Soil Isolation for Seismic Protection Using a Smooth Synthetic Liner

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Abstract: A synthetic liner consisting of a nonwoven geotextile over an ultrahigh molecular weight polyethylene, geotextile/UHMWPE, placed within a soil profile can dissipate seismic energy transmitted to the overlying soil layer and structure. This concept of soil isolation can be an effective and inexpensive way of reducing seismic ground motions through slip displacements. Shaking table tests on soil layers isolated using cylindrical and tub-shaped liners were conducted using harmonic and earthquake base excitations. The results show that an isolation liner can significantly reduce the accelerations at the surface of the isolated soil mass. Accompanying such a reduction in accelerations are slip displacements that manifest around the perimeter of the isolated soil. Because of the curved nature of the liner, permanent slips are minimized by the restoring effect of the gravitational forces of the isolated soil mass. Analytical results under field scale conditions indicate that a soil isolation liner can dramatically reduce the peak and spectral accelerations of a vertically propagating shear wave. Such a reduction can provide seismic protection to a structure founded on soil-isolated ground.

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Introduction

Earthquakes are one of the most destructive natural hazards. The human and economic loses experienced from earthquakes in California (1994), Japan (1995), Turkey (1999), Taiwan (1999), and India (2001) are recent reminders of the potential devastation that metropolitan communities can suffer when exposed to this natural hazard. To minimize the seismic risk to a structure, base isolation systems are being developed and implemented. For example, frictional base isolation devices are installed at the column–foundation connection points, which under seismic forces allows large deformations to take place at the points of the isolators and dissipate much of the seismic energy before it is transmitted to the overlying structure. Although structures on base isolation have performed very well during recent earthquakes, the high cost of installation and maintenance of these systems have limited their use for large and important structures. There is a need for advancing the seismic isolation concept to develop simple and inexpensive systems that can offer the advantages of isolation to a much wider application worldwide.

During the past years, the writers have been conducting research on dynamic response characteristics of geosynthetic interfaces (Catan 2000). Shaking table tests have demonstrated that slip deformations occur during seismic shaking along smooth, synthetic interfaces. Associated with such slip, there is reduction in the transmitted accelerations to a structure overlying the synthetic liner. Hushmand and Martin (1991); Kavazanjian et al. (1991); and Yegian and Lahlaf (1992a,b) described an innovative concept of using horizontally placed smooth high density polyethylene (HDPE) underneath building foundations to dissipate seismic energy in the horizontal direction, the direction most detrimental to structures. This concept is similar to seismic mechanical isolation described earlier, except that it can be simpler and less expensive.

A research program was implemented which identified synthetic materials that are ideally suited for isolation applications. Two alternate schemes for the implementation of the concept in geotechnical earthquake engineering were explored and the technical feasibilities of both schemes were experimentally and analytically demonstrated. In the first scheme, the synthetic liner is placed immediately underneath the foundations of a structure. This type of application of the liner is referred to as *foundation isolation*. In the second scheme, the liner is placed within the soil profile to absorb seismic energy before it arrives at the ground surface or at the base of a building foundation. This application is referred to as *soil isolation*. Example applications of soil isolation are shown in Figs. 1(a and b). In the research program described herein, the concepts of foundation and soil isolation were experimentally and analytically evaluated and benefits and limitations were identified. In a companion paper by Yegian and Kadakal (2004), the results of the research on the synthetic liner and its application to foundation isolation are presented. This paper focuses on the use of the synthetic liner for soil isolation.

This paper briefly presents the dynamic frictional properties of the synthetic liner. The details of the testing of the liner are presented in the companion paper. The paper also presents experimental and analytical results that demonstrate the potential benefits of using the synthetic liner for soil isolation in which the horizontal earthquake energy is dissipated through slip deformations along the liner.

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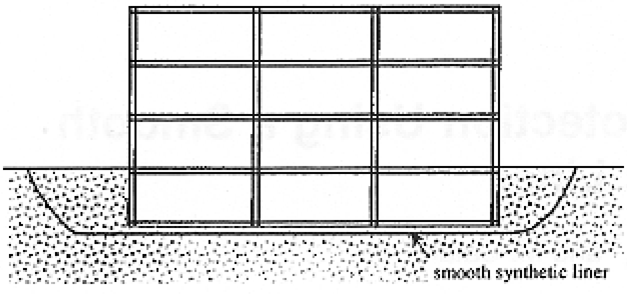
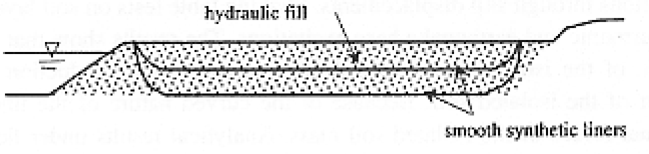


(a) Soil Isolation for buildings



(b) Soil Isolation for reclaimed land

Fig. 1. Soil isolation for seismic protection using smooth synthetic liner

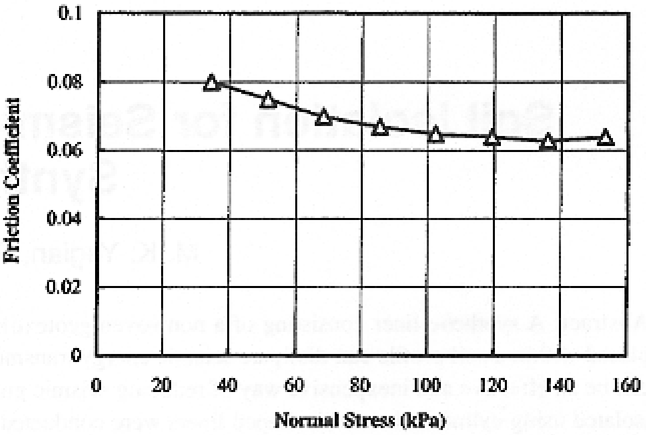


Fig. 2. Effect of normal stress on the friction coefficient of geotextile/UHMWPE interface

Soil Isolation Using Geotextile/UHMWPE Liner

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 because the soil layer above the liner is isolated from the underlying soil deposit that is experiencing the seismic shaking. Soil isolation can be potentially beneficial if applied in the construction of new buildings, slopes, embankments, and reclaimed land using hydraulic fill that is known to liquefy during seismic shaking.

