Shaking table experiments on geotechnical seismic isolation for low-rise buildings using geosynthetics

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ABSTRACT: This paper present the preliminary research works on a potential geotechnical seismic isolation (GSI) method using geosynthetics for the protection of low-rise buildings. GSI systems can be regarded as distributed seismic isolation systems which involve isolating the entire contact surface of the foundation structure. Smooth synthetic liners placed underneath the foundation of structures for the dissipation of the seismic energy via sliding are defined as "foundation isolation". Geosynthetic liners placed under foundations can absorb seismic energy and transmit smaller ground motions to an overlying structure. The concept of this study is the placement of the geotextile-geomembrane couple immediately underneath the foundation of the structure. The main novelty of this research is to determine the effects of foundation isolation with geosynthetics on the seismic performance of the low-rise buildings by a reduced scale shaking table tests. Three shaking table test set-up were tested to determine the effects of foundation isolation on the seismic performance of low-rise building model under the different earthquake motions. Six performance indicators including the peak and RMS values of horizontal acceleration at the roof and the foundation as well as the first-floor inter-story drift have been chosen for comparing and evaluating the effectiveness of the two configuration types of foundation isolation. The test results of the isolated models were compared with the identical model without isolation.

Keywords: Geosynthetics, Foundation isolation, Earthquake, Geotechnical seismic isolation, 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. Difficulties in application of these systems for developing countries should be considered. 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. From now on, geosynthetics and rubber-soil mixtures (RSM) were used 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) .

Several researches were conducted a series of tests on using geosynthetics as a seismic isolation material. GSI with geosynthetics was defined as soil and foundation isolation materials (Kavazanjian et al. 1991, Yegian et al. 199), Yegian and Catan 2004, Yegian and Kadakal 2004, Georgarakos et al. 2005, Edincliler and Sekman 2016 and Edincliler and Calikoglu 2017). 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 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 is called as “Distributed Seismic Isolation System”. The proposed GSI system in this study aims to transmit lower levels of earthquake motion to the superstructure by using foundation isolation by geosynthetic layers. 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. The effects of the configuration type of geosynthetic layers were discussed.

2 MATERIAL AND METHOD

In order to evaluate the effects of the proposed GSI method on the seismic performance of low rise building. a laminar box designed for the pevious researhes was used (Sekman 2016; Goztepe 2016). Production and design of these types of containers are quite important to obtain accurate results from seismic performance tests. A series of performance tests was performed before starting to the shaking table tests (Calikoglu 2017). Performance tests are composed of inertia, friction, membrane and boundary condition tests. 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. After foundation soil prepared, the low rise building model without isolation was placed on the foundation soil. For the base isolated model tests, the most important point is to select the proper geosynthetic couple as GSI material via series of block test results. A 1/10 scaled building model was created in accordance with the scaling law of Iai (1989). Scaling parameters were given in Table 1. A 1/10 scaled three story building model is shown in Figure 1.

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

Parameter	Scaling Factor	
	Prototype/Model	Scaling Factor for 1/10 Scaled Tests
Length	L	1/10
Time	√L	1/√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

2.1 *Instrumentation*

Geosynthetic layer is composed of two parts that are 190 gr/m^3 nonwoven geotextile on the top and 1 mm thick PTFE geomembrane on the bottom. 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 1.2 m were placed. Sensors were arranged at the middle of each floor in front of the building model. In this study, the effects of the placement of a geosynthetic liner (geotextile-geomembrane (GG) couple) as “curve shaped liner-CL” and “straight liner-SL” underneath the foundation of a building were evaluated. As a result of shaking table experiments, seismic responses of unisolated and isolated building models were compared. Typical experimental setups are shown in the Figure 1. Placement of two different configurations of geosynthetic liners as “curve shaped liner” and “straight liner” are given in Figure 2.

