Geosynthetics for Earthquake Hazard Mitigation

Yegian, M. K, Kadakal, U., and Catan, M.

Northeastern University, Boston, MA

ABSTRACT

Geosynthetic or related materials placed under foundations can absorb seismic energy, and hence transmit smaller levels of excitation to an overlying structure. This concept of using geosynthetics as foundation isolation can be a cost-effective way of mitigating earthquake hazards to civil engineering structures. The authors have been exploring the suitability of various synthetic materials for the purpose of foundation isolation. The dynamic interface properties of these materials are being investigated using a shaking table to identify the most promising material for this application.

To demonstrate the technical feasibility of using synthetic materials for foundation isolation, shaking table tests were performed. A single-story building model was placed on the shaking table and its response to harmonic and earthquake motions was measured. The accelerations and story drifts of the model building with and without foundation isolation were measured. The results from these tests demonstrate that using geosynthetics as foundation isolation reduced the column shear forces in the building model by as much as 70%. Associated with this reduction are slip deformations along the geosynthetic interface ranging from a 1 to 10 cm depending on the earthquake record and its intensity.

INTRODUCTION

During the past few years, significant advancements were made in our understanding of the dynamic interface shear properties of geosynthetic interfaces. Kavazanjian et al. (1991), Yegian and Lahlaf (1992), and Zimmie et al. (1994) have demonstrated that under dynamic shear excitations, slip deformations occur along smooth geosynthetic interfaces. As a result of such slip, the energy transmitted through the interfaces is limited. Thus, in a landfill application, seismically induced slip deformations along a bottom geosynthetic liner can result in reduced accelerations transmitted to the landfill waste.

This potential benefit of smooth geosynthetics reducing landfill or other structural response during an earthquake was first investigated by Kavazanjian et al. (1991) and Yegain and Lahlaf (1992). Their preliminary shaking table tests on smooth High Density Polyethylene (HDPE) and geotextiles showed that this concept of using geosynthetics to isolate a structure from incoming seismic waves had great promise.

The authors have been investigating the technical feasibility and practicality of using geosynthetic liners to mitigate the potential damaging effects of earthquakes to buildings with an initial grant from the North American Geosynthetics Society, and subsequently with a major grant from the National Science Foundation.

This paper presents selected results from shaking table tests that were carried out to identify a geosynthetic interface that is ideally suited for this new application. The paper also describes shaking table tests of a building model placed on a selected geosynthetic liner. The results from these tests are presented to demonstrate the benefits of utilizing a special geosynthetic liner as an energy absorbing system that can reduce building response during an earthquake.

FOUNDATION ISOLATION

Figure 1.a shows a typical structure founded on a soil profile experiencing earthquake-induced ground motions. In a conventional design, the foundation of the structure rests firmly on the soil. During an earthquake, because of the large friction between the foundation and the underlying soil, the ground motions are fully transmitted to the superstructure (the building above the foundation). This seismic energy then causes lateral distortion of the building and introduces shear forces in the columns.

To limit the seismic energy transmission to a structure, structural engineers have been developing mechanical devices referred to as base isolators. In a building application, a base isolator provides a discontinuity between a footing and the overlying column. Typically, a base isolator performs two functions: (1) It shifts the natural period of the building away from that of the earthquake (2) It provides additional damping to absorb the energy. Figure 1.b shows a schematic drawing of a building using conventional base isolators. Structural isolation systems have been used in a number of important buildings and bridges in the United States and Japan. During the 1994 Northridge earthquake, structures on base isolators, generally performed well (Hussain, 1994). However, at the present, the cost of installation and maintenance of such isolation systems is prohibitively high for their wide application in engineering practice.

The authors have been investigating the use of geosynthetic materials as seismic energy absorbing systems for application in earthquake hazard mitigation. A concept that is being