The companion paper describes the details of the research program that led to the identification of a suitable liner for the purpose of seismic isolation. It was determined that Typar 3601 geotextile over an ultrahigh molecular weight polyethylene UHMWPE (Tivar 88-2 AntiStatic) (geotextile/UHMWPE liner) had friction characteristics that made this liner an excellent candidate for soil and foundation isolation. UHMWPE is a linear, low-pressure polyethylene resin. Its average molecular weight is approximately 10 times that of high molecular weight, high-density polyethylene (HDPE) resins. UHMWPE has the highest abrasion and impact resistances of any plastic, a self-lubricating and nonstick smooth surface, and a low coefficient of friction. The static and dynamic friction coefficients of UHMWPE on polished steel are significantly lower than the values for steel on steel and most plastic materials on each other including HDPE.

The dynamic frictional properties of various candidate materials including the liner consisting of geotextile/UHMWPE were investigated extensively using cyclic load and rigid block shaking table tests. The companion paper includes summary results for each liner tested. Briefly, the geotextile/UHMWPE liner was ideal because of its very low dynamic friction coefficients (0.06–0.08). As shown in Fig. 2, the friction coefficient only slightly changed with normal stress, reducing from a value of 0.08 at 3 kPa to 0.063 at a normal stress larger than 100 kPa. Also, an important advantage of this liner over the other interfaces tested was that as shown in Fig. 3, the dynamic friction coefficient was insensitive to the slip rate (sliding velocity), thus making it easy to introduce in analytical models. Therefore, the geotextile/UHMWPE was the liner that was used in all the soil isolation research experiments performed for this study.

Curved Liners

For soil isolation to function properly, an allowance has to be made for the slip deformations to occur along the liner. In addition, the permanent deformations associated with slip along the isolation liner need to be within acceptable limits if soil isolation is used to protect an overlying building or other structures. For these reasons, instead of considering horizontal placement of the liner, curved shapes were explored, in which the ends of the isolation liner terminated at the ground surface where provisions could be made for slip deformations that are anticipated to occur along the liner. Figs. 4(a and b) show two curved (cylindrical- and tub-shaped) liners that were considered in the experiments on soil isolation. It is noted that since the shaking table tests were to be conducted in a uniaxial horizontal direction, the liners were curved only in the direction of shaking as indicated in Fig. 4. Initially, the cylindrical-shaped liner was devised in order to generate a restoring gravitational force that would bring the isolated sand deposit back to its horizontal position, thus reducing the permanent slip of the ground. Experimental results confirmed the

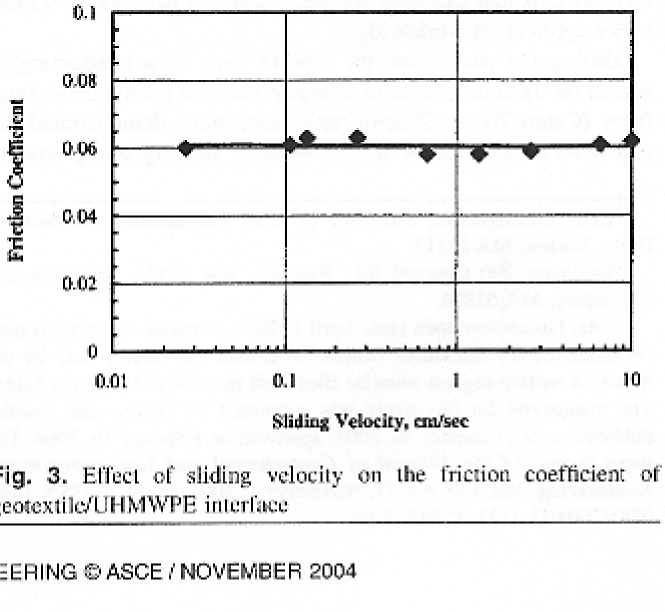
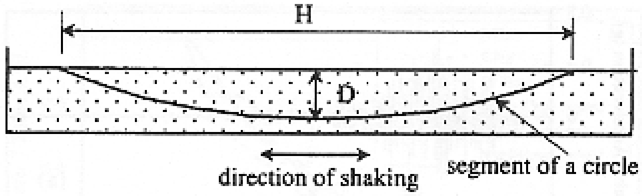
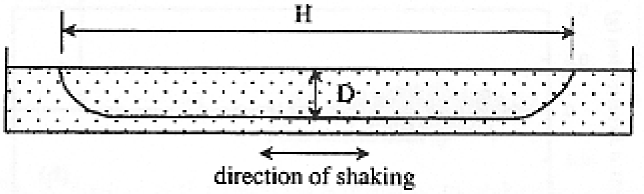


Fig. 3. Effect of sliding velocity on the friction coefficient of geotextile/UHMWPE interface



(a) Cylindrical-shaped soil isolation liner test, H/D = 6.6



(b) Tub-shaped soil isolation liner test, H/D = 9

Fig. 4. Cylindrical-shaped and tub-shaped soil isolation systems tested using a shaking table

effectiveness of this restoring gravitational force. Also, it was determined experimentally as well as analytically that the cylindrical shape of the liner, when its penetration into the soil layer (*D*) relative to the horizontal length of the isolated soil mass (*H*) was small, it did not significantly reduce the effectiveness of the liner as an energy absorbing system. Furthermore, using a cylindrical shape allowed the development of an analytical procedure that was used for validation and interpretation of the experimental data as well as for the evaluation of the effectiveness of the liner in real field applications where the dimensions of the isolated mass typically will be much larger than what could be used in the laboratory. Subsequent to the tests on the cylindrical-shaped liner, the experimental tests were repeated using a tub-shaped liner [Fig. 4(b)], which was deemed to be more practical for application in real field conditions.

Shaking Table Experiments

In this section, selected test results from investigations using cylindrical- and tub-shaped liners are presented to demonstrate the effectiveness of soil isolation within the constraints of the experimental conditions.

