic couples. In addition, the test results of the isolated model were compared with the identical model without foundation isolation. The results of shake table tests under three different destructive earthquake motions are summarized as follows.

3.1. Seismic Response under Kocaeli Earthquake Motion

Maximum reduction in acceleration response was observed at the second floor as 48.82% in RMS, and 26.64% in peak value. Large amount of reduction in story drift was observed in the results. Maximum reduction was observed at top story as 98.98% in RMS value and 80.86% in peak value. Maximum reduction in Arias intensity appeared at the second floor as 38.36%. Moreover, 32.11% reduction was measured at the first floor in peak spectral acceleration. Comparative results can be seen in Figure 4. A little bit period shift was observed at the top floor with an increasing factor of 1.07. Great reduction percentages were obtained in base shear and base moment, especially in RMS values as about 47%.

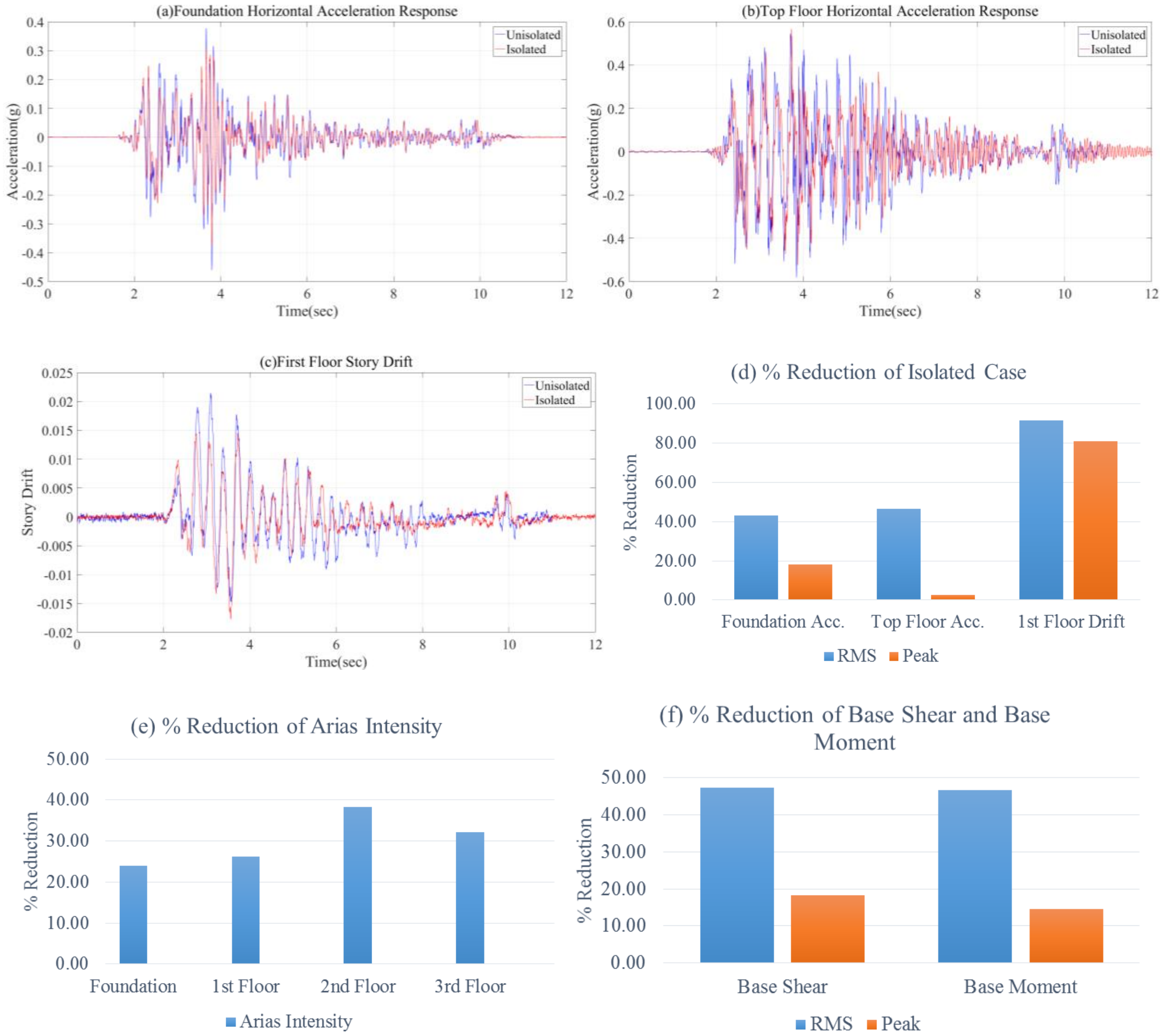

Figure 4. (a) Foundation acceleration response, (b) Top floor acceleration response, (c) First floor drift response, (d) % Reduction of isolated case, (e) % Reduction of Arias intensity, (f) % Reduction of base shear and base moment under Kocaeli Earthquake