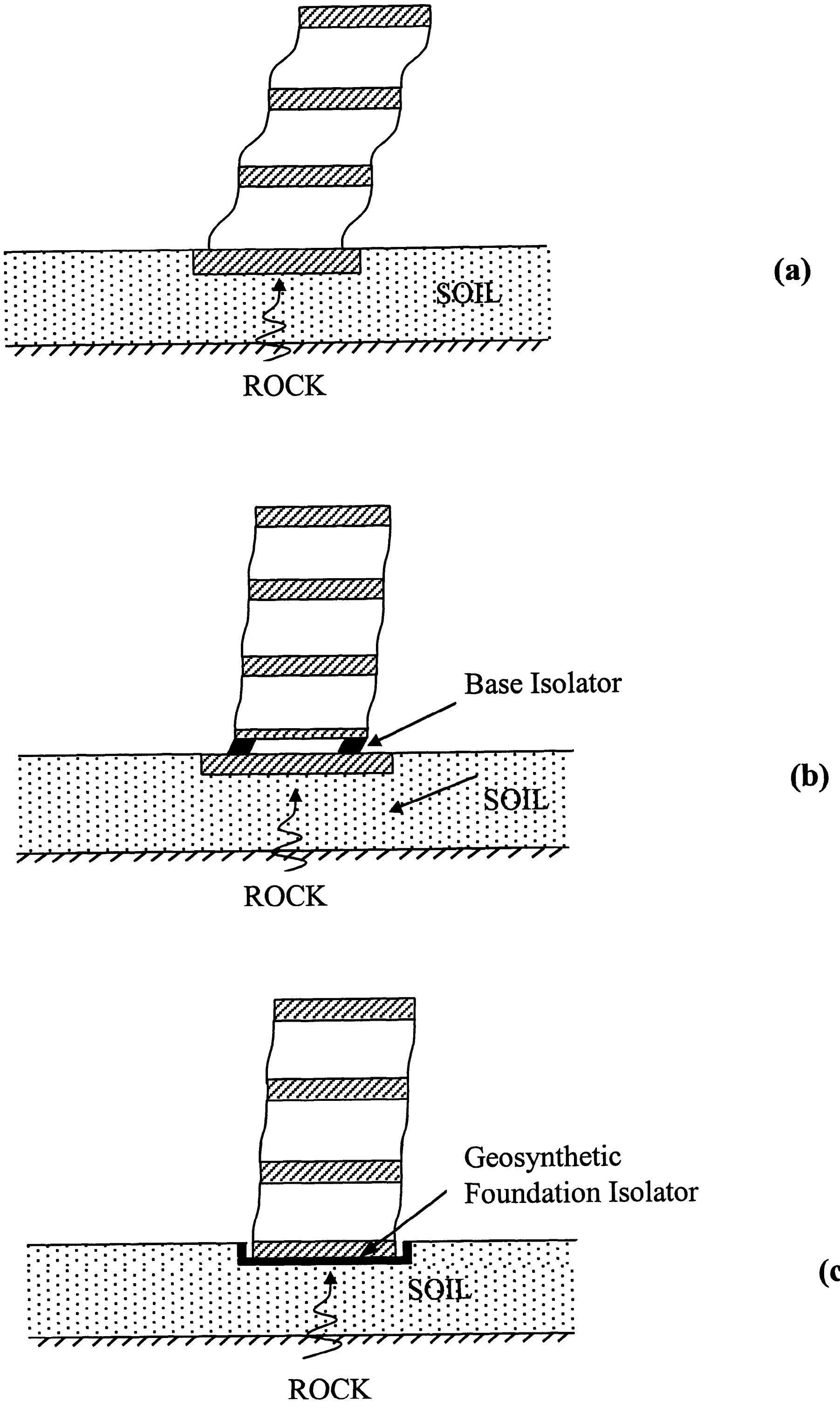

Figure 1. Seismic response of a typical building (a) founded on soil, (b) with base isolation, (c) with geosynthetic foundation isolation.

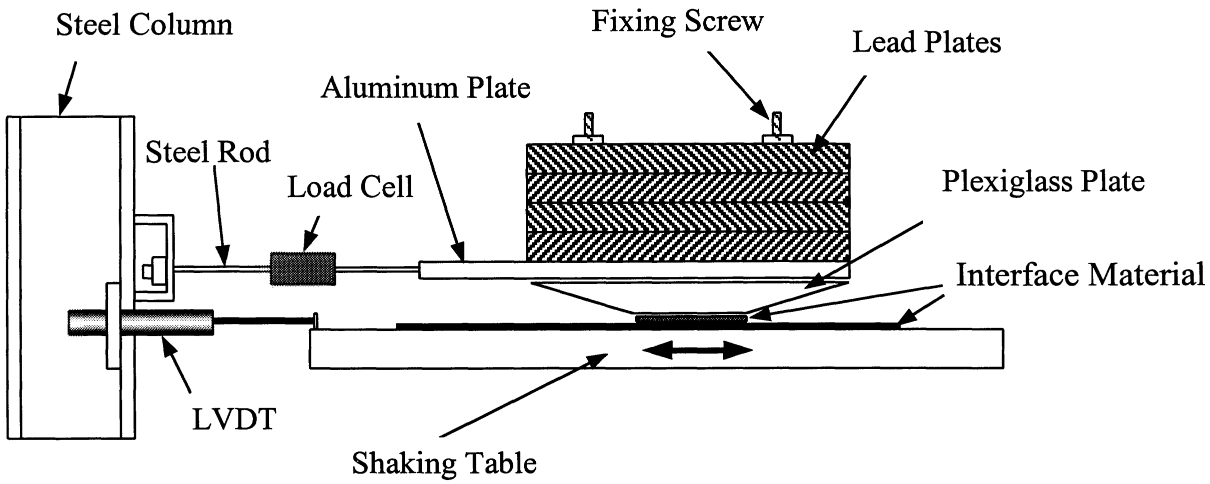

Figure 2. Schematic diagram of the cyclic load test setup.

evaluated for its technical feasibility is the use of horizontally placed smooth geosynthetics underneath building foundations that will absorb seismic energy, and thus transmit significantly smaller accelerations to the overlying structure. This concept hereafter referred to as **foundation isolation** is similar to base isolation except that, in this case, the entire building is isolated from the ground through the use of a geosynthetic liner. Figure 1.c shows a schematic depiction of the seismic response of a building that utilizes foundation isolation.

The following sections of this paper will present some of the results that demonstrate the technical feasibility of foundation isolation using geosynthetics.

SHAKING TABLE TESTS

The first task of this research was to identify geosynthetic interfaces that are suitable for use as foundation isolation. Initially, three interfaces were selected for testing based on earlier test results that showed that the interfaces had low dynamic friction angles. These interfaces were 1) Smooth HDPE/HDPE; 2) Smooth HDPE/Nonwoven spunbonded Geotextile; and 3) Polytetrafluoroethylene (PTFE)/PTFE. A special cyclic test setup was devised to investigate the response of these interfaces under varying conditions. Figure 2 shows a schematic diagram of the cyclic test arrangement. The bottom plate shown in Figure 2 is the top of a shaking table that was used to apply the horizontal shear along the geosynthetic interface tested. Tests were carried out by varying the normal contact stress, amplitude of displacement (slip) and the rate of slip. Under these different test conditions, the friction coefficients of the interfaces were measured and evaluated.