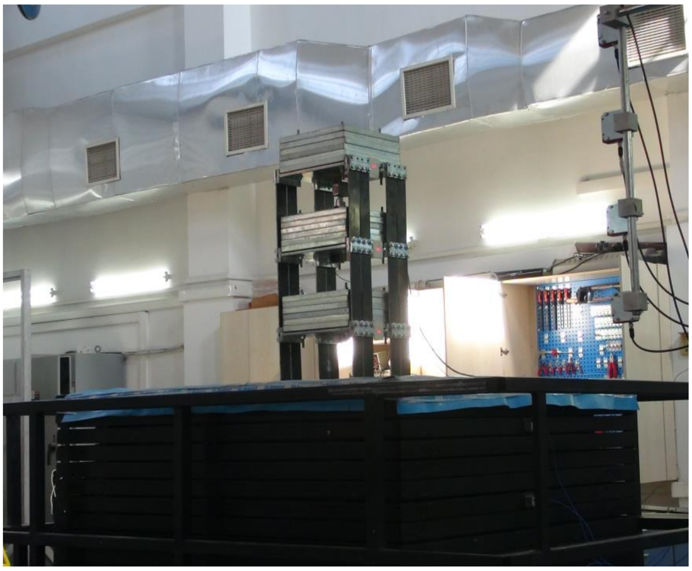

Figure 1. A 1/10 scaled 3-story building model.

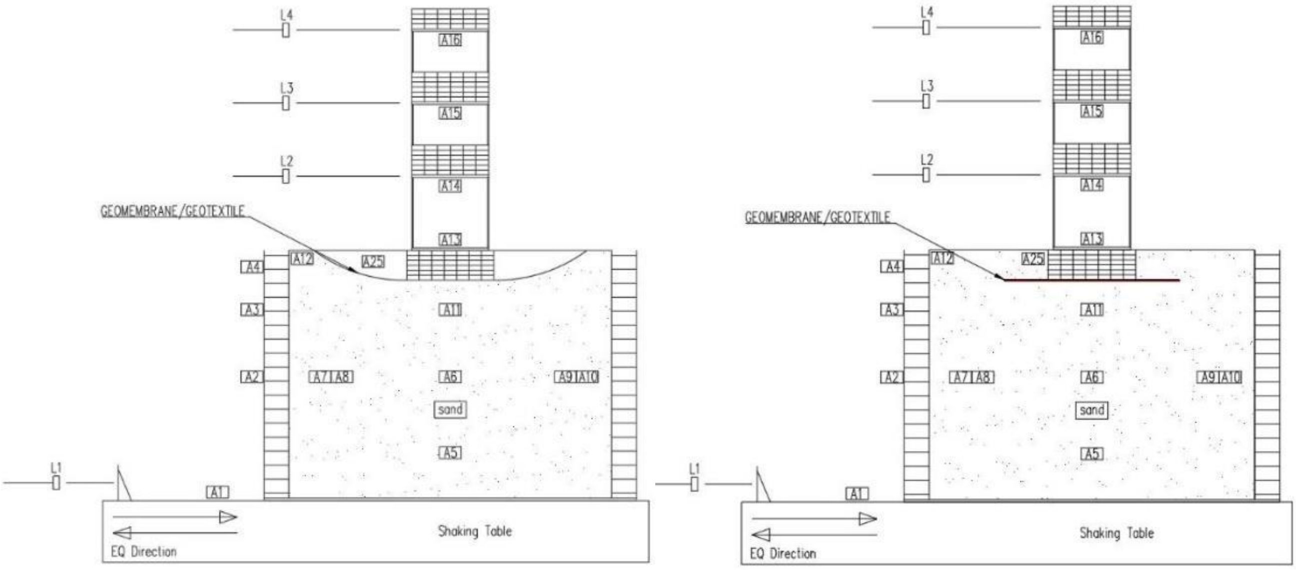

Figure 2. Curve shaped liner (left) and straight liner (right) experimental setup.

2.2 *Seismic input preperation*

As input data, the scaled 1940 El Centro (PGA=0.232g) and the 1999 Kocaeli earthquake (PGA=0.22g) records were used. Earthquake motions are given in Figure 3a and 3b.

