

DYNAMIC INTERFACE SHEAR STRENGTH PROPERTIES OF GEOMEMBRANES AND GEOTEXTILES

By M. K. Yegian,¹ Member, ASCE,
and A. M. Lahlaf,² Associate Member, ASCE

ABSTRACT: Shaking-table tests to measure the dynamic interface shear strength properties between geotextiles and geomembranes were performed and the results are reported. It was observed that there is a limited shear stress, hence a limited acceleration, that can be transmitted from one geosynthetic to another. Beyond this acceleration, relative displacement along the geosynthetic interface is initiated. Hence, the primary concern about the dynamic response of a geotechnical facility that incorporates geosynthetics should be the permanent relative displacement that may accumulate along the geosynthetics interfaces. The dynamic interface friction angles measured at the onset of relative displacement between the geosynthetics are not appreciably different from those obtained from static tests. It was also observed that the dynamic interface friction angle increased slightly as the table acceleration increased beyond the level causing initial sliding. This increase could not be attributed to the potential effect of the frequency of motion of the shaking table and normal stress. Finally, an innovative use of geosynthetics as base isolation for earthquake hazard mitigation is proposed and its applicability is demonstrated. Further exploration of this application of geosynthetics may lead to products that can provide varying degrees of base isolation, especially in geotechnical earthquake engineering.

INTRODUCTION

During the 1980s the use of geosynthetics in geotechnical engineering practice increased remarkably. Today, geosynthetics are used for filtration, drainage, separation, soil reinforcement, seepage control, and many other applications. Current research and design practice relating to the stability concern of geotechnical facilities that utilize geosynthetics are primarily directed at ensuring their adequate performance under static loading. Examples of such facilities include geomembrane-lined canals, reservoirs, and hazardous-waste containments; geomembrane-lined tunnels; earth-retaining structures; slopes reinforced with geotextiles and geogrids; and geotextile-stabilized embankment foundations, roads, and so on.

Recent research on the use of geosynthetics has made significant contributions to our understanding of the behavior of geosynthetic-soil systems under static loads. The results of extensive static tests on the interface shear strength properties of various geosynthetic materials and soils have been reported by Myles (1982), Martin et al. (1984), Saxena and Wong (1984), Williams and Houlihan (1986), Miyamori et al. (1986), Negussey et al. (1989), O'Rourke et al. (1990), and Mitchell et al. (1990). These results have direct applications in static stability analysis of geotechnical facilities that include geosynthetics.

While many projects that incorporate geosynthetics are presently being designed and built, the dynamic behavior of such systems is not yet ade-

¹Prof., Dept. of Civ. Engrg., Northeastern Univ., Boston, MA 02115.

²Geotech. Engr., GEI Consultants Inc., Winchester, MA 01890; formerly Res. Asst., Northeastern Univ., Boston, MA.

Note. Discussion open until October 1, 1992. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on November 28, 1990. This paper is part of the *Journal of Geotechnical Engineering*, Vol. 118, No. 5, May, 1992. ©ASCE, ISSN 0733-9410/92/0005-0760/\$1.00 + \$.15 per page. Paper No. 953.

quately addressed in design or in research. To ensure survival of such facilities under seismic, blast, or other man- or machine-induced vibrations, dynamic and cyclic behavior of geosynthetic-soil systems needs to be considered.

This paper reports the results of a research program conducted to evaluate the dynamic interface properties between a geomembrane and a geotextile. A shaking-table facility and an instrumentation system were used to measure the dynamic interface shear strength properties, and to investigate the factors upon which they depend. Based on the results, conclusions are presented on the effect of dynamic loads upon geosynthetic interface properties. In addition, the results are used to demonstrate a new concept of using geosynthetics as base isolation in seismic hazard mitigation.

STATIC INTERFACE PROPERTIES

Investigators have conducted static shear tests on combinations of different geosynthetics and soils to evaluate interface strength properties. Table 1 shows selected results from Martin et al. (1984), Williams and Houlihan (1986), and Negussey et al. (1989) for geomembranes and geotextiles. It is noted that the friction angle between a geosynthetic and soil is lower than that of the soil without geosynthetics. Moreover, the friction angle between two geosynthetics can be even smaller. For example, Martin et al. (1984) reported that the friction angle of Ottawa sand is 28°. The friction angle between CZ 600 geotextile and Ottawa sand is 26°, and between CZ 600 and high-density polyethylene (HDPE) geomembrane is 8°. Such low friction angles between various geosynthetics can be of major concern in slope-stability problems such as the Kettleman Hills slide, reported by Mitchell et al. (1990). The latter noted that the interface strength properties are affected by factors such as dry versus submerged condition, orientation of the geosynthetics with respect to the direction of shear-stress application (in some cases), and the degree of polishing (in the case of HDPE-geotextile interface) of the geomembrane by the geotextile. They also pointed out that the residual interface strength is fully mobilized at very small strain levels.

In the research reported in this paper, shaking-table tests were conducted to evaluate the interface friction angle between a geomembrane and a geotextile under dynamic loads. In addition, static shear tests were performed to allow a comparison between the static and dynamic interface properties. In this section, the results of these static tests are presented and compared with other published data.

A simple experimental setup was used to measure the relationship between shear stress and shear displacement between an HDPE geomembrane and a nonwoven geotextile. As shown in Fig. 1, a large piece of HDPE geomembrane was attached to a fixed table. On the geomembrane a segment of geotextile rested freely, over which a concrete block of 20.3 × 30.5 cm (8 in. × 12 in.) base cross section was placed. Static weights were added on the concrete block to vary the normal stress, from 3.4 kPa (0.5 psi) to 34 kPa (5 psi). The horizontal shear force was applied on the concrete block by means of a variable loading-rate unit. The shear force and the horizontal displacement were measured by a proving ring and a dial gage, respectively. All tests were performed at a constant shear displacement rate of approximately 1.27 mm/min (0.05 in./min). Tests were performed under dry and submerged conditions of the geosynthetics.