3.2. Seismic Response under Kobe Earthquake

Maximum reduction in acceleration response was observed at the second floor as 9.5% in peak value, and at the first floor as 26.04% in RMS value. At the second floor, maximum reduction was obtained as 66.59% in story drift. On the other hand, the first story was exposed to maximum reduction in Arias intensity as 25.9 %. Moreover, the second floor showed reduction in peak spectral acceleration as 38.54%. The results can be seen in Figure 5. Almost 10 times greater fundamental period was observed in isolated case with an increasing factor of 10.95 when compared to unisolated case. Furthermore, larger reduction values were obtained in base shear and base moment in RMS values as about 22% when compared to peak values that were 2.85% for base shear and 6.40% for base moment.

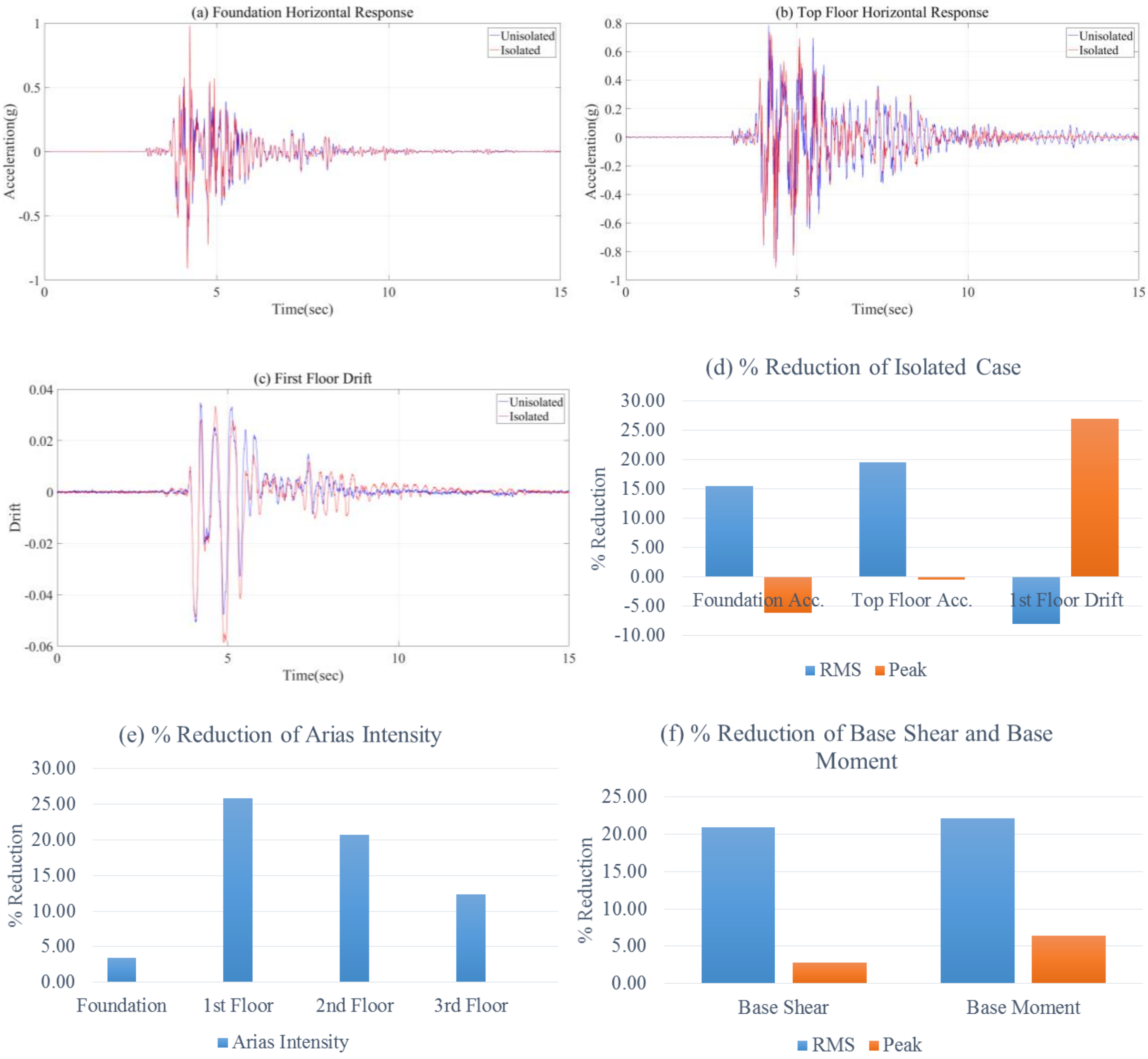

Figure 5. (a) Foundation acceleration response, (b) Top floor acceleration response, (c) First floor drift response, (d) % Reduction of isolated case, (e) % Reduction of Arias intensity, (f) % Reduction of base shear and base moment under Kobe Earthquake.

3.3. Seismic Response under El Centro Earthquake

Maximum reduction in horizontal acceleration response was observed at the second floor as 32.59% in RMS value and 25.54% in peak value. At the first story, maximum reduction in story drift was measured as 95.11% which means enormous reduction in occurrence of soft story phenomenon. Similarly, second floor was exposed to maximum reduction in Arias intensity and peak spectral acceleration as 40.46% and 23.50%, respectively. Finalized results were tabulated and graphed in Figure 6. Maximum period shifting was observed at the second floor with a factor of 7.47. Moreover, larger reduction values in base moment and base shear was observed in RMS values. However, about 15% increase in base shear value was obtained in peak value.