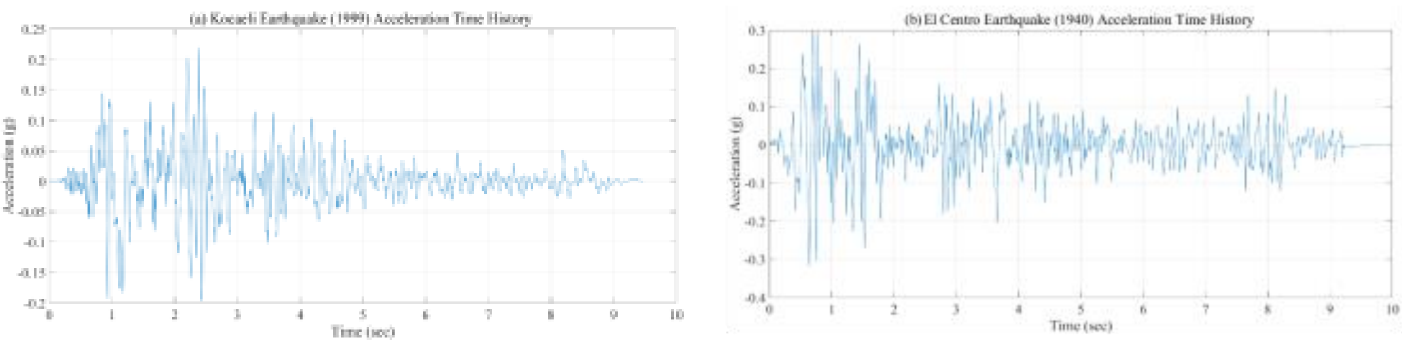

Figure 3. (a) 1999 Kocaeli Earthquake (Izmit Station), and (b) 1940 El Centro Earthquake (El Centro Array #9) acceleration-time histories.

3 SHAKING TABLE EXPERIMENTS

In order to compare unisolated and isolated building models for different configurations, horizontal acceleration, story drifts and peak spectral acceleration values were investigated in terms of evaluation of seismic performance. Acceleration and story drift values were given as peak and RMS (Root-Mean-Square). To compare unisolated case and isolated case with curved liner, top story horizontal acceleration, foundation horizontal acceleration and first story drift graphs were shown in Figure 4, Figure 5 and Figure 6, respectively. Furthermore, comparison between unisolated case and isolated case with straight liner were shown in Figure 7, and Figure 8. Comparison results of SL and CL was shown in Figure 9, and Figure 10. Comparison between unisolated (U) and isolated building models (CL and SL) was given in the Table 2 and Table 3.

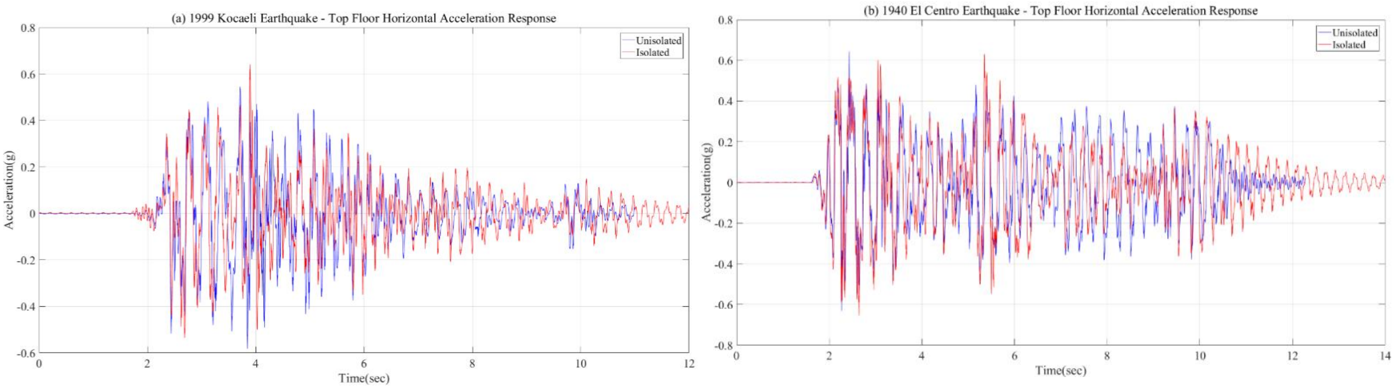

Figure 4. Comparative results of top story horizontal acceleration responses between unisolated and isolated with curve shaped liner (CL) under (a) 1999 Kocaeli Earthquake, and (b) 1940 El Centro Earthquake