Figure 3 shows a summary results of friction coefficients as a function of slip rate. From

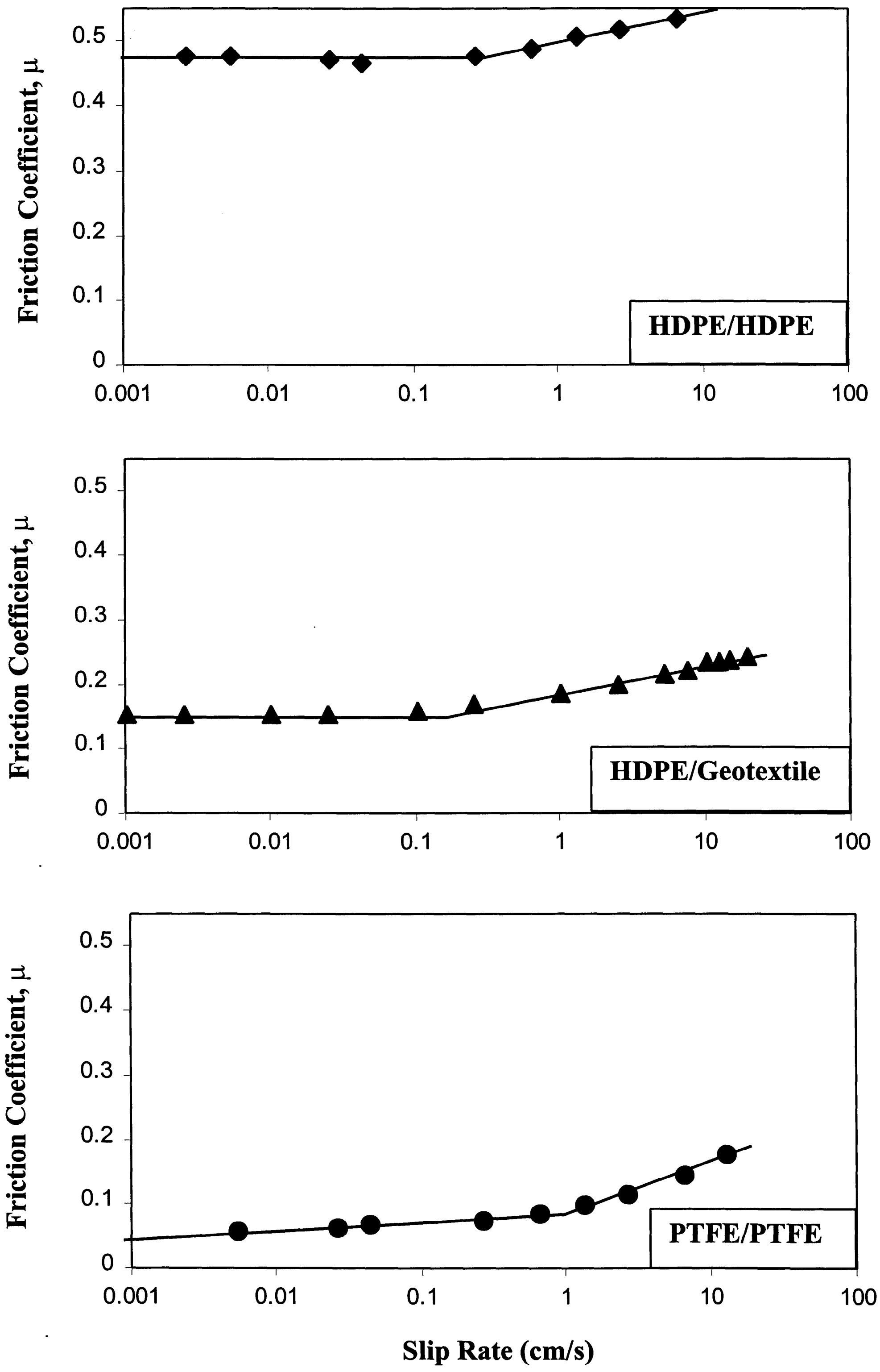

Figure 3. Friction coefficients as a function of slip rate, from cyclic load tests.

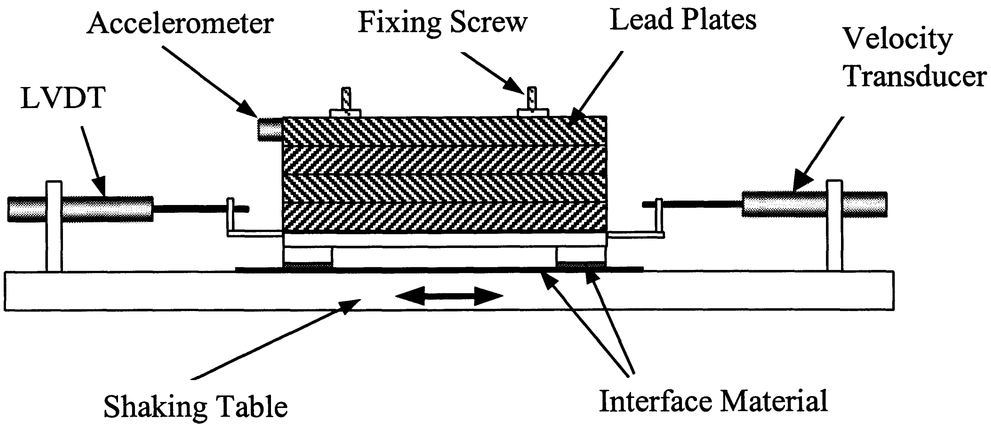

Figure 4. Schematic diagram of the cyclic load test setup.

these and other test results it was observed that the interface consisting of PTFE against PTFE had the lowest coefficient, about 0.06 at very small slip rates. Also, the test results showed that the friction coefficients for all the interfaces depended on the slip rate. At slip rates of larger than 2cm/s, comparable to rates expected during a moderate size earthquake, the friction coefficients increased substantially, especially for the PTFE/PTFE interface.

Similar behaviors were observed from rigid block tests. Figure 4 shows the schematic of the test setup in which a rigid block is placed on the interface and subjected to sinusoidal table accelerations. The response of the block was measured by an accelerometer, LVDT, and a velocity transducer. Tests were carried out at increasing levels of table accelerations.

Figure 5 shows results obtained from the rigid block tests carried out at 2 and 5 Hz table excitations. Again, it is observed that the PTFE/PTFE interface has the smallest transmitted acceleration of about 0.15g, at a base acceleration of 0.15g, after the initiation of sliding. Beyond a base acceleration of 0.15g the acceleration transmitted to the block slightly increased due to the effect of the slip rate. These shaking table test results are consistent with the cyclic test results shown in Figure 3.