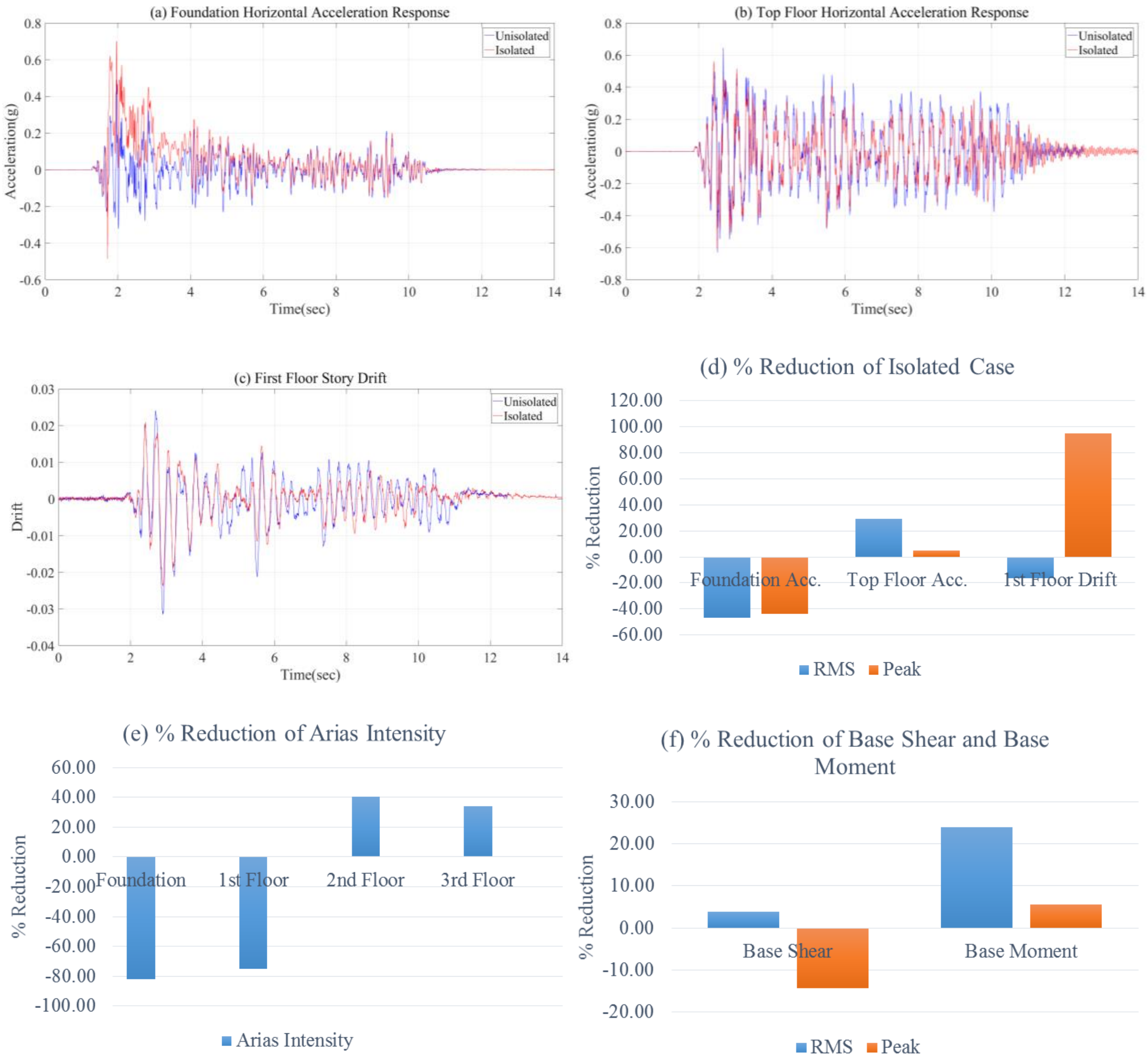

Figure 6. (a) Foundation acceleration response, (b) Top floor acceleration response, (c) First floor drift response, (d) % Reduction of isolated case, (e) % Reduction of Arias intensity, (f) % Reduction of base shear and base moment under El Centro Earthquake.

4. DISCUSSION OF TEST TESULTS

In order to compare the isolated building models, horizontal acceleration, story drifts, Arias intensity, peak spectral acceleration, base shear and base moment values were investigated in terms of evaluation of seismic performance. Acceleration and story drift values were given as peak and RMS (Root-Mean-Square). Reduction values under Kocaeli, El Centro and Kobe earthquakes were determined. Comparison among isolated building models under these three earthquakes were given in the Table 3. Reductions in acceleration, story drift and peak spectral acceleration values under three earthquakes are given in Figure 7. In addition, reductions in another performance indicators as Arias intensity, base shear and base moment values under three earthquakes are given in Figure 8.

As a result of shaking table experiments, maximum reduction in acceleration was observed at the second floor under all the earthquakes. The most reduction was observed under Kocaeli earthquake as 49% for RMS, and 27% for peak values. Maximum reduction in story drift was observed at the first story for all given ground motions. In peak response, G-G couple worked more properly under El Centro with a reduction of 95% whereas a 92% reduction was observed under Kocaeli earthquake in