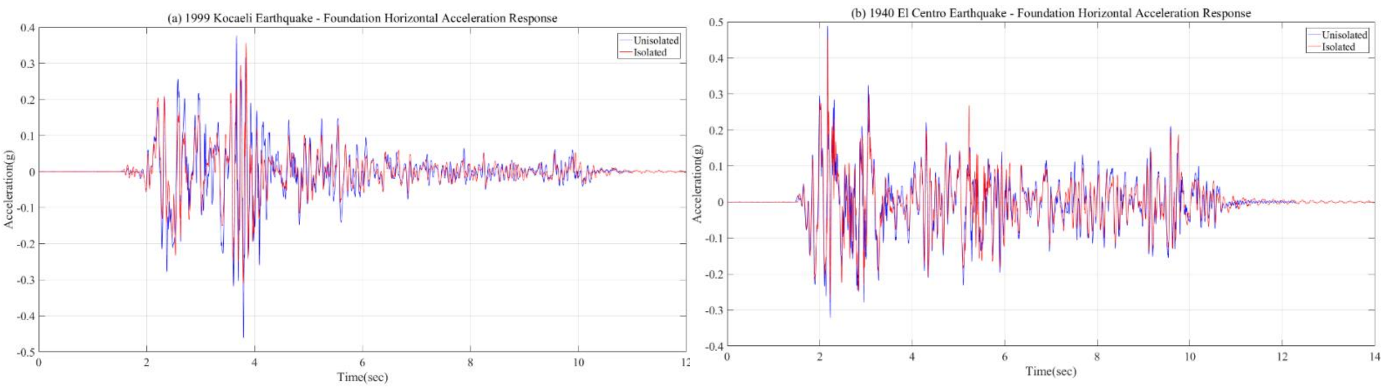

Figure 5. Comparative results of foundation horizontal acceleration responses between unisolated and isolated with curve shaped liner (CL) under (a) 1999 Kocaeli Earthquake, and (b) 1940 El Centro Earthquake

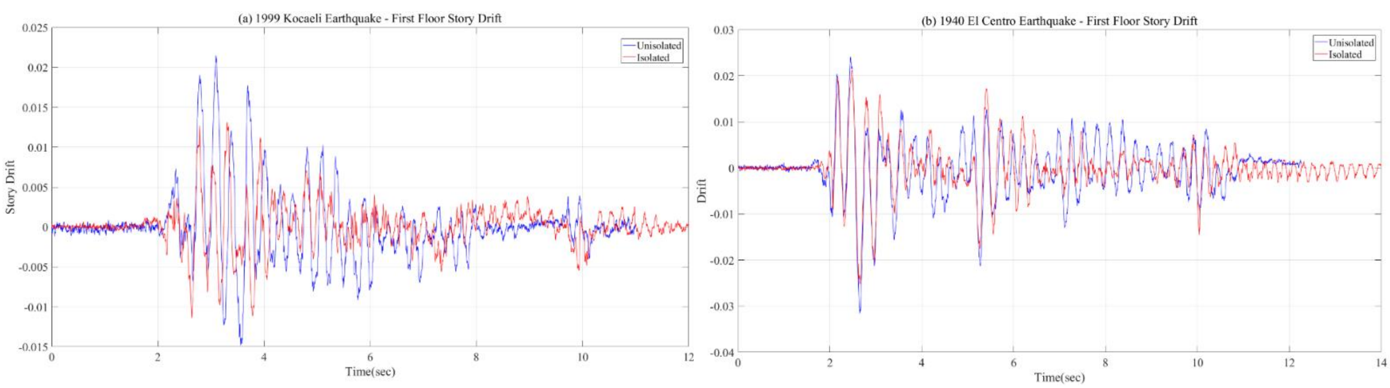

Figure 6. Comparative results of first story drift responses between unisolated and isolated with curve shaped liner (CL) under (a) 1999 Kocaeli Earthquake, and (b) 1940 El Centro Earthquake