Cylindrical-Shaped Liner

The experimental apparatus consisted of a 179 cm × 46 cm × 46 cm Plexiglas tank. The thickness of each Plexiglas plate was 2 cm, and they were glued to each other to form a watertight tank (Fig. 5). The tank was fixed to the shaking table by eight screws to prevent sliding. A segment of a circular curve (radius = 118 cm) was drawn on the side walls of the tank and then the tank was filled with coarse sand and gravel approximately to that line. A piece of UHMWPE (46 cm × 203 cm) was forced into the tank to take the shape of the circular curve drawn on the tank sidewall. The tank was then shaken until the gravel below the liner was fully compacted. No further settlement was observed during the experiments. Two pieces of UHMWPE were cut and glued to the sidewalls above the curved UHMWPE to minimize friction between the sand that was to be placed over the liner and the sidewalls of the Plexiglas box. A piece of the geotextile was cut in the shape of the curved UHMWPE and was placed over it. Fine Ottawa sand was then placed and vibro compacted in the tank to a height of 22 cm in the center of the tank. The resulting length (H) of the sand surface was 142 cm.

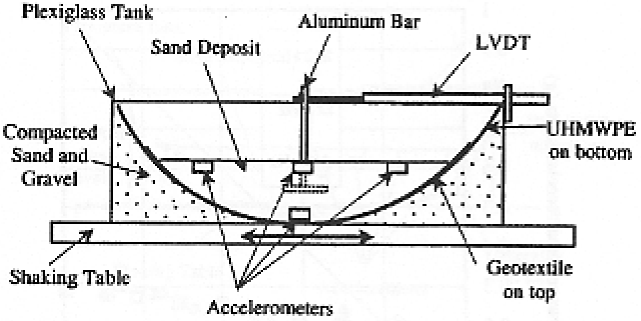


Fig. 5. Schematic of the shaking table setup using cylindrical-shaped isolation liner

Three force-balanced accelerometers were used to measure the transmitted accelerations at the surface of the sand layer. The edge effect was checked by the two accelerometers placed 46 cm to the left and right of the center of the isolated soil mass. Another accelerometer was used to measure the transmitted acceleration at the very bottom of the sand layer as shown in Fig. 5. The purpose of using the fourth accelerometer was to analyze the effect of the soil (amplification or deamplification) on the sliding system. In order to measure the horizontal displacement of the center point of the ground surface, a t-shaped aluminum bar was located 13 cm below the surface of the sand deposit. An LVDT positioned 24 cm above the soil surface was attached to the aluminum bar to obtain the horizontal displacements at that level and then compute the horizontal slip of the center portion of the soil deposit.

A series of tests was carried out with harmonic table excitations of frequencies 2, 5, and 10 Hz. For each frequency, the table acceleration was increased from 0 to 1g in 10 steps. The excitation signal consisted of at least 10 cycles to ensure that the system had reached a steady-state condition.

It was observed that the difference between the measurements made by the three accelerometers positioned on the surface of the sand deposit were insignificant, indicating that the soil layer was acting as a rigid block undergoing pure rotation. For this reason, only the results from the center accelerometer were analyzed. The transmitted acceleration measured on the sand deposit under steady-state condition is plotted against table accelerations in Fig. 6. As can be seen from the figure, the system started sliding when the table acceleration exceeded about $0.18g$. This value is larger than what the friction coefficient of the liner in the horizontal plane would suggest $(0.08-0.063g)$. This increase in the friction coefficient (hence transmitted acceleration) is due to the curved shape of the liner, the side friction effect in the system, and the very low normal stress. Also, it is noted that the transmitted acceleration is almost frequency independent, however, it increases slightly with increase in table acceleration. The maximum transmitted acceleration was about $0.3g$ when the system experienced $1g$ harmonic excitation.

A comparison of the transmitted accelerations measured at the bottom of the soil deposit and those measured at the top of the deposit showed that the sand deposit only slightly amplified the motion. In general, in the cylindrical-shaped experiments, the soil deposit had a rigid body response to the table excitation.

The slip displacement amplitudes measured under steady-state

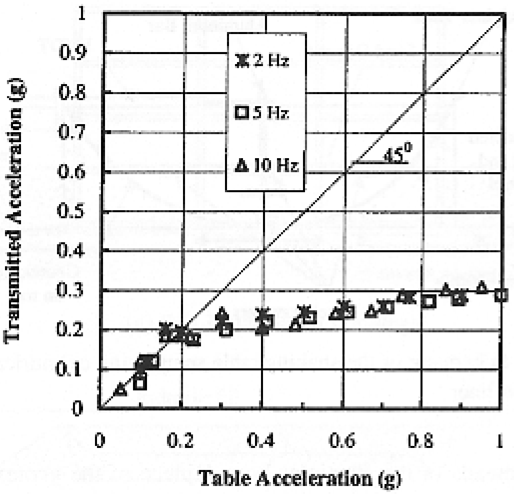


Fig. 6. Transmitted acceleration versus table acceleration under harmonic excitation tests using cylindrical-shaped liner

conditions are plotted against table acceleration in Fig. 7. The results confirm that the system started sliding at table acceleration greater than 0.18g. As expected, the slip displacements measured on the sand surface are larger when the excitation frequency is smaller.

After completing the shaking table tests using harmonic excitations, the experiments were repeated using earthquake motions to excite the table. The purpose of these tests was to understand the transmissibility and slip characteristics of the sand deposit under transient conditions. In the harmonic tests, since the motions were steady state, the permanent slip displacements (slip at the end of excitation) were not measured. However, under a transient earthquake excitation a permanent slip may occur. In this phase of the experimental work, the shaking table was excited using selected earthquake records and the transmitted accelerations and slips (peak-to-peak during shaking and permanent) were measured and compared with the values predicted by theory.