Fig. 2 shows typical shear stress versus shear displacement curves gen-

TABLE 1. Interface Angles of Friction for Various Geosynthetics

Author (1)	Interface (2)	Peak angle of friction ϕ (3)	Residual angle of friction ϕ (4)
Martin et al. (1984)	Ottawa sand/Ottawa sand	28°	—
	CZ 600 geotextile ^a /Ottawa sand	26°	—
	500X geotextile ^b /Ottawa sand	24°	—
	PVC geomembrane ^c /CZ 600 geotextile ^a	21°	—
	PVC geomembrane ^c /500X geo- textile ^b	24°	—
	HDPE geomembrane ^d /Ottawa sand	18°	—
	HDPE geomembrane ^d /CZ 600 geotextile ^a	8°	—
	HDPE geomembrane ^d /500X geotextile ^b	10°	—
Williams and Houlihan (1986)	PVC geomembrane ^c /Trevira 2125 geotextile ^e	—	18°
	PVC geomembrane ^c /Geolon 1500 geotextile ^f	—	20°
	HDPE geomembrane ^d /Trevira 2125 geotextile ^e	—	10°
	HDPE geomembrane ^d /Geolon 1500 geotextile ^f	—	9°
Negussey et al. (1989)	HDPE geomembrane ^d /Texel 7612 geotextile ^g	—	6.5°
	HDPE geomembrane ^d /HDPE geomembrane ^d	—	6.5°

^aNonwoven, needlepunched, polypropylene fabric.

^bWoven, slit-film polypropylene fabric.

^cSmooth, polyvinyl chloride membrane.

^dHard, smooth, high-density polyethylene membrane.

^eNonwoven, needlepunched, staple polyester fabric.

^fWoven, polypropylene (warp), polyester (fill).

^gNonwoven geotextile.

erated from these static tests for dry geomembrane-geotextile interface system. In Fig. 3 the peak and the residual shear strengths are plotted as a function of the normal stress.

The friction angles at peak and residual strengths were computed for both dry and submerged conditions. Table 2 summarizes the computed friction angles.

From these static shear tests, the following conclusions are made.

The shear displacements at which the peak shear strengths were mobilized in dry and submerged tests for a geomembrane-geotextile interface were very small (less than 0.25 mm). The measured shear displacement at peak shear stress increased slightly from 0.13 mm to 0.25 mm (0.005 in. to 0.01 in.) as the normal stress increased from 8.5 kPa to 32.7 kPa (1.21 psi to 4.74 psi). The stress-displacement curve resembles very closely that of a rigid-plastic system.

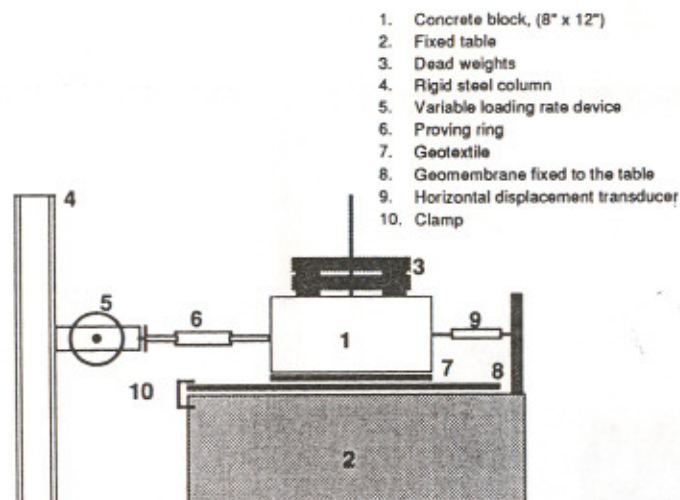


FIG. 1. Setup for Static Shear Strength Test

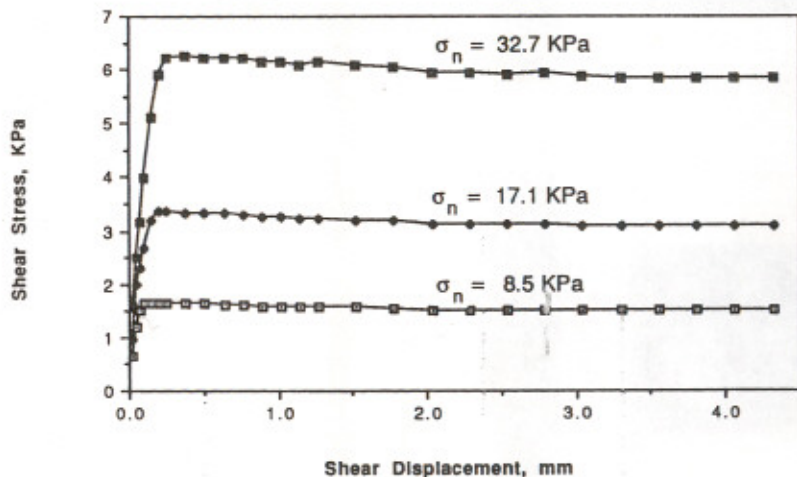


FIG. 2. Shear-Stress versus Shear-Displacement Curves from Dry Geomembrane-Geotextile Static Tests

The residual friction angle is only about 1° less than the peak friction angle.

The friction angles corresponding to the submerged condition were consistently smaller than those corresponding to the dry condition by about $1-2^\circ$.

The results obtained for the dry geomembrane-geotextile system compare well with other published data shown in Table 1. This confirms that the overall experimental setup and testing procedure, although different from those used by other investigators, yielded valid and comparable results.

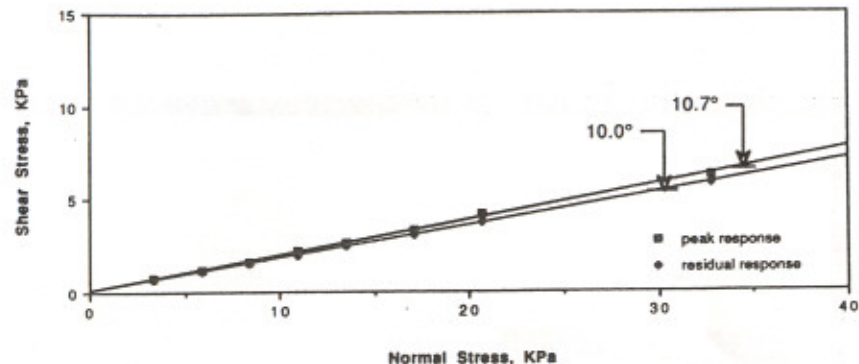


FIG. 3. Static Peak and Residual Angles of Friction for Dry Geomembrane-Geotextile Interface

TABLE 2. Measured Static Angles of Friction

Interface condition (1)	Peak angle of friction ϕ (2)	$\tan \phi$ (3)	Residual angle of friction ϕ (4)	$\tan \phi$ (5)
Geomembrane ^a /geotextile ^b dry	10.7°	0.19	10.0°	0.18
Geomembrane ^a /geotextile ^b submerged	9.6°	0.17	8.5°	0.15

^aGundle HD60: hard, smooth HDPE.
^bPolyfelt TS700: Nonwoven, continuous filament, needlepunched geotextile.