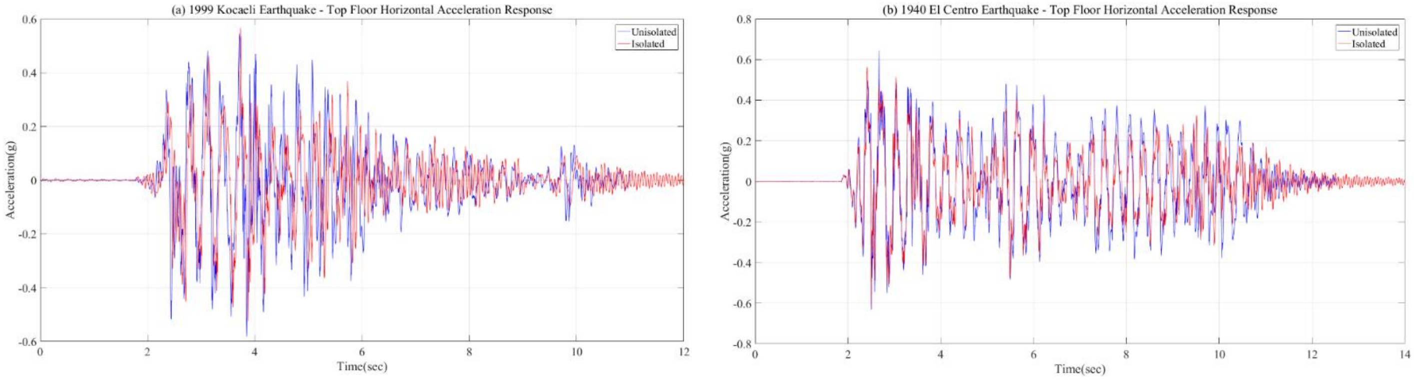

Figure 7. Comparative results of top story horizontal acceleration responses between unisolated and isolated with curve shaped liner (SL) under (a) 1999 Kocaeli Earthquake, and (b) 1940 El Centro Earthquake

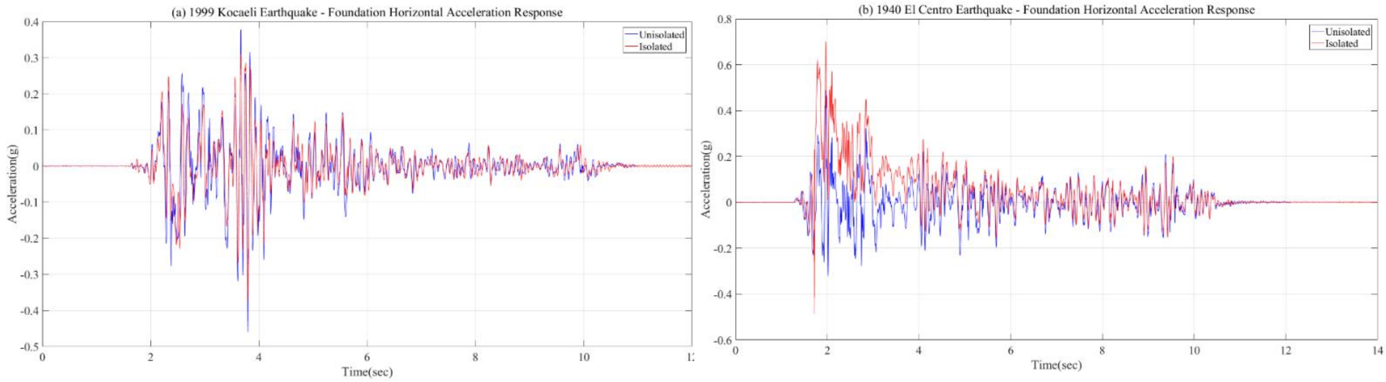

Figure 8. Comparative results of foundation horizontal acceleration responses between unisolated and isolated with curve shaped liner (SL) under (a) 1999 Kocaeli Earthquake, and (b) 1940 El Centro Earthquake

Overall comparison between SL and CL under both earthquakes was shown in Figure 13. Comparison of the test results under different earthquake motions is given in the following part.