The following three records were used to test the isolated soil layer on a geotextile/UHMWPE liner: Santa Cruz and Capitola records that were recorded during the 1989 Loma Prieta Earthquake (East-West component), and the 1994 Northridge Earthquake (City Terrace, East-West component). Each earthquake record was scaled to three different peak accelerations ranging from about 0.4 to 0.8g. No cutoff filter was applied to the measured responses of the sand layer. Therefore, peak responses due to possible stick-slip behavior of the interface were recorded and included in the data interpretation. Fig. 8 shows typical results from the Santa Cruz record. This figure presents the table acceleration record and the time histories of the response records (transmitted accelerations and slip displacements) measured at the center of the surface of the sand layer. In all the earthquake excitation tests, the peak transmitted accelerations were smaller than 0.4g. Also, it was noted that the permanent slips from all three earthquakes used were almost zero (Fig. 8 for the Santa Cruz results). This indicates that a cylindrical-shaped geotextile/UHMWPE liner can provide a restoring-force mechanism, in which the gravitational force of the soil wedge brings the mass back to equilibrium position, thus minimizing the permanent slip of the isolated soil.

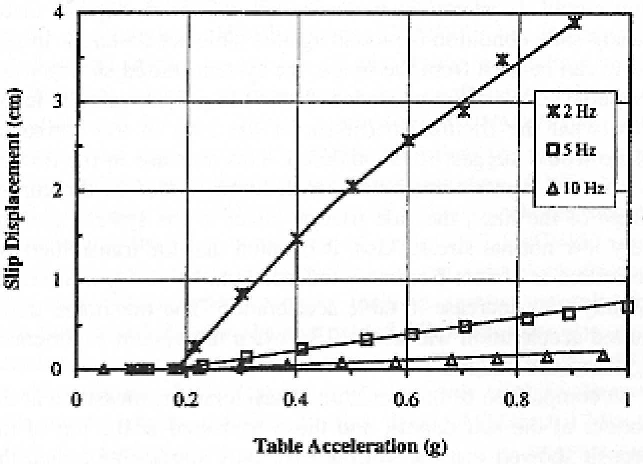


Fig. 7. Slip displacement versus table acceleration using cylindrical-shaped isolation liner

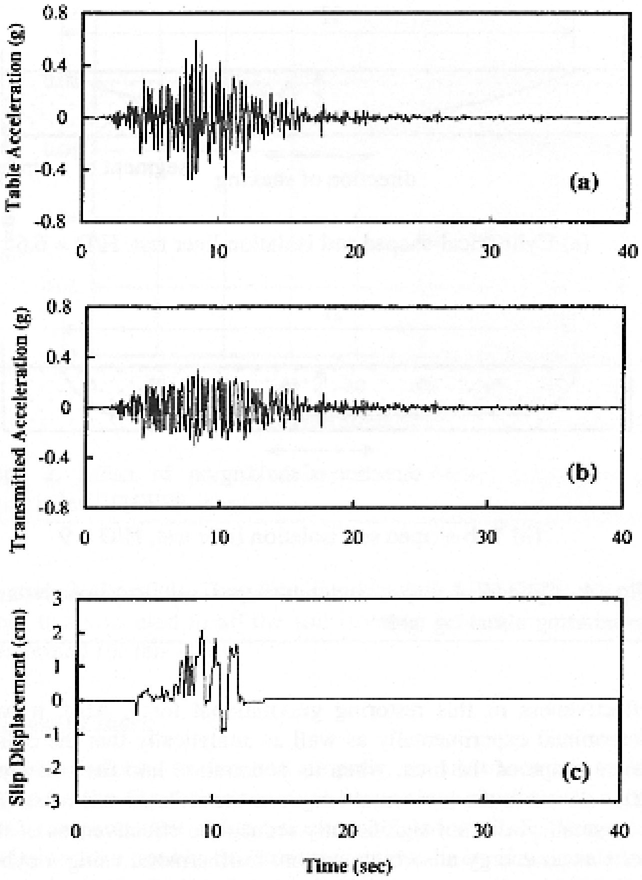


Fig. 8. Measurements from tests with the Santa Cruz record scaled to 0.6g peak acceleration: (a) table acceleration; (b) transmitted acceleration; and (c) slip displacement

The effectiveness of isolation in reducing the peak transmitted accelerations during the harmonic and earthquake excitations is best shown in Fig. 9. This figure presents the ratio of recorded peak transmitted acceleration to peak table acceleration as a function of table acceleration. As can be seen from the figure, the benefit of soil isolation increases with increasing table acceleration. At table acceleration of 0.5g, the transmitted acceleration with soil isolation is about $\frac{1}{2}$ of that without soil isolation. It is noted that these results are from a sand deposit that experienced some frictional resistance from the sidewalls of the tank, resulting

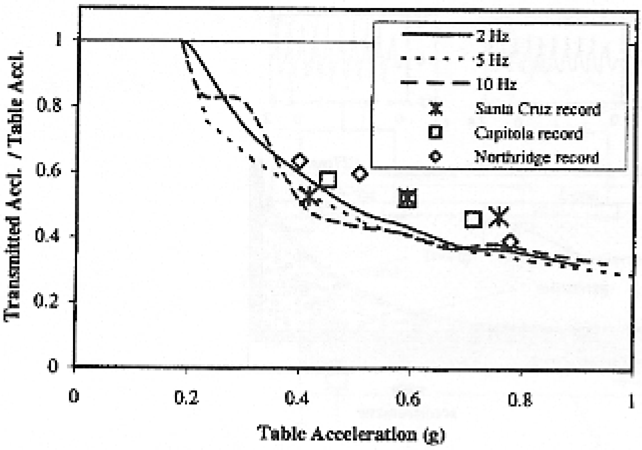


Fig. 9. Ratio of peak transmitted acceleration to peak table acceleration as a function of peak table acceleration

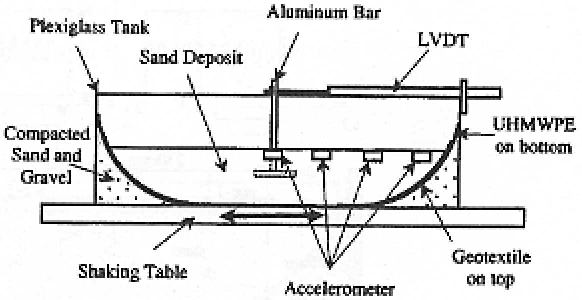


Fig. 10. Schematic of the shaking table setup for the tub-shaped isolation liner

in an overestimation of transmitted acceleration (although this effect was minimized through the use of UHMWPE on the sidewalls of the tank).