It was concluded from the tests described above that the PTFE/PTFE interface is better suited for foundation isolation than HDPE/HDPE or HDPE/Geotextile interfaces. Yet, the transmitted acceleration through this interface is still relatively high at high slip rates for its application as foundation isolator. Furthermore, the velocity dependence of the friction coefficient (Figure 3) poses a difficulty for proper modeling of its behavior. Efforts were made to identify an alternate interface that has a friction coefficient as small as the PTFE/PTFE interface and is not so dependent on slip rate. Through interaction with geosynthetic manufacturers, we learned that the friction coefficient of a plastic material is influenced by its molecular weight. Research on the availability of different plastics resulted in the identification

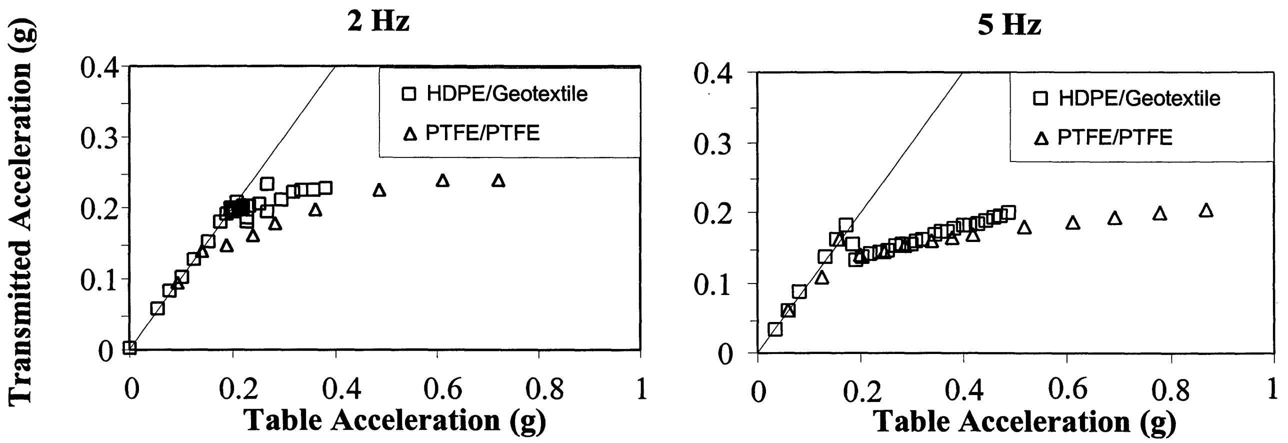

Figure 5. Accelerations transmitted through geosynthetic interfaces tested at 2 and 5 Hz sinusoidal table excitations.

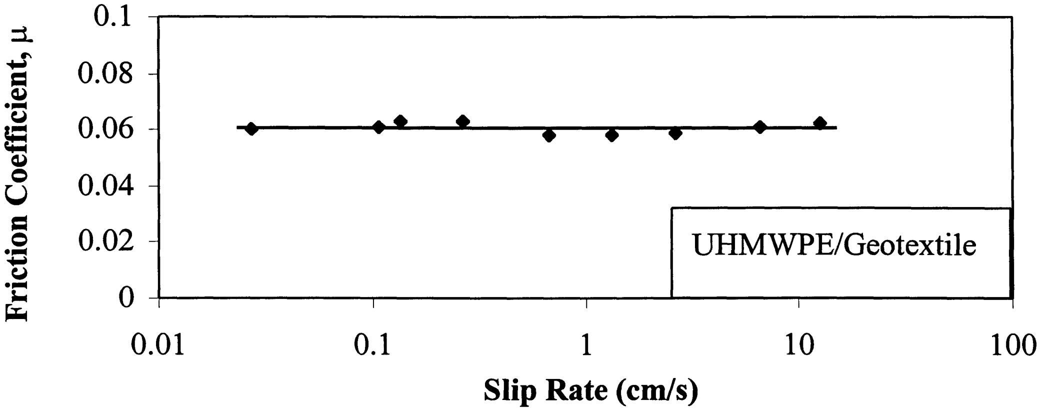

Figure 6. Friction coefficients of UHMWPE/Geotextile interface tested in the cyclic load apparatus.

of one that showed the best promise for application as foundation isolation. The interface thus identified is an Ultrahigh Molecular Weight Polyethylene (UHMWPE) and a nonwoven spunbonded geotextile.

Cyclic load and shaking table tests were conducted using an UHMWPE/geotextile interface, and the frictional characteristics were evaluated. Figure 6 shows sample test results from the cyclic load tests which indicate that the friction coefficient of the interface is quite low (0.06), and is nearly constant over a wide range of slip rates. In Figure 7, the slip rate dependency of the various interfaces tested is compared. Friction coefficient from each interface was normalized with its value (μ_0) measured at small slip rates (0.001-0.01 cm/s). Clearly, UHMWPE/geotextile is a superior interface that has a friction coefficient independent of slip rates.