SHAKING-TABLE TESTS

Test Facility

Fig. 4 is a schematic of the shaking-table facility used to evaluate the dynamic interface properties between the geomembrane and geotextile. The shaking table consisted of a vibration exciter connected to a rigid aluminum table mounted on frictionless linear bearing pillow blocks moving on two stainless steel guide rails. The dimensions of the table are 91 cm (3 ft) in the direction of the motion and 81 cm (2 ft and 8 in.) in the transverse direction. The amplitude and the frequency of the table motion were controlled by a signal generator. The concrete block used in the static tests (Fig. 1), with the weights attached to it, rested on a segment of a geotextile, which in turn rested on a large piece of a geomembrane that was fixed to the shaking table. The block-geosynthetic system was also placed in a tub when submergence was desired. The acceleration of the table and that of the block were measured simultaneously by piezoelectric accelerometers at a rate of 100 measurements per second. In addition, the displacement of the block relative to the table was recorded using a linear variable-displacement transducer (LVDT). All data acquisition and analysis were made using a personal computer and a commercially available software.

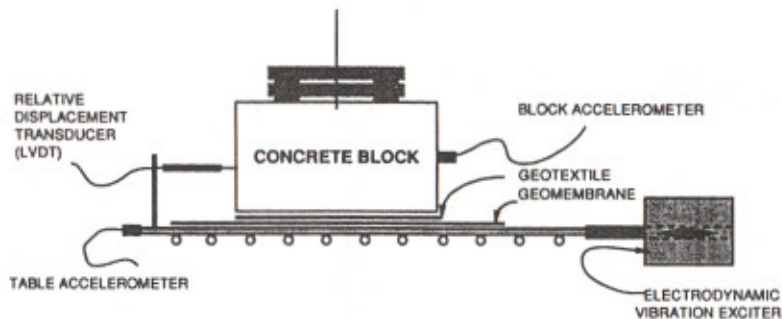


FIG. 4. Shaking-Table Facility

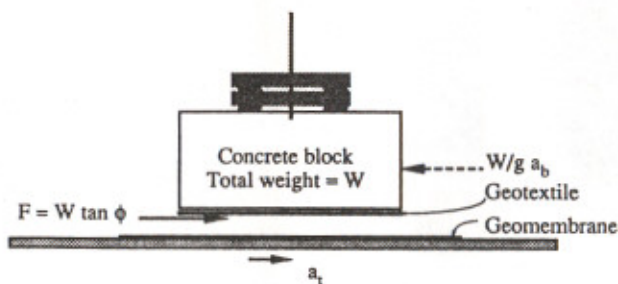


FIG. 5. Free-Body Diagram of Block

Dynamic Interface Properties

A series of shaking-table tests were performed to evaluate the maximum shear (or acceleration) transmitted to the block, and its dependency upon the table acceleration, frequency of motion of the table, normal stress, and dry versus submerged conditions.

To relate the measured acceleration of the block to the shear stress transmitted through the geosynthetic system, the following formulation is presented. Fig. 5 presents schematically the free-body diagram of the block. The frictional resistance between the concrete block that had a rough base and the geotextile was very large. In fact, attempts to induce sliding between the block and the geotextile would result in tearing and wrinkling of the fabric. Hence, any sliding that took place was always observed between the geotextile and the geomembrane. As the table accelerates with an acceleration a_t , it transmits a frictional force F to the block. This frictional force cannot exceed the interface shearing strength between the geomembrane and the geotextile. Assuming a Mohr-Coulomb type of failure mechanism, the value of F can be written as

$$F = W \tan \phi_d \dots\dots\dots (1)$$

where W = weight of the block and added weights; and ϕ_d = geomembrane-geotextile interface dynamic friction angle.

This limiting shear force induces a limiting block acceleration, referred to as a_b , and given by

$$W \tan \phi_d = \frac{W}{g} a_b \dots\dots\dots (2)$$

or

$$a_b = \tan \phi_d g \dots\dots\dots (3)$$

This implies that starting from the at-rest position, as the acceleration of the table is increased the block and the table move together for as long as the table acceleration (a_t) is smaller than the limiting block acceleration (a_b) given by (3). When the acceleration of the table (a_t) exceeds the limiting value (a_b) relative movement will be induced between the block and the table. Thus, measurement of the acceleration of the block can provide the

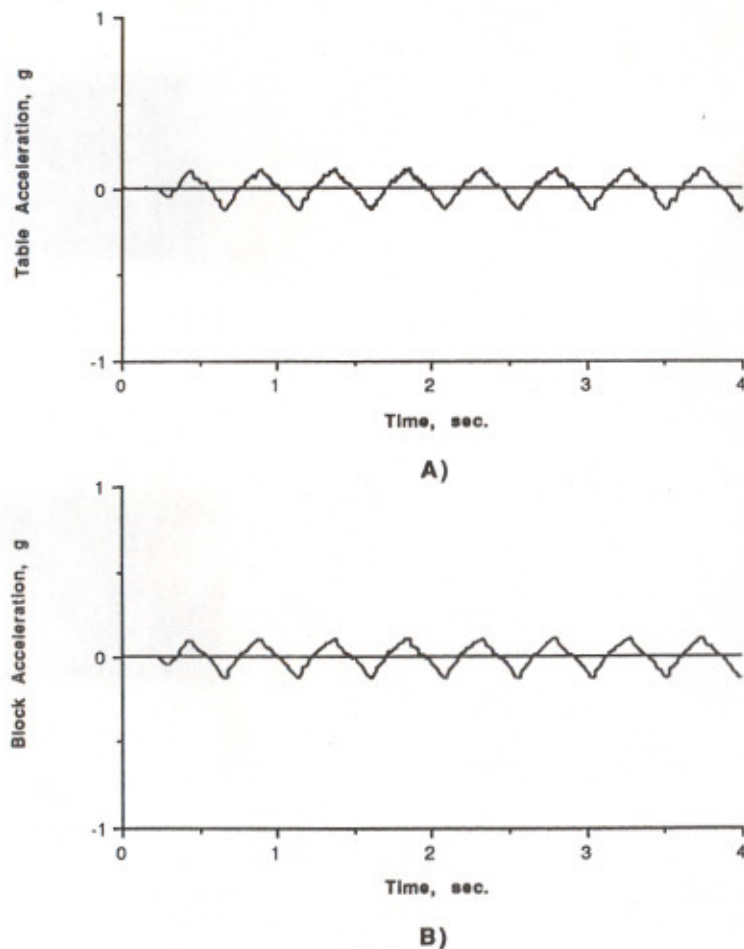


FIG. 6. Shaking-Table Test Results for Geomembrane-Geotextile Interface, Dry Condition. (a) Table-Acceleration Record with Peak Value of 0.13 g; (b) Block-Acceleration with Peak Value of 0.13 g