In summary, tests on cylindrical-shaped soil isolation led to the observations that a curved liner, which, although it may transfer larger accelerations than a horizontally placed one, can still be effective as an energy dissipating system. An advantage of the cylindrical shape is that it provides a restoring mechanism that minimizes the permanent slip deformations along the liner, a condition desirable for practical application of soil isolation.

Tub-Shaped Liner

Although soil isolation applied in a cylindrical-shaped form is capable of reducing the transmitted accelerations during an earthquake, the installation of such a system might not be very practical in field applications. To give a cylindrical shape to the ground prior to the installation of the liner would be expensive and impractical. Therefore, to improve the practicality of using soil isolation under field conditions, an alternative and simpler shape of the isolation liner was investigated. It was decided that a liner that is placed mostly in a horizontal way with sharply curving sideslopes (tub-shaped) would be more practical to install in the field [Figs. 1(a and b)].

The same Plexiglas tank described earlier was used for the tub-shaped liner tests. The UHMWPE was cut to 46 cm × 203 cm size and was fitted in the tank by giving the tub-shape (Fig. 10). In the bottom, front, and back of the tank, coarse sand and gravel was placed. The UHMWPE material was pushed from both ends to maintain a horizontal shape in the midportion of the membrane and assume steeply inclined edges (generally 1:1 slope). Then, two other pieces of UHMWPE were taped to the sidewalls on the inside in order to reduce the friction between the sand deposit and the Plexiglas sidewalls. A large geotextile sheet (152 cm × 229 cm) was placed on top of the UHMWPE liner. The tank was then filled with Ottawa sand up to 18 cm inches deep in the center of the tank. The horizontal length of the sand surface was 163 cm.

Because of the complex response of tub-shaped isolated soil, especially near the edges, the tests were run using four accelerometers on one-half of the sand surface. In this setup, four, forced-balanced accelerometers were positioned on the surface of the sand deposit as shown in Fig. 10. Because of symmetry, only one side of the sand deposit was monitored. Starting from the center, the accelerometers were located 23 cm apart from each other. The LVDT and the aluminum bar used in the previous setups were again used to measure horizontal displacements. The four-accelerometer tests were run under both harmonic- and earthquake-based excitations. In the harmonic excitation tests, three different frequencies were used: 2, 5, and 10 Hz. For each frequency, three different peak table accelerations (0.18, 0.5, and 1.0g) were assigned. The results showed that generally when the table acceleration exceeded 0.2g, sliding was initiated along the isolation liner, thus resulting in reduced accelerations at the surface of the soil deposit. Fig. 11 presents a typical set of results showing the measured records from the four surface accelerometers, as well as that of the table. As can be seen, when the table acceleration was 1.0g, because of sliding along the geotextile/UHMWPE liner, the transmitted acceleration in the central portion of the isolated soil (0.2g) was much smaller than the table acceleration, indicating the benefit of soil isolation. It is also noted that the transmitted accelerations near the edges of the tub-shaped sand deposit were higher than those measured at the center. This can be explained by the difference in strains in sand between the two locations. The shaking table experiments showed that, because of the flexibility of the sand deposit, the central portion moved horizontally while the edges moved along the inclined slopes of the isolation liner. Such differences in the displacements were evidenced through observations of failure lines on the surface of the sand, across the tank width, right above the point where the liner sloped upward, referred to as the break-points. Generally, the measurements of the accelerometers in the horizontal region of the liner were almost identical and much smaller than the table acceleration (about 0.3g regardless of the table acceleration). While the accelerometers near and past the "break points" (the curved section) recorded spikes of higher transmitted accelerations.

The tests described above were repeated using earthquake-based excitations. Earthquake records were scaled to peak accelerations ranging from 0.18 to about 0.9g. The results were quite similar to those obtained from the harmonic excitation tests. When the peak acceleration of the table was greater than 0.2g, the peak transmitted accelerations in the central region of the sand were much smaller than the peak table accelerations. However, the peak transmitted accelerations near the edge of the sand deposit (acc-3 and acc-4) were larger because of the edge effects also observed in the previous harmonic tests. Fig. 12 shows typical test results obtained using the Santa Cruz record scaled to 0.8g to excite the table. The tremendous reduction in transmitted acceleration in the horizontal region of the liner is quite evident. Near the curved portion, the transmitted accelerations are still

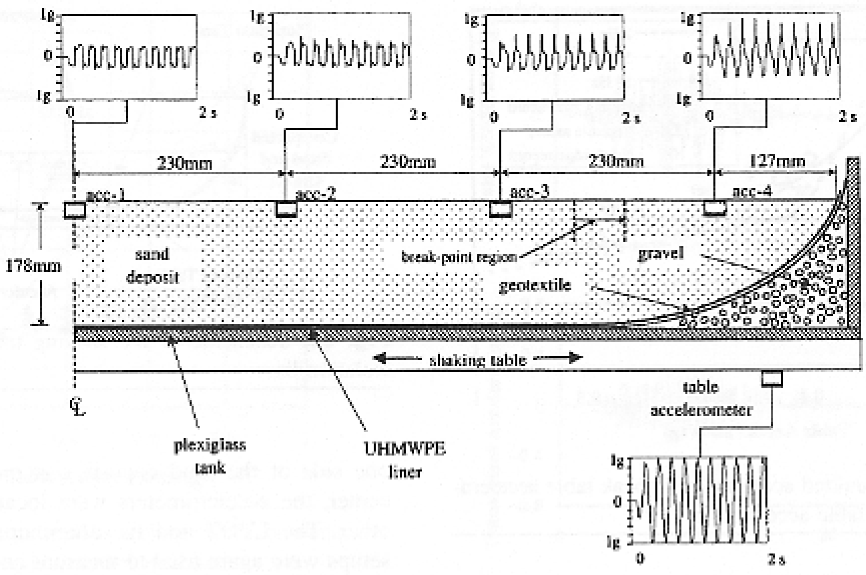


Fig. 11. Acceleration records from shaking table tests on tub-shaped isolated soil subjected to a 5 Hz harmonic motion

much smaller than the table acceleration, but include a few spikes with accelerations larger than those measured in the horizontal portion of the liner. It is noted that these higher transmitted acceleration regions are close to the liner edges, approximately outside the middle two-third region of the isolated soil.