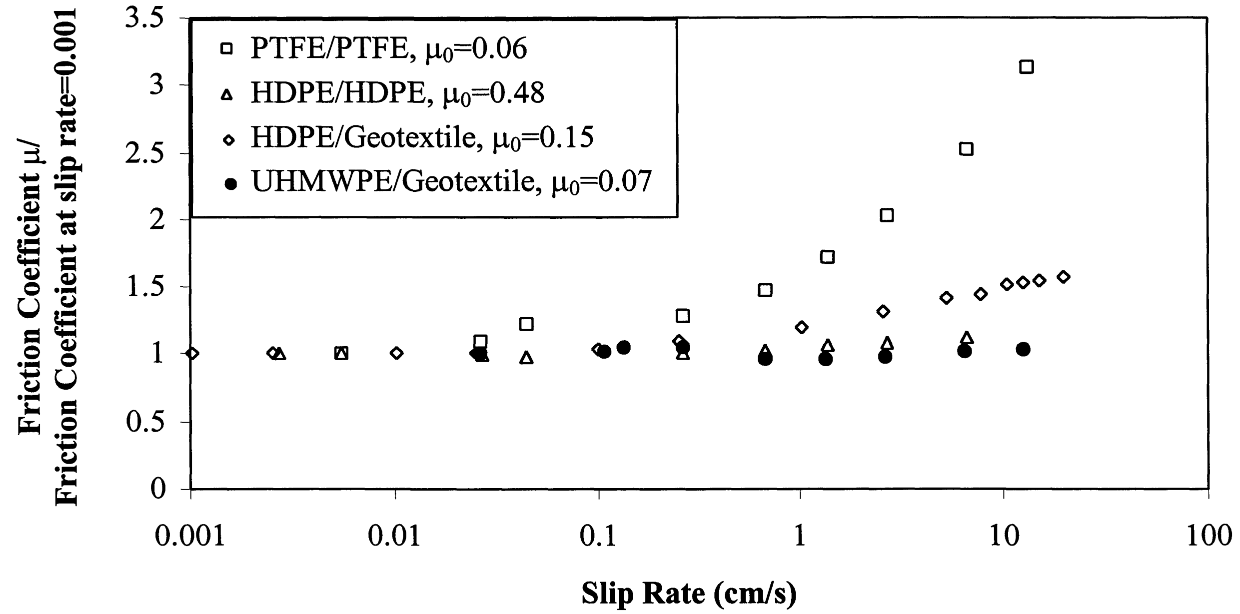

Figure 7. Influence of slip rates on friction coefficients normalized with friction coefficients (μ_0) measured at small slip rates (0.001-0.01 cm/s)

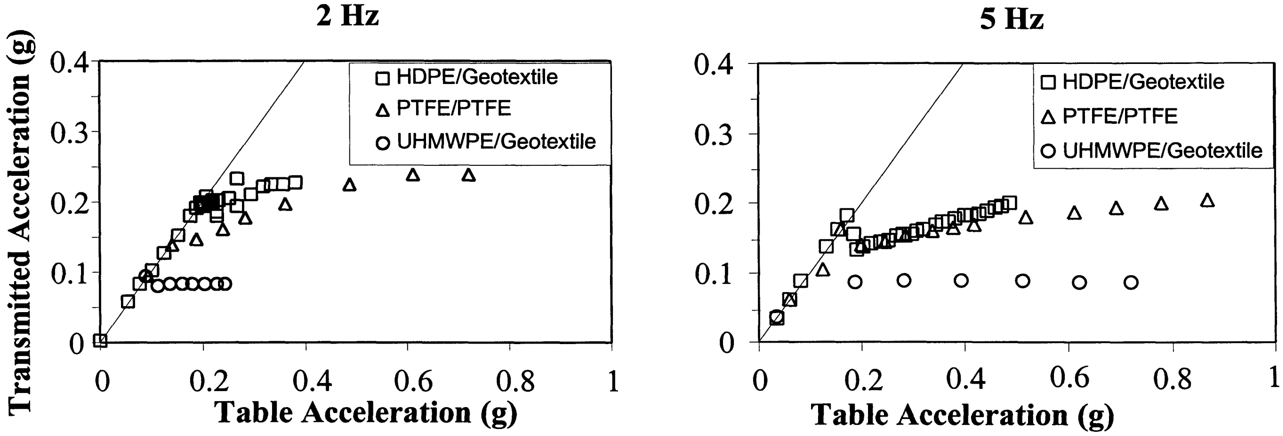

Figure 8. Accelerations transmitted through geosynthetic interfaces tested at 2 and 5 Hz sinusoiadal table excitations.

The UHMPE/geotextile interface was tested further using the shaking table. Figure 8 shows the accelerations transmitted through this interface, and are compared with those measured from other two interfaces tested. Again, the better suitability of the UHMWPE/geotextile interface is clearly observed. Sliding is initiated when the base acceleration exceeds 0.1g, a value associated with the peak shear resistance of the interface. Once slip occurs, the transmitted acceleration drops to about 0.07g. Such a low friction coefficient indicates excellent suitability of the UHMWPE/geotextile interface as foundation isolator even for small levels of ground shaking.