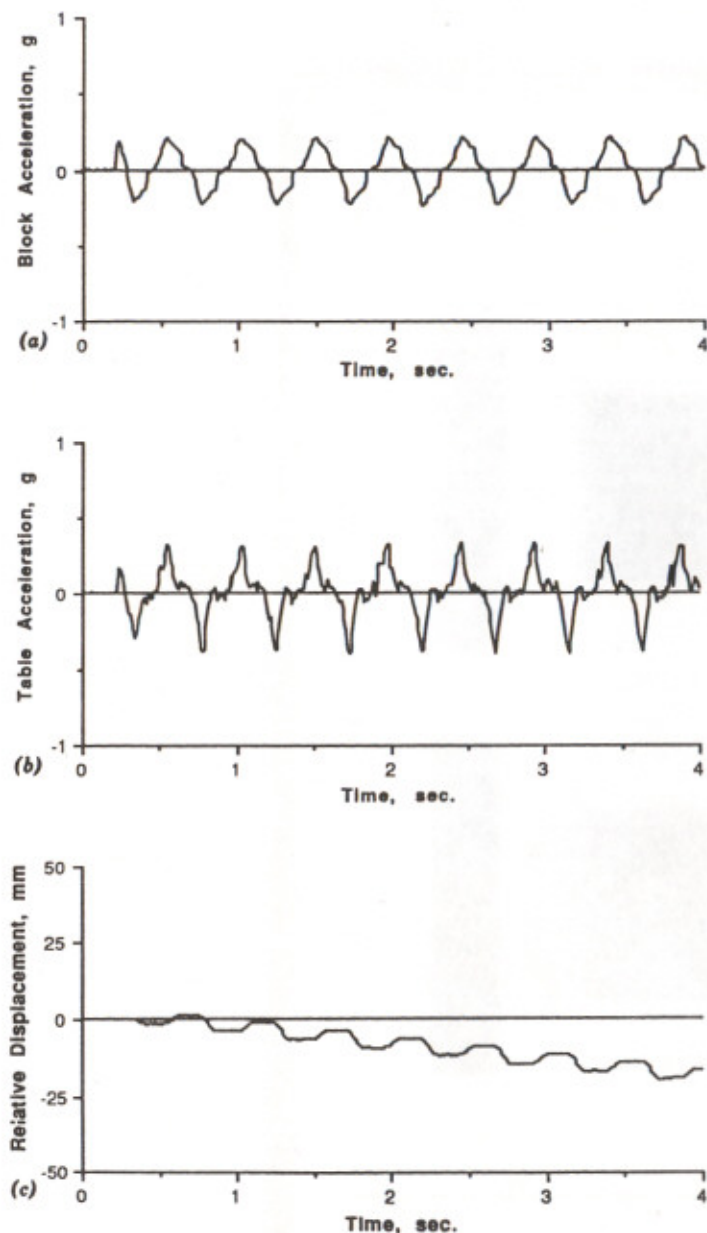


FIG. 7. Shaking-Table Test Results for Geomembrane-Geotextile Interface, Dry Condition: (a) Table-Acceleration Record with Peak Value of 0.40 g; (b) Block-Acceleration with Peak Value of 0.23 g; (c) Relative Displacement

dynamic characteristics of the interface shear properties between the geomembrane and the geotextile, as given by (4).

$$\phi_d = \tan^{-1} \frac{a_b}{g} \dots \dots \dots (4)$$

Fig. 6 shows typical test results that correspond to a peak table acceleration of about 0.13 g. Note that during this test the block acceleration was almost identical to that of the table and, therefore, no relative displacement between the geotextile and the geomembrane was recorded by the LVDT. This indicates that at 0.13 g there was a complete transfer of interface shear stress from the geomembrane to the geotextile. This is not surprising since under static loads and for dry conditions (Fig. 3), $\tan\phi$ was equal to $\tan(10.7^\circ) = 0.19$ at peak response, and $\tan(10^\circ) = 0.18$ at residual response.

Fig. 7 shows the results from another test performed under the same conditions as those for the test shown in Fig. 6, except that the peak table acceleration was larger. As is observed in Fig. 7(a), the table-acceleration pulses are not perfectly identical and symmetric about the zero-acceleration axis. Therefore, the peak table accelerations in all tests were computed by averaging the peak values of five pulses in the direction of larger acceleration. Also, this procedure was consistently followed for estimating the peak block acceleration, which occurred in all tests in the direction of higher table acceleration. For the test results shown in Fig. 7, the peak table acceleration was 0.4 g and the peak block acceleration was 0.23 g. Since the acceleration of the block was smaller than that of the table, a relative displacement, as shown in Fig. 7(c), along the geomembrane-geotextile interface (between the block and the table) was recorded by the LVDT. In this particular test, in which the table acceleration was 0.4 g, there was a 30% increase in the shearing resistance along the geomembrane-geotextile interface under the dynamic load, or an increase of $\tan^{-1}(0.23) - \tan^{-1}(0.18) \approx 3^\circ$ over the static residual friction angle. It is noted that the slight accumulation of relative displacement, shown in Fig. 7(c), is due to the inability of the experiment to produce perfectly symmetrical pulses.

Similar tests were performed for values of peak table acceleration ranging from 0.12 g to 0.4 g. A plot of the peak block acceleration versus the peak table acceleration is shown in Fig. 8. The tests were conducted for a dry geomembrane-geotextile interface condition with a normal stress of 8.5 kPa (1.2 psi), and a frequency of excitation of 2 Hz. The solid lines shown in Fig. 8 represent the least-squares fit of the data. A number of significant observations can be made from these and other similar results. The initial segment that has a slope angle of about 45° confirms that the block initially moves with the table (no sliding occurs between the geomembrane and the geotextile) up to a limiting table acceleration of about 0.20 g. This corresponds to a block acceleration, $a_b = 0.20$ g, or a friction angle of $\tan^{-1}(0.20) = 11.3^\circ$. It is noted that this value is only slightly higher than the peak friction angle of 10.7° measured from the static tests (Table 2). Immediately after sliding of the block is initiated the block acceleration invariably drops slightly. This reduction is attributed to the residual shear strength of the geomembrane-geotextile system, which is slightly smaller than the peak response as shown in Fig. 3 and Table 2. For the test results shown in Fig. 8, the block acceleration associated with the residual strength is about 0.19 g. This corresponds to a friction angle of $\phi_d = \tan^{-1}(0.19) = 10.7^\circ$, which is only slightly higher than the corresponding value of 10° , obtained from