In order to make a further comparison between the transmitted accelerations measured at different locations, the response spectra of the earthquake records measured on the sand surface were computed and plotted. Fig. 13 presents typical results using the Santa Cruz record. It is noted that the response spectra of the transmitted accelerations measured at four different locations are not very different from each other despite differences in peak transmitted accelerations. In other words, the large, high-frequency transmitted accelerations at accelerometer locations acc-3 and acc-4 did not have a dominant effect on the response spectra. From the response spectra, it can be also observed that the tub-shaped soil isolation is capable of reducing the spectral accelerations of the ground surface motion. It was observed that the effectiveness of the system increased with increasing peak table acceleration.

Fig. 14 shows typical table and transmitted accelerations at the center of the soil mass and slip displacements measured using the Santa Cruz record. As can be seen, the peak transmitted acceleration of $0.32g$ from the Santa Cruz record is much smaller than peak table acceleration of $0.8g$. In addition, it is noted that the permanent slips measured at the end of shaking is almost zero, which indicates that a tub-shaped geotextile/UHMWPE liner can have a restoring effect very similar to the cylindrical-shaped liner, thus minimizing the permanent slip deformation of the overlying soil deposit. However, provisions still have to be made for the maximum slip that will occur during an earthquake shaking. In

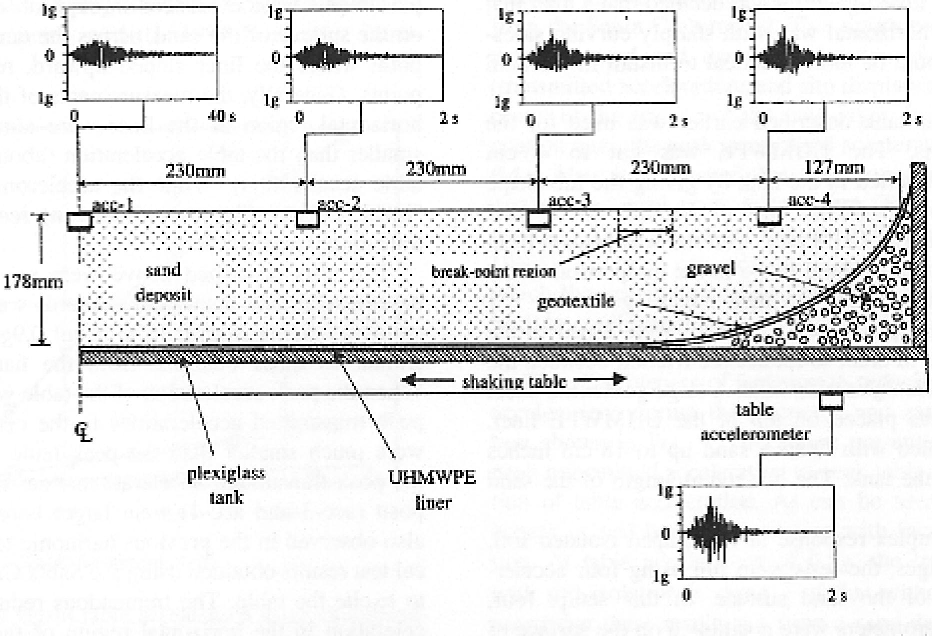


Fig. 12. Acceleration responses of tub-shaped isolated soil subjected to the Santa Cruz record scaled to $0.8g$

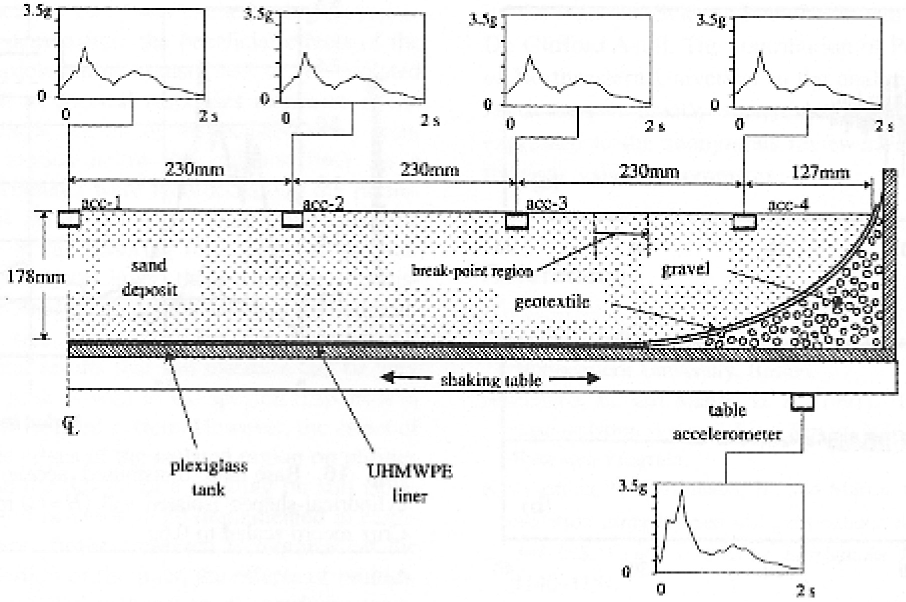


Fig. 13. Response spectra of the motions from tub-shaped isolated soil using the Santa Cruz record scaled to 0.8g (5% damping)

the case of the Santa Cruz record, a maximum slip of 4 cm was measured in the central portion of the isolated soil deposit.