Under the Kocaeli earthquake motion, maximum reduction in acceleration was observed at the second floor in the presence of straight liner as 35% in RMS value while maximum reduction in acceleration response was measured at the foundation level as 49% in RMS value. Maximum reduction in story drift was observed at the first story as 81% in peak value. It means, soft story phenomenon was substantially mitigated. In the case of using CL, maximum peak spectral acceleration was reduced at the second floor as 30%. On the other hand, maximum peak spectral acceleration was alleviated at the first floor as 32% in the presence of SL.

Under El Centro earthquake, maximum reduction in horizontal acceleration response was observed at the foundation level with a percentage of 22% in RMS value in the presence of curve shaped liner. On the other hand, a 33% reduction in acceleration response was observed at the second floor by the means of straight liner. For SL, maximum reduction in story drift was observed at the first story as 95% in peak value while a 61% reduction was obtained at the second floor for CL. Peak spectral acceleration was reduced up to 10% at the foundation level in the case of using curved liner. However, maximum reduction was observed at the second floor as 23% in the case of using straight liner as foundation isolation. Briefly, the proposed GSI system provided important reduction in all performance parameters.

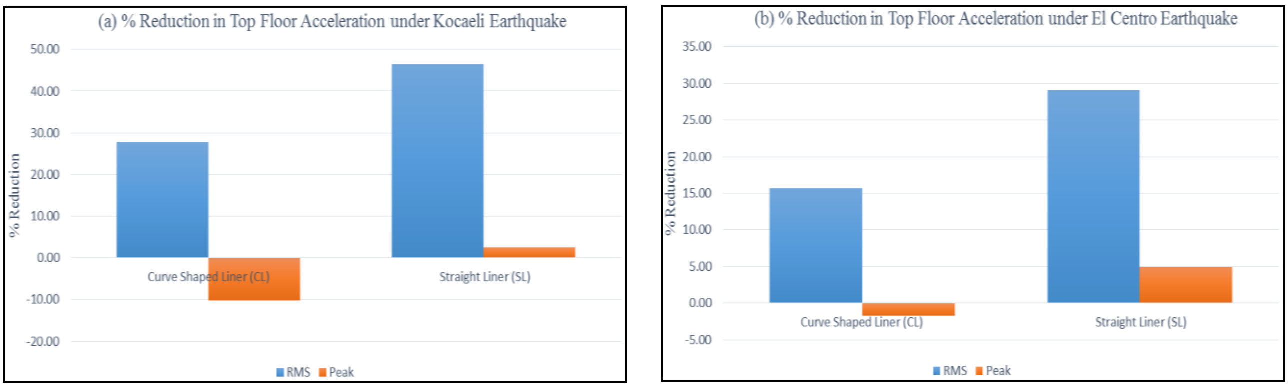

Figure 10. Comparative results of top story horizontal acceleration responses between the configuration types CL and SL under (a) 1999 Kocaeli Earthquake, and (b) 1940 El Centro Earthquake.