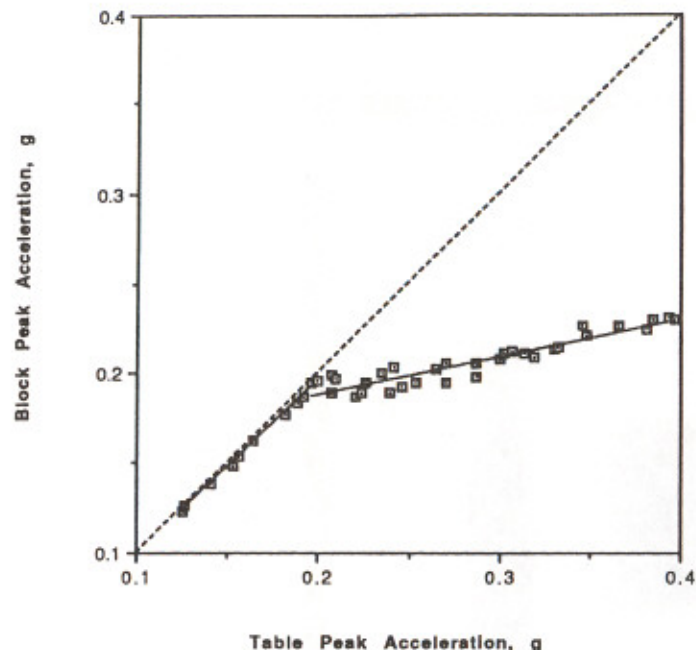


FIG. 8. Shaking-Table Test Results for Geomembrane-Geotextile Interface, Dry Condition, Normal Stress = 1.2 psi (8.5 kPa), Frequency of Excitation = 2 Hz

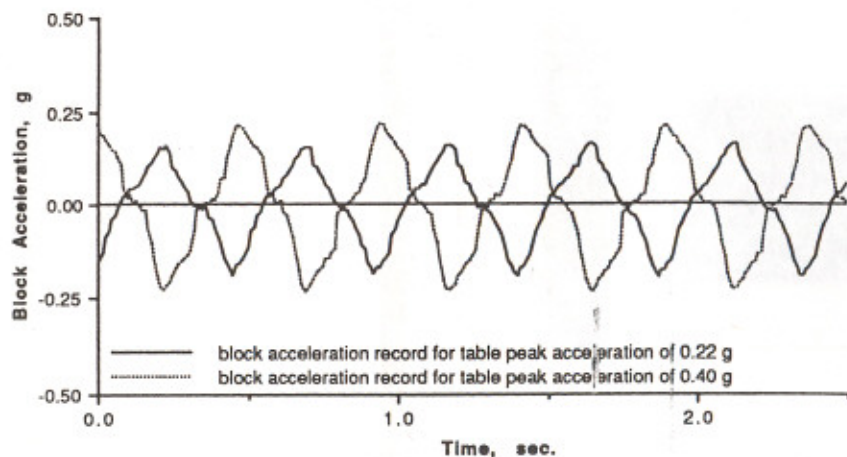


FIG. 9. Block-Acceleration Records, with Peak Values of 0.19 g and 0.23 g, Corresponding to Table Peak Accelerations of 0.22 g and 0.40 g, Respectively

the static tests (Table 2). The slight difference is within the accuracy of the experimental measurements.

The second segment of the regression line shown in Fig. 8 represents the behavior of the block for table accelerations greater than 0.20 g. In this

case, the block slides relative to the table; therefore, its acceleration is smaller than that of the table. However, the peak block acceleration increases slightly with increasing peak table acceleration. This leads to an increase in the computed residual friction angle from 10.7° to 13.5° within the range of peak table accelerations of 0.2–0.4 g. Such an observation was also made during shaking-table tests on model retaining walls by Lai (1979) and Jacobson (1980). Lai (1979) observed that the friction between sand and aluminum plate increased from 29° to 35° as the base acceleration increased from 0.05 g to 0.2 g. Similar tests were also performed by Jacobson (1980) between sand and an aluminum plate covered with sandpaper. The results obtained by Jacobson also indicate that the friction angle increased from 23° to 26° as the base acceleration increased from 0.09 g to 0.14 g.

Efforts were made in this research to explore the likely explanation for the observed slight increase in the peak block acceleration with increasing peak table acceleration beyond the onset of sliding. Initially, an examination was made to determine if this increase was related to the inability to produce perfectly symmetric table-acceleration pulses. Fig. 9 shows the block-acceleration responses corresponding to peak table accelerations of 0.22 and 0.4 g. The signals are purposely displayed with a shift in time to facilitate visual comparison. From Fig. 9 it is observed that the block-acceleration responses are slightly nonsymmetric. Yet, it is noted that on either side of the zero-acceleration axis, the peak block acceleration for peak table acceleration of 0.4 g is larger than that corresponding to 0.22 g. Hence, this slight increase in peak block acceleration cannot be attributed to the lack of symmetry in the pulses.

To determine if the slight increase in the dynamic interface shear strength (or i.e. in the block acceleration) with increasing table acceleration could be due to the effect of frequency upon the geomembrane-geotextile interface, the series of tests reported in Fig. 8 were repeated. In these tests, the frequency of the table motion was varied and the normal stress was maintained constant and equal to 8.5 kPa (1.2 psi). Fig. 10 shows the results for table-motion frequencies of 2, 5, and 10 Hz. The data indicate that the frequency of excitation, within the range investigated (2–10 Hz), has little effect upon the peak block acceleration. Furthermore, for each frequency investigated, the general tendency of the block acceleration to increase with increasing table acceleration could still be observed (Fig. 10).

Additional tests were also performed to evaluate the influence of the normal stress upon the dynamic interface friction angle. The tests were performed using different weights on the concrete block. To avoid the potential effect of the rocking inertia that might come into play as the weights are placed over the block, a maximum normal stress of 13.6 kPa (1.9 psi) was maintained. Fig. 11 shows these results for a constant frequency of 2 Hz. The general conclusion that can be made from Fig. 11 is that the increase in block acceleration with increasing table acceleration beyond the onset of sliding cannot be attributed to the potential effect of normal stress.