Analysis of Field-Scale Application

The cylindrical- and tub-shaped soil isolation experiments were conducted under many laboratory and experimental constraints. The most serious limitation was the size of the tank, and hence the depth of the isolated soil deposit used relative to its horizontal length. One would expect under realistic field conditions, if a building with one basement is to be isolated through its foundation soils, a 3 m penetration of the liner below the ground surface (D=3 m) would suffice. The horizontal length of the isolated soil (H) would be slightly larger than the length and width of the building. For a typical isolated region of 60 m × 60 m, the aspect ratio H/D would be about 20. In the experiments, this ratio was about 7. Also, the experimental setup suffered from unfavorable effects of sidewall friction from the box. In order to eliminate these limiting boundary effects and make an assessment of the potential effectiveness of soil isolation under field conditions, a simple analytical model was developed for the evaluation of the dynamic response of the isolated soil mass (Catan 2000). It is noted that the experimental results and conclusions from the cylindrical-shaped and tub-shaped liner tests were generally very similar. Hence the theoretical model was developed using a cylindrical-shaped liner over which a cylindrical-shaped rigid block was placed. The rotation of the block under a horizontal excitation was solved for using Lagrange formulation of the equations of motion, in which the work done by the friction force along the liner was included. The analytical model was validated using test results on a rigid mass placed on a cylindrical liner.

For the purpose of simple illustration, an isolated mass of length H=60 m and soil depth of 3 m was analyzed using the Santa Cruz record scaled to 0.6g. Fig. 15(a) shows the base acceleration corresponding to the motion immediately below the liner. Fig. 15(b) shows the acceleration at the top of the isolated soil mass, which clearly shows the effect of sliding and the resulting reduction of acceleration to a maximum value of 0.08g.

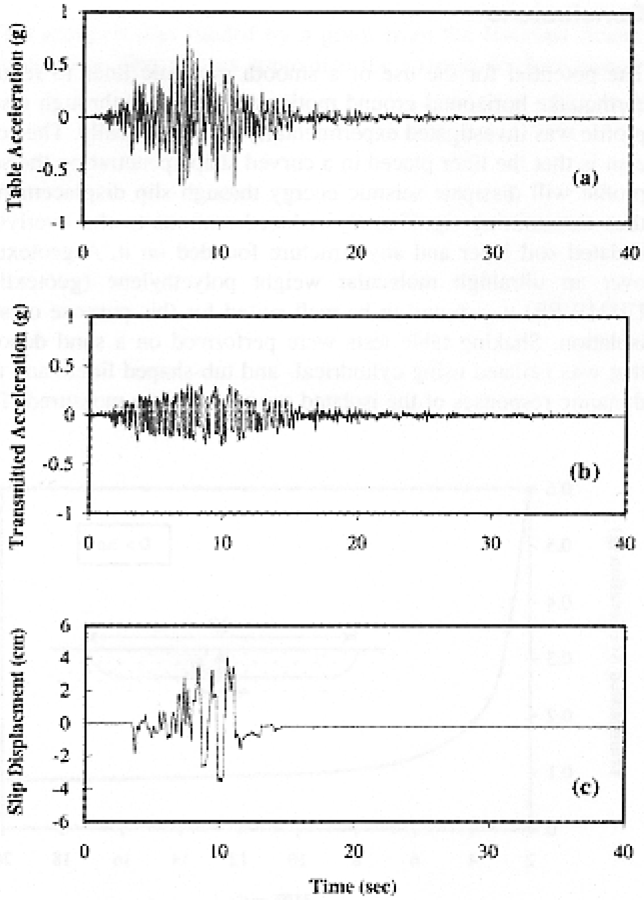


Fig. 14. Typical measured responses of tub-shaped isolated soil subjected to the Santa Cruz record scaled to 0.8g: (a) table acceleration; (b) transmitted acceleration; and (c) slip displacement

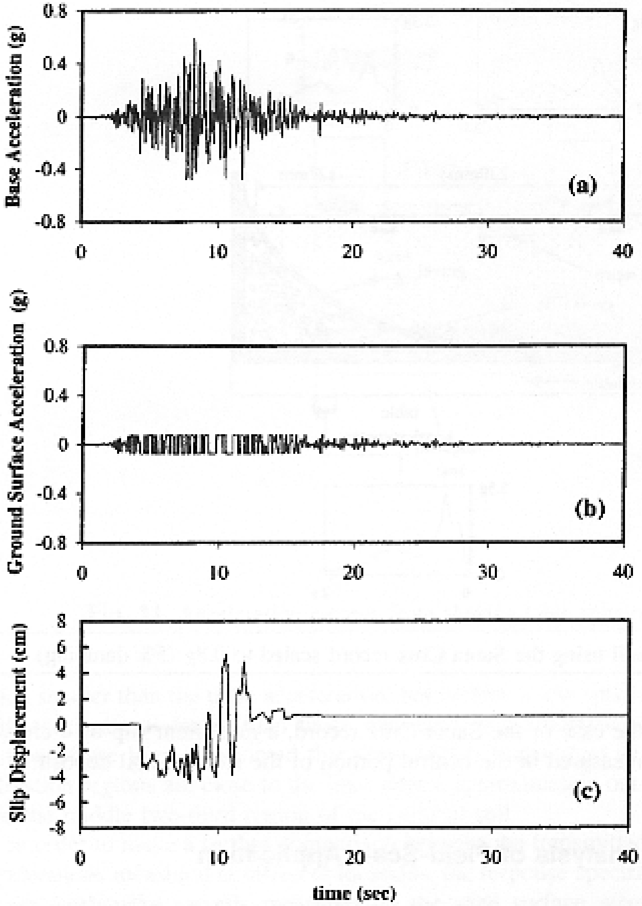


Fig. 15. Calculated time history responses of a cylindrical-shaped isolated soil wedge (H=60 m,D=3 m) when subjected to the Santa Cruz record scaled to 0.6g: (a) base acceleration; (b) ground surface acceleration; and (c) slip displacement

This reduction in transmitted acceleration resulted in a maximum slip of about 5 cm, and a permanent slip of 1.3 cm of the isolated mass. Considering the size of the isolated soil region, such slips observed near the edges of the liners surfacing at the ground level can be considered inconsequential to the safety of a structure founded near the center of the isolated region. However, the effect of slip deformations near the edges of the isolated region on utilities need to be considered in design just as it is done for mechanically isolated structures.