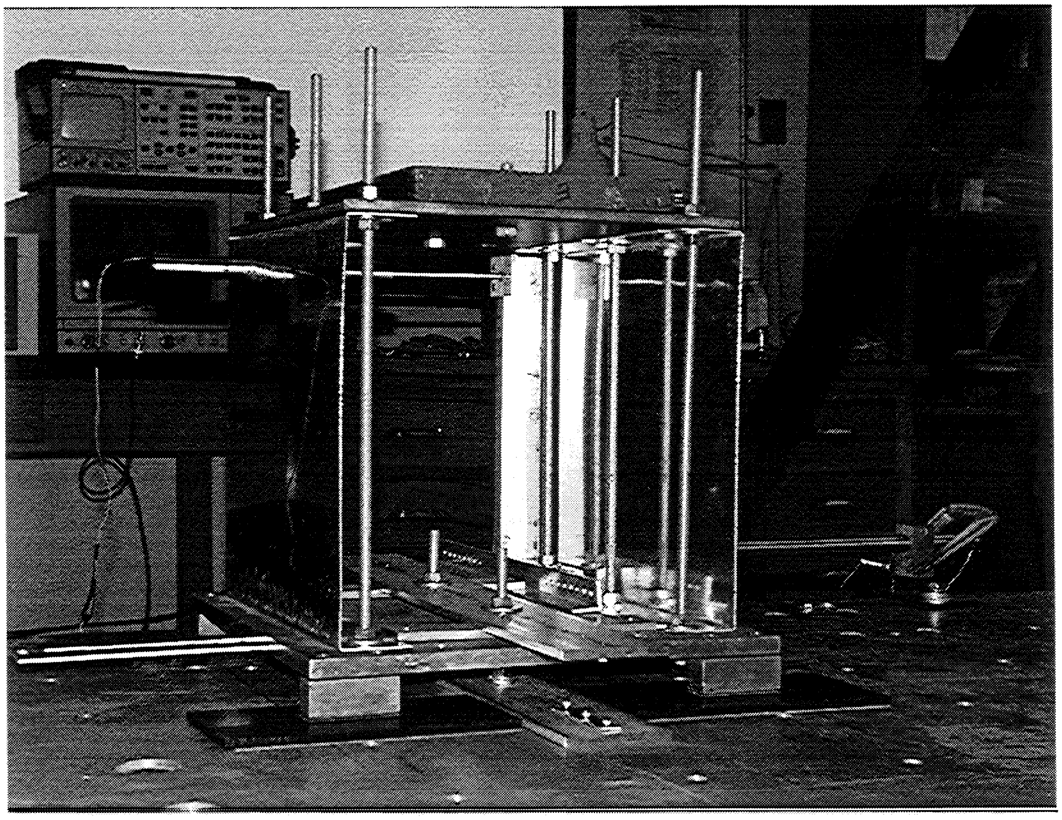

Figure 9. Photograph of the single-story building model tested on the shaking table.

MODEL BUILDING RESPONSE

The above geosynthetic interfaces were tested using harmonic base excitations. Also, the measured transmitted accelerations were those of a rigid block placed on the interface. These tests were useful to identify the geosynthetic interface that showed the best promise for application as foundation isolator. To evaluate the technical feasibility and benefits of using the selected geosynthetic interface as a foundation isolator for buildings, shaking table tests were carried out on a single story building model placed on the UHMWPE/geotextile interface.

Figure 9 shows a photograph of the building model that is resting on the shaking table. Figure 10 shows the measurement instruments used which included accelerometers to measure the building top floor and base accelerations, as well as the acceleration of the shaking table. Displacement transducers were used to measure the slip along the UHMWPE/geotextile interface, and to measure the distortion of the columns of the building model. Dynamic characteristics of the model were determined by free vibration tests. Its natural frequencies and critical damping value were measured as 8.6 Hz and 1% respectively. Two sets of test were performed. In the first set, the base of the building model was fixed on the table representing

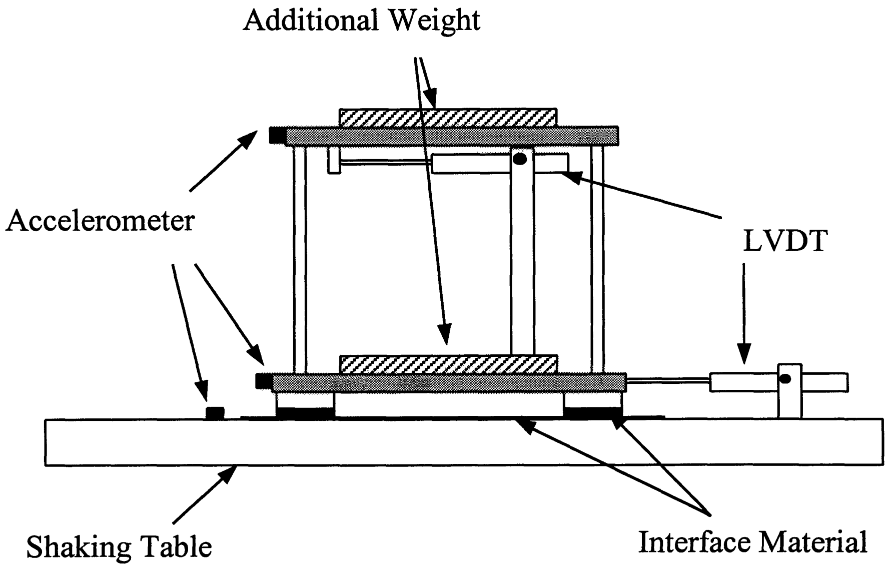

Figure 10. The experimental setup and measurement instruments used in testing the building model on the shaking table.

conventional design without foundation isolation. In the second set, the building model was placed on a geotextile, that was free to slide over the UHMWPE geomembrane.

Tests were run to understand the real dynamic interaction between the building top mass and its foundation, under earthquake excitations using three acceleration-time history records obtained from the 1989 Loma Prieta Earthquake. The records that were selected based on their frequency contents were: 1) Santa Cruz (with high frequency) 2) Capitola (with intermediate frequency), and 3) Corralitos (with low frequency). Different Tests were carried out by scaling the peak accelerations of the records, and by changing the mass ratios (top mass divided by the total mass) of the building model.

Figure 11 shows a comparison of the model responses with and without foundation isolation. The input table motion is the Santa Cruz record scaled to 0.35g. The results on the left side of Figure 11 show the building accelerations when the model was fixed to the table (without foundation isolation). It is observed that the dynamic response of the building model experiencing this earthquake record has amplified the base motion of 0.35g to a value of 0.77g at the roof level. The results of the shaking table tests on the model that was placed on UHWMPE/geotextile interface, as a foundation isolator, are presented on the right hand side of Figure 11. In this case, the peak acceleration at the roof level is only 0.33g, a reduction of 60% in comparison to the fixed based conditions.