RMS value. Besides, Arias intensity was attenuated mostly at the second floor with a maximum reduction percentage of 40% under El Centro earthquake. Results under Kocaeli and El Centro earthquakes were similar to each other for Arias intensity at second floor. Peak spectral acceleration was mostly reduced at the second floor in overall. On the other hand, maximum reduction was observed as 39% under Kobe earthquake at second floor. Reduction in base shear and base moments were similar to each other under Kocaeli and Kobe earthquakes. A 47% reduction and a 22% reduction in base shear and base moment values were obtained under Kocaeli and Kobe earthquakes, respectively. In contrast to Kocaeli and Kobe earthquake motions, maximum reduction in base moment and base shear was observed as 24% and 4% for RMS value, respectively. Briefly, the proposed GSI system provided an important reduction in all performance parameters. Obtained results for each floor were shown in Table 3.

Table 3. Comparative results of shaking table experiments.

REDUCTION VALUES (%)								
Earthquakes	Foundation		1st Floor		2nd Floor		3rd Floor	
	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak
Horizontal Acceleration (g)								
Kocaeli	43	18	44	21	49	27	47	3
El Centro	-47	-43	-16	-42	33	26	29	5
Kobe	15	-6	26	9	23	10	20	0
Horizontal Story Drift								
Kocaeli	-	-	92	81	15	-95	99	45
El Centro	-	-	-16	95	38	-105	4	1
Kobe	-	-	-8	27	-43	67	-5	-25
Arias Intensity (g-sec)								
Kocaeli	24		26		38		32	
El Centro	-82		-75		40		34	
Kobe	3		26		21		12	
Peak Spectral Acceleration (g)								
Kocaeli	4		32		28		18	
El Centro	-31		12		24		10	
Kobe	-14		35		39		3	
	Base Shear (kN)				**Base Moment (kN-m)**			
	RMS		Peak		RMS		Peak	
Kocaeli	47		18		47		14	
El Centro	4		-14		24		6	
Kobe	21		3		22		6	