Further effects of soil isolation can be observed through the spectra of the computed ground motion shown in Fig. 16. In this figure, the response spectra of the motions with and without soil isolation are compared. The reduction in spectral acceleration due to soil isolation is tremendous. In the case of using the Santa Cruz record, soil isolation reduced the maximum spectral acceleration from 2.5 to 0.8g.

Further sensitivity analysis was performed to determine analytically the effect of liner curvature on the effectiveness of soil isolation. Fig. 17 shows the peak horizontal acceleration of the center of gravity of the isolated mass, experiencing a 2 Hz harmonic horizontal excitation below the liner, as a function of the ratio of horizontal length (H) to depth (D) of the isolated soil mass. It is noted that the effect of liner curvature is minimized when H/D is greater than about 10. Thus, for a building that has its foundation about 3 m below the ground, the minimum isolated zone will have to have a length of about 30 m at the ground surface level. A further requirement would be that the curved portion of the liner be outside the footprint of the building extending away from the edge of the building a distance of approximately equal to the depth of the isolated zone. Shallower foundations would require even smaller isolated regions. Hence, soil isolation does hold good promise for real field applications.

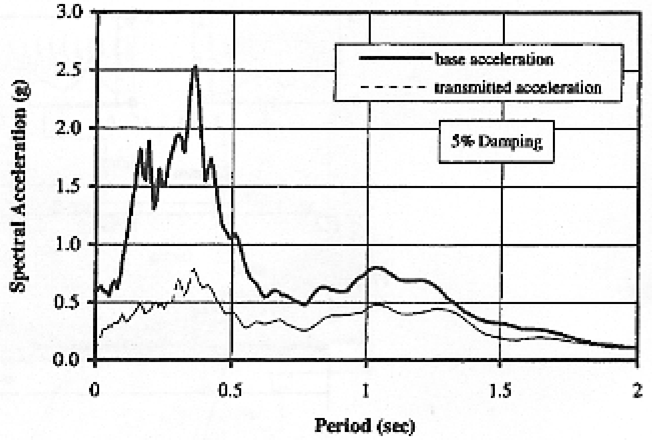


Fig. 16. Base and transmitted acceleration response spectra of cylindrical-shaped isolated soil (H=60 m,D=3 m) using the Santa Cruz record scaled to 0.6g

Conclusions

The potential for the use of a smooth synthetic liner to reduce earthquake horizontal ground motions propagating through a soil profile was investigated experimentally and analytically. The concept is that the liner placed in a curved shape penetrating the soil profile will dissipate seismic energy through slip displacements, thus transmitting significantly reduced motions to the overlying isolated soil layer and any structure founded on it. A geotextile over an ultrahigh molecular weight polyethylene (geotextile/UHMWPE) was found to be well suited for this purpose of soil isolation. Shaking table tests were performed on a sand deposit that was isolated using cylindrical- and tub-shaped liners and the dynamic responses of the isolated sand mass were measured. The

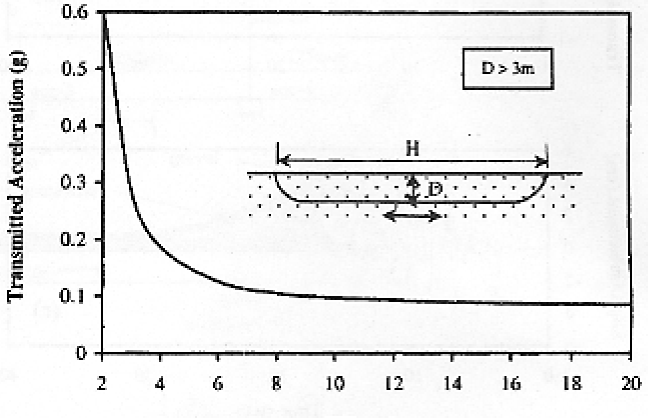


Fig. 17. Transmitted acceleration as a function of H/D ratio computed analytically using 2 Hz cyclic shaking, with 0.6g base acceleration amplitude

results from tests in which the table was excited using harmonic and earthquake motions demonstrate the beneficial effects of the liner in reducing the accelerations transmitted to the isolated mass. Both peak as well as spectral responses measured at the surface and near the central region of the isolated mass were much smaller than the motion below the isolation liner. As a consequence, slip displacements were recorded along the perimeter of the isolated soil layer where the liner penetrated the ground surface. Because of the restoring force effect of gravitational weight of the isolated soil layer, the permanent slip displacements were small. Analytical results using a cylindrical-shaped liner and field size dimensions for the isolated soil confirmed the experimental results that soil isolation can be very effective in reducing the peak as well as the spectral responses in the central region of a soil-isolated system. However, the effect of slip deformations near the edges of the isolated region on utilities needs to be considered in the design of a building on soil isolation. For the concept of soil isolation to be implemented in earthquake engineering practice, further research is required on the manufacturing and installation of the liner, the effects of multidirectional shaking on the isolated soil and on an overlying structure, the effect of environmental conditions on the liner, the long-term performance of the liner under creep and liner deformations induced by soil settlement, soil type, and compaction level, and development of an analytical tool for the evaluation of a three-dimensional soil-liner-structure system under seismic excitation.

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References

Catan, M. (2000). "Soil isolation using geosynthetic liner." MS thesis, Northeastern University, Boston.

Hushmand, B., and Martin, G. R. (1991). "Layered soil-synthetic liner base isolation system." *Final Report*, NSF Small Business Innovative Research Program.

Kavazanjian, E., Hushmand, B., and Martin, G. (1991). "Frictional base isolation using layered soil-geosynthetic liner system." *Proc., ASCE, 3rd U.S. Conf. on Lifeline Earthquake Engineering*, Los Angeles, 1140–1151.

Yegian, M. K., and Kadakal, U. (2004). "Foundation isolation for seismic protection using smooth synthetic liner." *J. Geotech. Geoenviron. Eng.*, 130(11), 1121–1130.

Yegian, M. K., and Lahlaf, A. M. (1992a). "Dynamic interface shear properties of geomembranes and geotextiles." *J. Geotech. Eng.*, 118(5), 760–779.

Yegian, M. K., and Lahlaf, A. M. (1992b). "Geomembranes as base-isolation." *Geosynthetic Fabric Report*, September.