Finally, to evaluate the effect of dry versus submerged conditions of the geomembrane-geotextile system, the tests with varying frequency were repeated by submerging the geosynthetic medium in a tub placed on the shaking table. Fig. 12 shows the results, which are very similar to those obtained for dry conditions shown in Fig. 10, except that the data from submerged tests plot slightly but consistently lower than from the dry tests. Table 3 summarizes the results of these measured accelerations and the corresponding friction angles for both dry and submerged conditions.

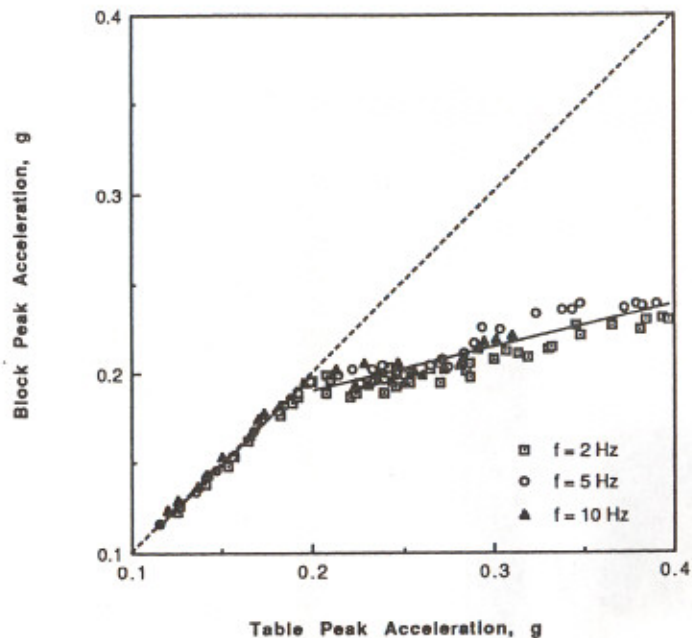


FIG. 10. Shaking-Table Test Results for Geomembrane-Geotextile Interface, Dry Condition, Normal Stress = 1.2 psi (8.5 kPa), Frequencies of Excitation = 2, 5, and 10 Hz

In summary, the following observations and conclusions are made from the shaking-table test results shown in Figs. 8–12, and summarized in Tables 2 and 3.

There is a limited shear stress, hence a limited acceleration, that can be transmitted from a geomembrane to a geotextile under dynamic excitation. Beyond this level, a relative displacement along the geomembrane-geotextile interface is initiated. Thus, concern about the dynamic response of a geotechnical facility, such as a waste containment that uses a geosynthetic system, should be primarily associated with the permanent displacement that may accumulate along the interface of the geosynthetics.

For the geomembrane (Gundle HD 60) and the geotextile (Polyfelt TS 700) used, the static interface residual friction angles for dry and submerged conditions are 10° and 8.5° , respectively. The corresponding values from the shaking-table tests, at the first observation of sliding, are 10.7° and 9.6° for dry and submerged conditions respectively. This indicates that, within the frequency range of 2–10 Hz, there is very little difference between the interface friction angles measured at the onset of sliding from the shaking table and those from static tests. The same observation was also made by Elgamal et al. (1990) for a sliding block with a sandpaper-covered base moving on a table coated with sandpaper. Therefore, shaking-table tests, for which large representative samples of geosynthetics can be easily used, can adequately provide values of the dynamic friction angles as well as values of the static interface peak and residual friction angles.

The dynamic interface friction angle slightly increases as the table acceleration is increased beyond the level required to initiate sliding between

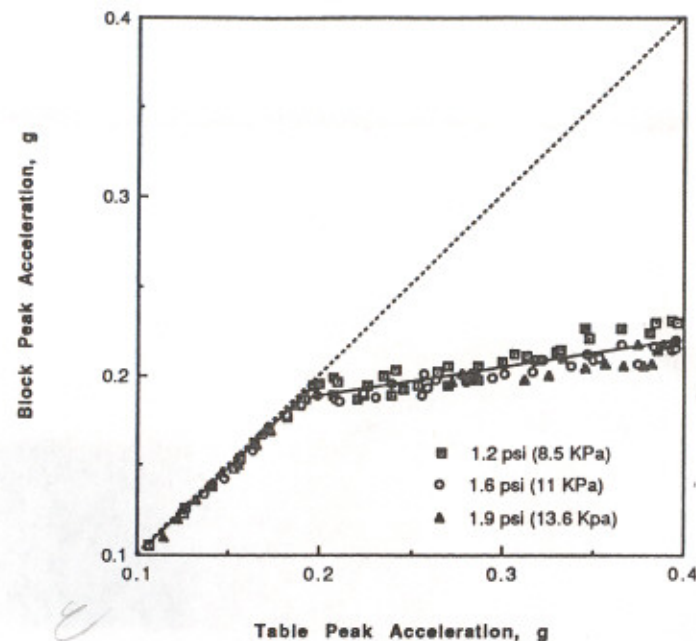


FIG. 11. Shaking-Table Test Results for Geomembrane-Geotextile Interface, Dry Condition, Normal Stress = 1.2, 1.6, and 1.9 psi (8.5, 11, and 13.6 kPa), Frequency of Excitation = 2 Hz

the geomembrane and the geotextile (Table 3). This slight increase could neither be attributed to experimental conditions nor potential effects of frequency and normal stress. Similar observations have been made by other investigators. Further studies are needed to provide a likely explanation for this observation.

Submergence of the geosynthetics during the shaking-table tests had the same effect as that observed in the static tests. The average value of the friction angle for the submerged condition was about 1° smaller than that for the dry condition.