As described earlier, the seismic energy transmitted to a building will lead to column distortions and shear forces. The column shear forces from tests with and without foundation isolation are compared in Figure 12 to further evaluate the benefit of using UHMWPE/geotextile liner. The vertical axis in the figure defines the ratio of the column shear force in the building

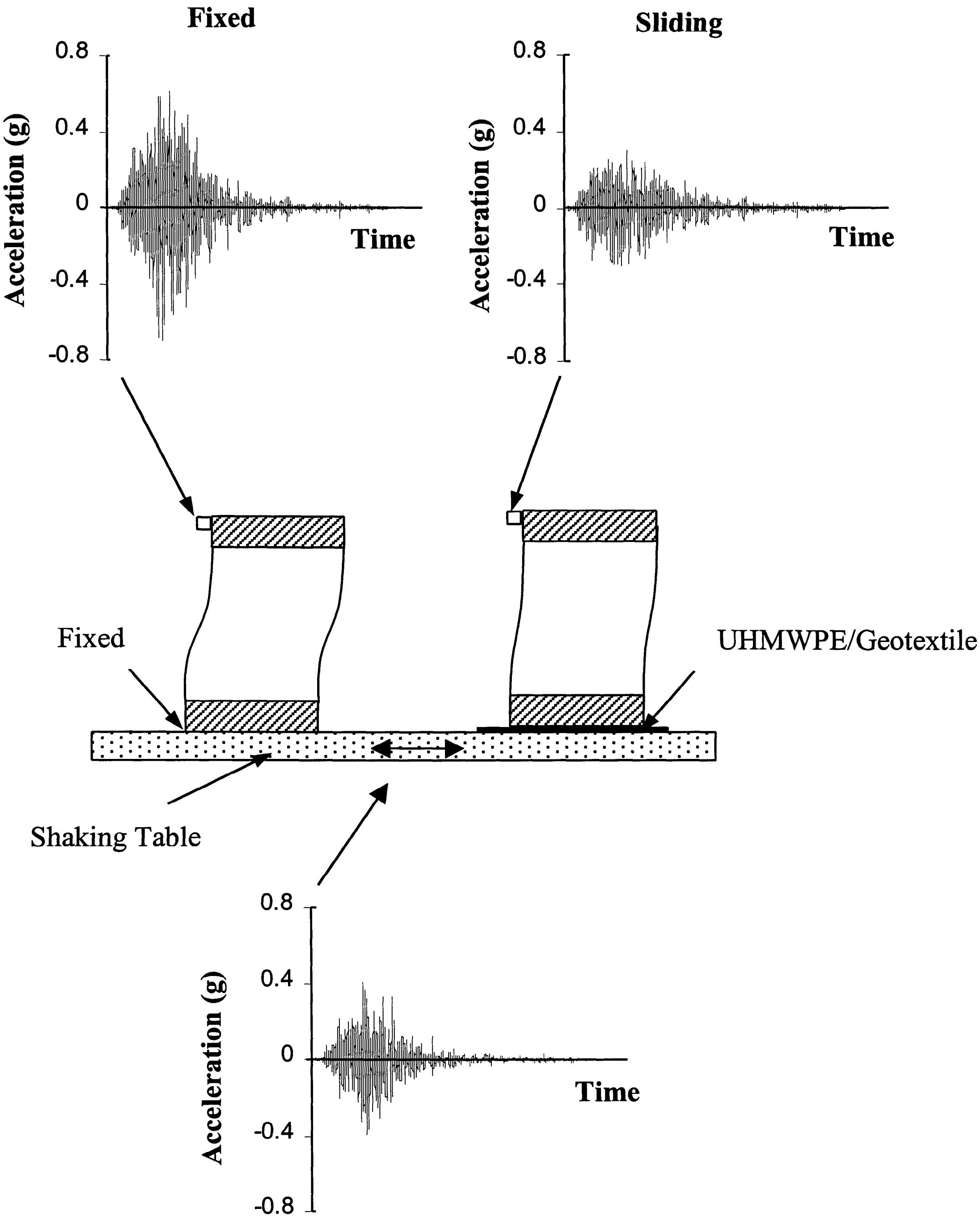

Figure 11. Comparison of model responses with and without geosynthetic foundation isolation.

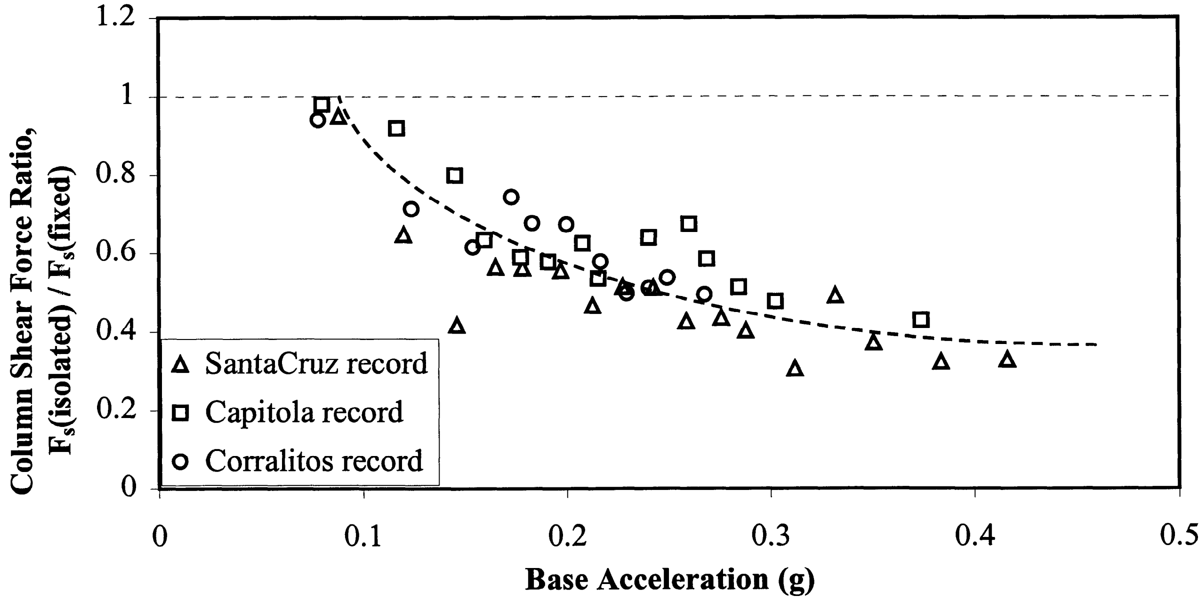

Figure 12. Reduction in column shear forces due to geosynthetic foundation isolation as a function of ground accelerations.