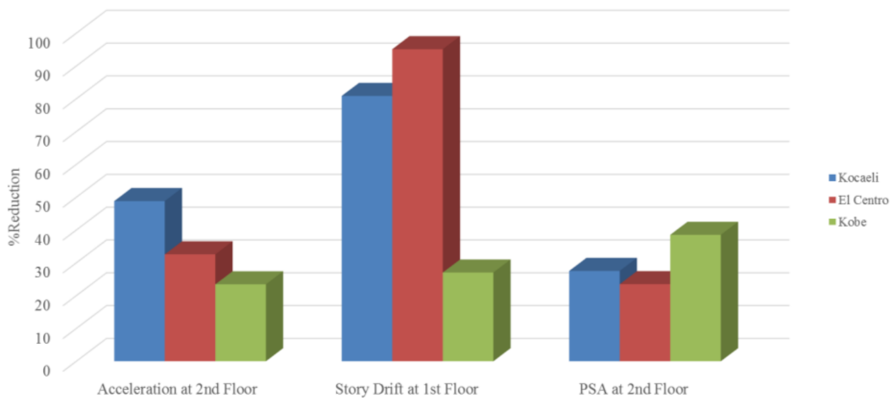

Figure 7. Reductions in acceleration, story drift and peak spectral acceleration values under three earthquakes

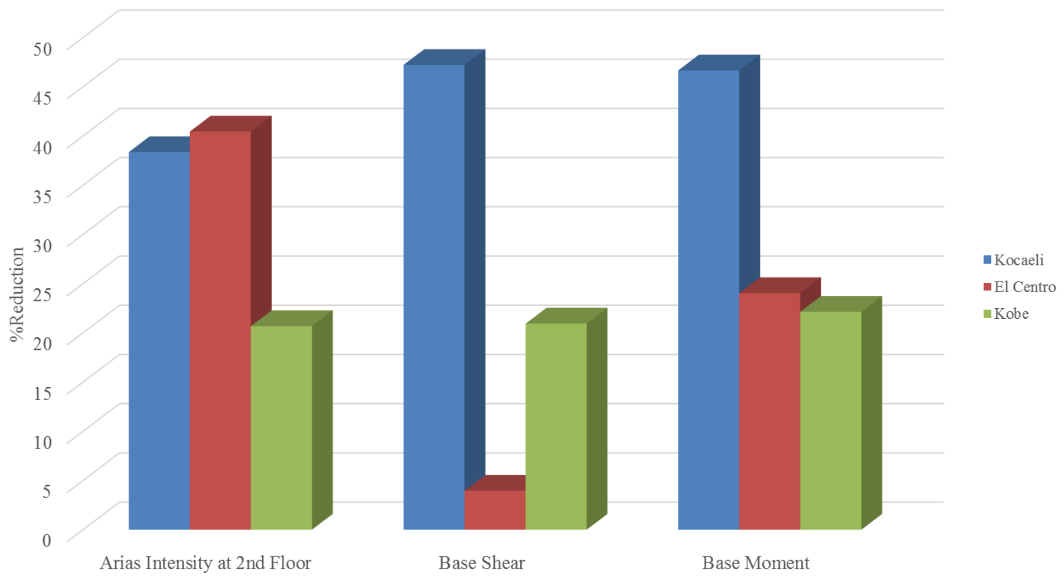

Figure 8. Reductions in Arias intensity, base shear and base moment values under three earthquakes

5. RESULTS AND CONCLUSIONS

In this study, the effects of geosynthetic couples placed as a straight liner underneath the foundation of building on the seismic performance of the scaled low-rise building model were evaluated. The obtained results were summarized as follows:

- Spectral accelerations were minimized up to 39%. It means damping of the system increased in the presence of the straight liner.
- Under Kocaeli earthquake, accelerations exerted on the building were decreased with a reduction percentage of 27% in peak value and 49% in RMS value at the second floor.
- The maximum reduction was observed in story drifts up to 95% at the first floor. It means soft story phenomenon was mitigated substantially.
- Except story drift, other three performance parameters were mostly deamplified at the second floor.
- Straight liner worked more efficiently under the Kocaeli earthquake when compared to the other earthquakes.
- When looked into overall results, the straight liner provided more efficiency under Kocaeli earthquake rather than El Centro and Kobe earthquakes in all performance parameters. However, the straight liner provided more promising results in reducing spectral acceleration values under Kobe earthquake motion.
- Depending on the earthquake motions, the effectiveness of the proposed foundation isolation system changed.
- In general, the straight liner improved the seismic performance of the low rise building model.

As a result of shaking table experiments, it can be obviously seen that utilization of geosynthetics in mitigation of earthquake hazards is beneficial. Moreover, this proposed system can be a good alternative for the developing countries. These results are obtained for the defined distinctive geotextile-geomembrane (GG) couples by the block tests as a GSI material under the selected earthquake motions. Shaking table tests demonstrated that GG couples may be a suitable and affordable foundation isolation material. For future studies, the effects of new parameters as a number of storey, width of the building, earthquake characteristics, GG type and properties on the seismic performance of a low-rise building model are need to be investigated.

6. ACKNOWLEDGMENTS

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