GEOSYNTHETICS AS BASE ISOLATION

The results of the shaking-table tests performed on a geomembrane-geotextile system clearly show that there is a limiting value for the shear stress than can be transmitted from a geomembrane to a geotextile. Thus, any structure, or a soil deposit that is resting on the geotextile, can experience only a limiting acceleration, beyond which relative displacement will be initiated along the geomembrane-geotextile interface. This limiting acceleration for the geosynthetics that were used in this research (Gundle HD 60 and Polyfelt TS 700) ranged between 0.2 g and 0.24 g. Hence, a geomembrane-geotextile or a smooth geomembrane-geomembrane system can act as a base isolator during earthquakes. Such a system can limit, in the plane of the geosynthetic, the transfer of energy to a structure or a soil mass placed on top of the geotextile or on a second layer of geomembrane, and

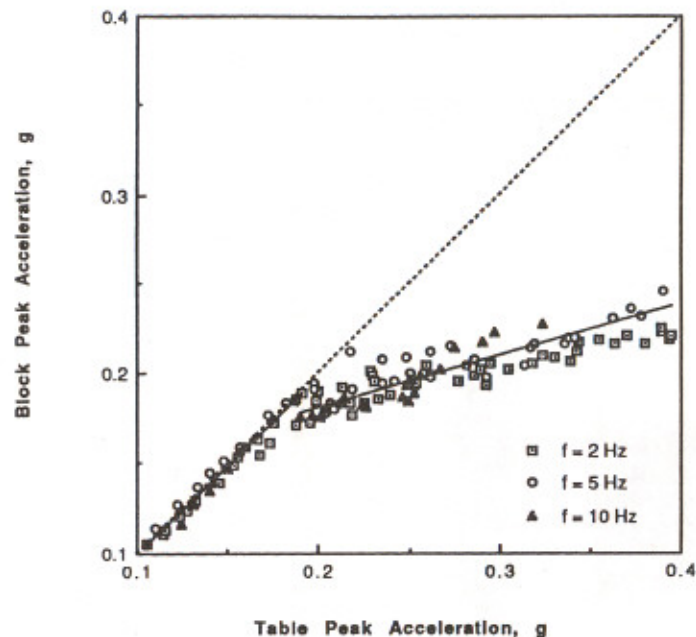


FIG. 12. Shaking-Table Test Results for Geomembrane-Geotextile Interface, Submerged Condition, Normal Stress = 1.2 psi (8.5 kPa), Frequencies of Excitation = 2, 5, and 10 Hz

TABLE 3. Measured Dynamic Angles of Friction

Interface condition (1)	Acceleration transmitted to block at first observation of sliding (2)	Peak dynamic friction angle (3)	Acceleration transmitted to the block after sliding is initiated (4)	Residual dynamic friction angle (5)
Geomembrane ^a /geotextile ^b dry	0.2 g	11.3°	0.19 g ^c -.24 g ^d	10.7-13.5°
Geomembrane ^a /geotextile ^b submerged	0.19 g	10.7°	0.17 g ^c -.23 g ^d	9.6-13°

^aGundle HD60: hard, smooth HDPE.

^bPolyfelt TS700: Nonwoven, continuous filament, needlepunched geotextile.

^cAt first observation of sliding.

^dAt table acceleration of 0.4 g.

can dampen it through frictional losses, as one geosynthetic slides over the other.

The purpose of seismic base isolation of a structure is to achieve a discontinuity between the ground and the structure so as to limit the levels of transmitted forces and acceleration from the ground to the structure. The concept of base isolation has been around for quite some time. In fact, Buckle and Mayes (1990) reported that designs for an earthquakeproof

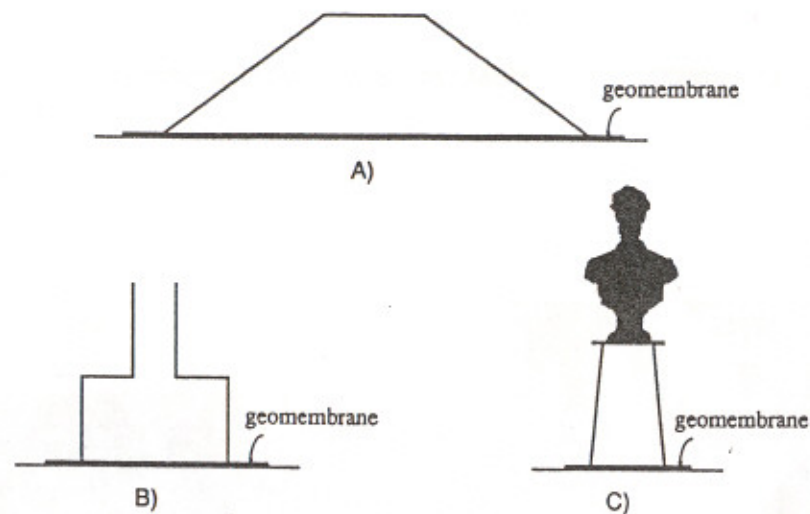


FIG. 13. Geomembrane Used for Base Isolation: (a) Embankment; (b) Spread Footing; (c) Slender Object Vulnerable to Toppling

building sitting freely on a mass of spherical bodies of hard material were proposed in 1906. Other isolation systems for structures have been proposed, offering varying degrees of feasibility and practicality. Mayes et al. (1984, 1990) have described successful applications of a lead-rubber bearing for isolation of buildings. These and many other base-isolation schemes reported in the literature have been devised primarily for structures. It is worthwhile to explore the potential application of base isolation for geotechnical facilities as well.

The application of geosynthetics as base isolators in geotechnical earthquake engineering can be cost-effective, especially in high-seismicity regions. For example, a horizontally placed geosynthetic system that can limit the transmitted acceleration to 0.2 g can be of major benefit in seismic hazard mitigation for embankments since most such facilities can adequately withstand 0.2 g. Of course, associated with this benefit is that along the geosynthetic interface permanent displacements will accumulate. However, the level of permanent displacement associated with such a geosynthetic base isolation during an earthquake causing a peak ground acceleration as large as 0.5 g, would be less than a few inches, as can be observed from Newmark's (1965) results on permanent deformations that can accumulate along a horizontal sliding surface.

Fig. 13 describes other possible applications of geosynthetics as base isolation, including spread footing or mat foundation; and slender objects that are vulnerable to toppling such as museum artifacts, statues, and equipment. To demonstrate the concept of using geosynthetics as base isolation, the example of slender objects that have the tendency to topple during earthquakes was selected. Shaking-table tests were performed on stiff cylindrical models made of aluminum of diameter D , equal to 1.5 in., and having varying height, H . Initially, the models were tested by simply placing them on the aluminum surface of the shaking table covered with masking tape to increase the sliding friction. Subsequently, the tests were repeated

after pieces of geomembrane were glued to the bases of the models, which were then placed on a sheet of geomembrane fixed to the shaking table. Fig. 14 shows the two experimental conditions described.