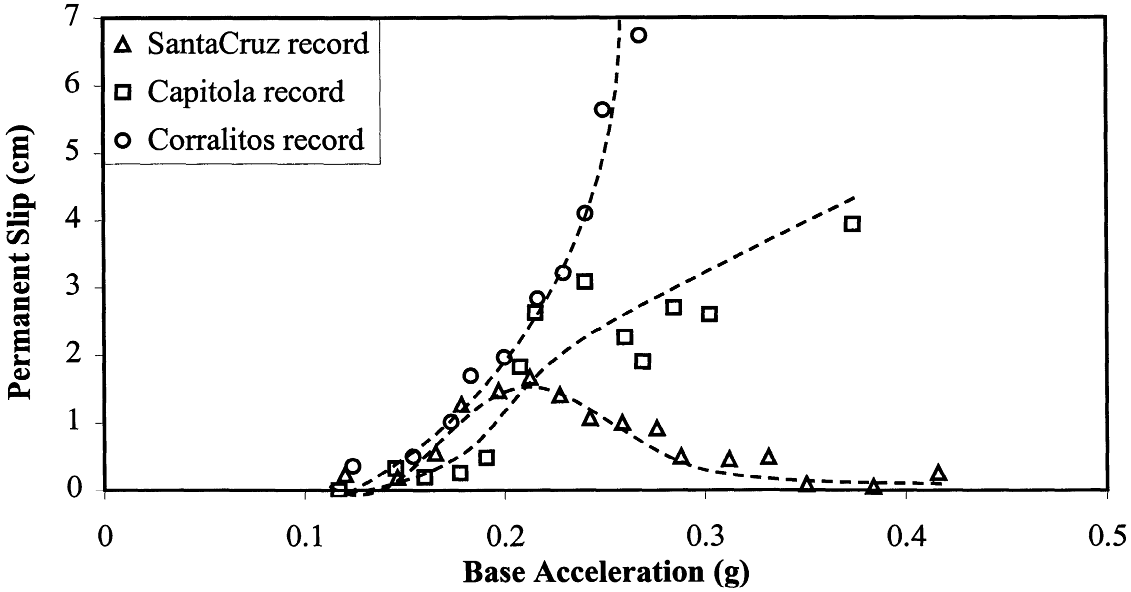

Figure 13. Slip deformations of the base as a function of ground accelerations.

model placed on the geosynthetic liner to the column shear force in the model that was fixed to the table. The horizontal axis defines the peak accelerations to which the three earthquake records were scaled. The results show that at a base acceleration greater than 0.07g the geosynthetic liner absorbs energy, and thus dramatically reduces the column shear forces in the building model. For example, at a base acceleration of 0.4g, the column shear force in the building model on foundation isolation is only 35% of that corresponding to the fixed case. This demonstrates the excellent energy absorption capacity of UHMWPE/geotextile interface.

Associated with this significant reduction in shear forces, as a result of foundation isolation, is the potential problem of slip deformations occurring along the geosynthetic interface. The measured slips from these shaking table tests are plotted in Figure 13. The results show that slip deformations typically are of the order of a few centimeters, and increase with increasing base accelerations.

At the present, the authors are continuing their research to evaluate the effect of various parameters that may influence the response of buildings on geosynthetic foundation isolators. Test results completed on UHMWPE/geotextile as foundation isolator have demonstrated a great potential for this interface to dramatically reduce the seismic loads on building structures.

CONCLUSIONS

Shaking table tests were carried out to demonstrate the effectiveness of using a smooth geosynthetic liner as foundation isolator that will reduce earthquake energy prior to being transmitted to a building structure. Various geosynthetic interfaces were investigated to identify a liner that is best suited for foundation isolation. Based on the experimental test results, Ultrahigh Molecular Weight Polyethylene (UHMWPE)/nonwoven geotextile interface was selected to be ideally suited for foundation isolation.

A model building structure was fabricated and tested on the shaking table to investigate the benefits of using UHMWPE/geotextile liner as foundation isolator. The column shears forces, the acceleration of the roof mass, and the slip along the liner interface were measured and analyzed under three earthquake excitations. The results show that through slip deformations the UHMWPE/geotextile liner reduces seismic energy, thus dramatically reducing the dynamic response of the building model. At a base acceleration of 0.40g, the column shear force in the building model on the UHMWPE/geotextile liner was 35% of that corresponding to a conventionally built, fixed base structure. Associated with this reduction in the column shear force was a permanent slip deformation measured to be about 4 cm for Capitola record.

In addition, using geosynthetics for foundation isolation to reduce seismic energy transmitted to buildings can be a very cost effective. It is also a simpler alternative to earthquake hazard mitigation measures conventionally used in current engineering practice.

ACKNOWLEDGMENTS

This research was initiated by a grant from the North American Geosynthetics Society, and the support of S.M. Bemben and D. A Schulze. This support is appreciated. The continuation of this research is being funded by a grant from the Earthquake Hazard Mitigation Program of the National Science Foundation. The authors express their appreciation to NSF and the program director Dr. Clifford Astill.

REFERENCES

Hussain, S.M. (1994) "Performance of base isolated buildings in the Northridge Earthquake", Proc. Seismic Base Isolation: State of the Practice, SEAOSC Seminar, CA.

Kavazanjian, E., Hushmand, B., and Martin, G. (1991) "Frictional base isolation using layered soil-geosynthetic liner system". Proceedings of the Third U.S. Conf. on Lifeline Earthquake Engineering, Los Angeles, CA, pp. 1140-1151.

Yegian, M.K., and Lahlaf, A.M. (1992) "Dynamic interface shear properties of geomembranes and geotextiles". Journal of the Geotechnical Engineering, ASCE, Vol. 118, No.5, pp. 760-779.

Zimmie, T.F., De, A., and Mahmud, M.B. (1994) "Centrifuge modeling to study dynamic friction at geosynthetic interfaces", Proc. Fifth International Conference on Geotextiles, Geomembranes and Related Products, Singapore, pp. 415-418.