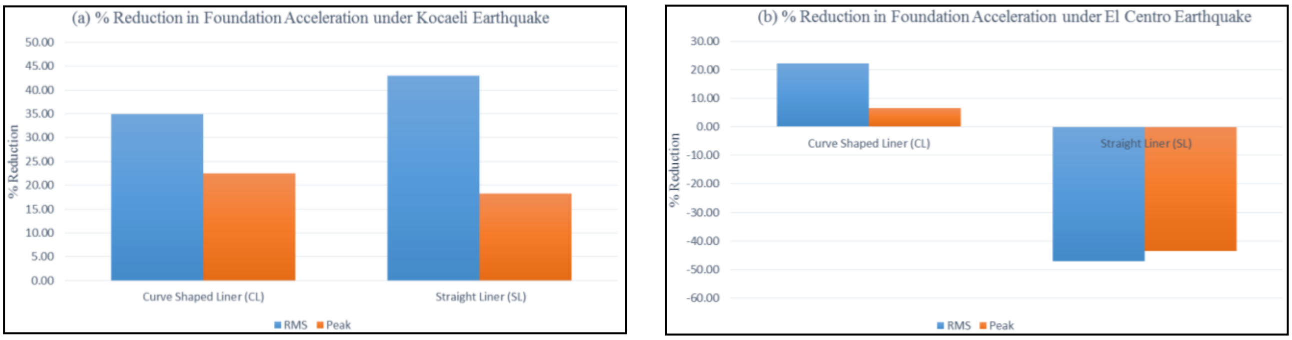

Figure 9. Comparative results of foundation horizontal acceleration responses between the configuration types CL and SL under (SL) under (a) 1999 Kocaeli Earthquake, and (b) 1940 El Centro Earthquake

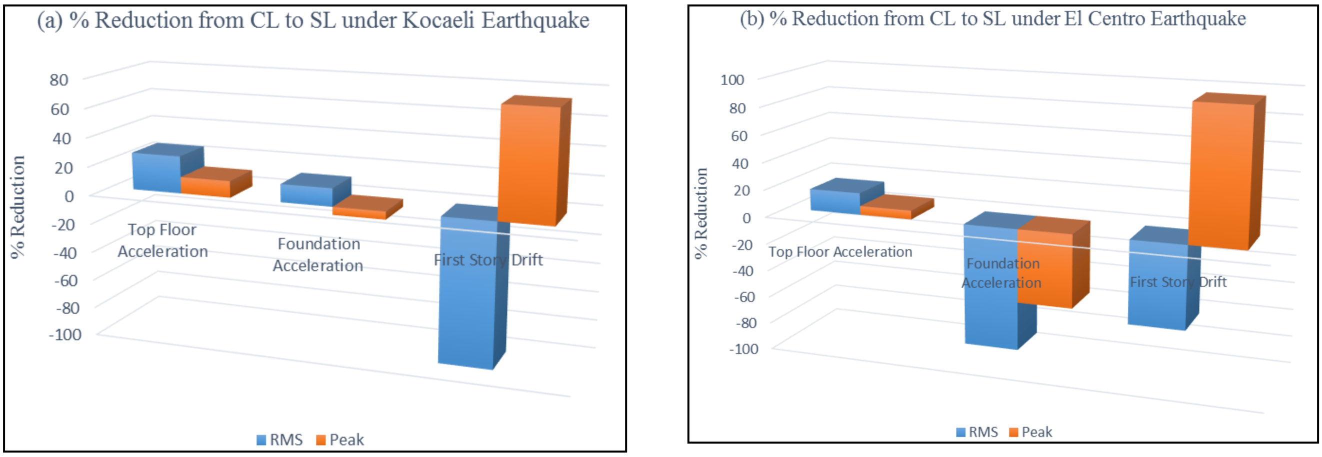

Figure 10. Comparative results of overall responses of the performance indicator parameters between the configuration types CL and SL under (a) 1999 Kocaeli Earthquake, and (b) 1940 El Centro Earthquake

Table 2. Experimental results under Kocaeli earthquake motion.

	Foundation		1st Floor		2nd Floor		3rd Floor	
	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak
Horizontal Acceleration (g)								
Unisolated - U	0.065	0.461	0.100	0.477	0.115	0.595	0.137	0.582
Foundation isolation - CL	0.042	0.357	0.069	0.443	0.080	0.475	0.099	0.640
Foundation isolation - SL	0.037	0.377	0.056	0.379	0.059	0.437	0.073	0.567
% Reduction (%) CL-U	34.87	22.45	30.90	7.19	30.51	20.18	27.82	-10.11
% Reduction (%) SL-U	43.01	18.20	44.10	20.63	48.82	26.64	46.54	2.56
% Reduction (%) SL-CL	12.50	-5.49	19.10	14.48	26.35	8.09	25.93	11.51
Horizontal Story Drift								
Unisolated	-	-	0.0012	0.0162	0.0013	0.0056	0.1373	0.0122
Foundation isolation - CL	-	-	0.0001	0.0123	0.0003	0.0047	0.0014	0.0149
Foundation isolation - SL	-	-	0.0001	0.0031	0.0011	0.0109	0.0014	0.0067
% Reduction (%) CL-U	-	-	95.83	24.07	73.85	16.07	98.98	-22.13
% Reduction (%) SL-U	-	-	91.67	80.86	15.38	-94.64	98.98	45.08
% Reduction (%) SL-CL	-	-	-100.00	74.80	-223.53	-131.91	0.00	55.03
Peak Spectral Acceleration (g)								
Unisolated - U	1.71		2.46		3.45		2.45	
Foundation isolation - CL	1.56		1.76		2.41		2.19	
Foundation isolation - SL	1.65		1.67		2.50		2.00	
% Reduction (%) CL-U	8.77		28.46		30.14		10.61	
% Reduction (%) SL-U	3.51		32.11		27.54		18.37	
% Reduction (%) SL-CL	-5.77		5.11		-3.73		8.68	

Table 3. Experimental results under El Centro earthquake.motion.

	Foundation		1st Floor		2nd Floor		3rd Floor	
	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak
Horizontal Acceleration (g)								
Unisolated - U	0.069	0.489	0.101	0.486	0.130	0.597	0.175	0.644
Foundation isolation - CL	0.054	0.456	0.084	0.554	0.110	0.677	0.147	0.655
Foundation isolation - SL	0.102	0.701	0.117	0.690	0.088	0.445	0.124	0.613
% Reduction (%) CL-U	22.22	6.59	16.90	-13.91	15.25	-13.34	15.64	-1.69
% Reduction (%) SL-U	-47.04	-43.49	-15.90	-41.93	32.59	25.54	29.11	4.87
% Reduction (%) SL-CL	-89.05	-53.62	-39.47	-24.60	20.45	34.31	15.96	6.46
Horizontal Story Drift								
Unisolated	-	-	0.0007	0.0045	0.0021	0.0074	0.0027	0.0158
Foundation isolation - CL	-	-	0.0005	0.0066	0.0008	0.0075	0.0022	0.0191
Foundation isolation - SL	-	-	0.0009	0.0002	0.0013	0.0152	0.0026	0.0156
% Reduction (%) CL-U	-	-	27.40	-46.67	60.95	-1.35	18.52	-20.89
% Reduction (%) SL-U	-	-	-16.44	95.11	38.10	-105.41	3.70	1.27
% Reduction (%) SL-CL	-	-	-60.38	96.67	-58.54	-102.67	-18.18	18.32
Peak Spectral Acceleration (g)								
Unisolated - U	1.10		2.03		2.17		2.64	
Foundation isolation - CL	0.99		2.24		2.25		2.84	
Foundation isolation - SL	1.44		1.78		1.66		2.37	
% Reduction (%) CL-U	10.00		-10.34		-3.69		-7.58	
% Reduction (%) SL-U	-30.91		12.32		23.50		10.23	
% Reduction (%) SL-CL	-45.45		20.54		26.22		16.55	

4 RESULTS AND CONCLUSIONS

In this study, the effects of placement of different geosynthetic couples underneath the foundation of building on the seismic performance of the scaled low-rise building model were evaluated. The obtained results on the foundation isolation with geosynthetics were summarized as follows:

- Spectral accelerations were minimized up to 23.5%. It means, damping of the system increased in the presence of straight liner.
- For SL type of configuration, earthquake accelerations exerted on the building were decreased with a percentage of 25.5% in peak value and 32.6% 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 El Centro earthquake compared to the curve shaped liner.
- When looked into overall results, straight liner provided more efficiency under the Kocaeli earthquake rather than the curve shaped liner. However, the curve shaped liner provided more promising results under the Kocaeli earthquake.
- In general, the straight liner improved the seismic performance of the low-rise building model more than the curved liner.

As a result of shaking table experiments, it can be obviously seen that utilization of geosynthetics in mitigation of earthquake hazards is beneficial. Moreover, the proposed foundation isolation 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 number of story, width of the building, earthquake characteristics, GG type and additional configurations are need to be investigated.

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