For a model to experience toppling, its base has to first lift-off and tilt along the edge. This will occur when the momentum from the horizontal inertial force is equal to the restoring moment associated with the weight of the model. From Fig. 14(a), the limiting value of the table acceleration,

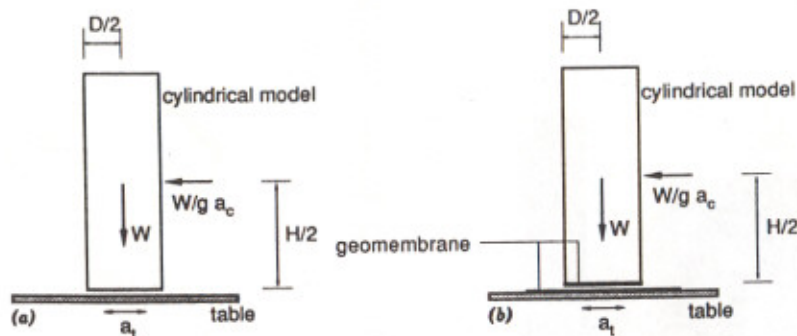


FIG. 14. Toppling Test Model: (a) Without Geomembrane, $a_c = a_t$, Complete Transfer of Shear from Table to Model; (b) With Geomembrane as Base Isolation, $a_c < a_t$

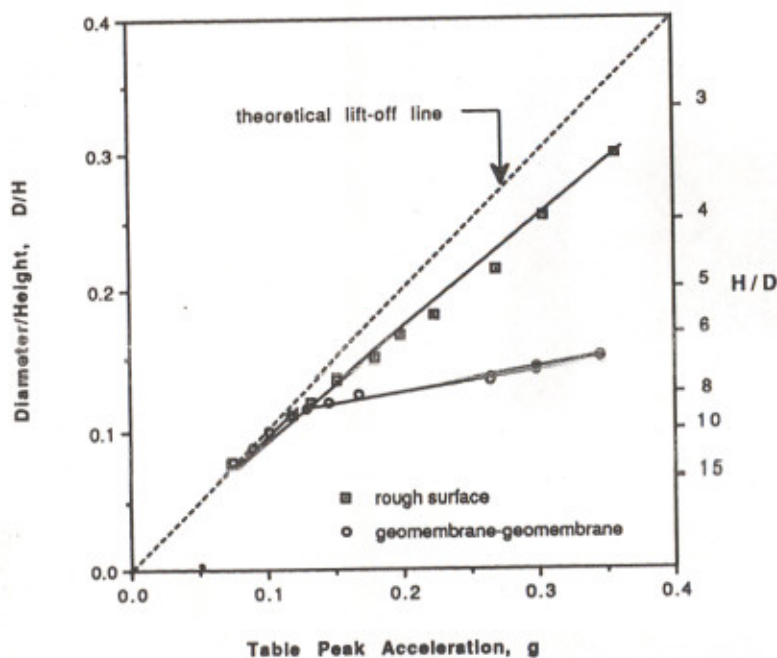


FIG. 15. D/H Ratio versus Peak Table Acceleration Causing Toppling of Rigid Cylinders

a_t , greater than that at which lift-off or tilting is initiated, can be obtained by equating the moment from the horizontal inertial force with the restoring moment from the weight

$$\frac{W}{g} a_c \frac{H}{2} = W \frac{D}{2} \quad \dots \dots \dots (5)$$

Since for prior to lift-off there is complete transfer of shear from the table to the cylinders, the acceleration of the cylinder is equal to the acceleration of the table

$$a_t = a_c \quad \dots \dots \dots (6)$$

thus combining (5) and (6), gives

$$\frac{a_t}{g} = \frac{D}{H} \quad \dots \dots \dots (7)$$

Eq. (7) expresses the value of the table acceleration at which the model lifts-off as a function of the D/H ratio of the model.

Fig. 15 shows the theoretical lift-off line given by (7). Because of the reversal in the direction of the acceleration pulse, for a model to topple a higher table acceleration than that given by the lift-off line will be required. This is confirmed by the results shown in Fig. 15 for tests on models that were simply placed on the table without geomembrane and subjected to pulses with a frequency of 2 Hz, similar to those shown in Fig. 7(a). For example, the model having a D/H ratio of 0.18 did not topple until the table acceleration was 0.23 g. The square data points in Fig. 15 correspond to the limiting table acceleration larger than that at which the models placed on the table (with a rough surface) toppled.

Fig. 15 also shows the shaking-table test results on the models that were placed on a geomembrane-geomembrane interface. For values of the ratio (D/H) less than about 0.12, the models with a geomembrane-geomembrane interface and those placed on a rough surface performed identically, always toppling when the acceleration of the table, a_t , was slightly higher than the ratio (D/H). This signifies that the geomembrane-geomembrane interface was capable of transmitting these small levels of acceleration that could cause toppling of objects with a ratio (D/H) less than 0.12. For models with (D/H) ratios larger than 0.12, the results from the geomembrane-geomembrane interface tests were dramatically different from those corresponding to a rough interface. At accelerations greater than 0.12 g, sliding of the models occurred along the geomembrane-geomembrane interface, thus limiting the transfer of acceleration from the table to the model, and significantly reducing the tendency of the models to topple. In fact, models having (D/H) ratios greater than 0.18, that toppled at 0.23 g on the rough surface, could not be toppled with a geomembrane-geomembrane interface for a table acceleration as high as 0.5 g.

From the test results shown in Fig. 15, the following conclusions are made.

The friction angle for a smooth HDPE geomembrane-geomembrane interface can be as low as $\phi_d = \tan^{-1}(0.12) \approx 7^\circ$, which agrees with the values reported for static tests by Mitchell et al. (1990), Yegian and Lahlaf (1992), and Lahlaf (1991).

Once sliding occurred, for the models that had a geomembrane-geomembrane interface the (D/H) ratios of the models that could be toppled slightly increased with increasing table acceleration, indicating the transfer of slightly

higher shear forces through the interface. This observation is consistent with the results presented in Figs. 8–12, where a slight increase in the interface shearing resistance was measured with increasing base acceleration.

A geomembrane-geomembrane interface can be used to isolate the base motion that can be transmitted to slender objects having the tendency to topple. The test results indicate that the models having (D/H) ratios greater than 0.18 (i.e. H/D less than approximately 6) safely experienced a base motion as large as 0.5 g without toppling if isolated by two layers of smooth HDPE geomembrane. This conclusion can be used for a prototype if the model-scale effect on the table frequency of 2 Hz is considered.

CONCLUSION

Shaking-table test results on the dynamic interface shear properties of a geomembrane and a geotextile were presented. The following observations and conclusions are made from this research.

Under dynamic excitation, the shear stress that can be transmitted from a geomembrane to a geotextile is limited. Beyond this level, relative displacement along the geomembrane-geotextile interface accumulates. Hence, concern about the dynamic response of a geotechnical facility, such as a waste containment that uses such geosynthetic systems, should primarily be associated with the permanent relative displacement that may accumulate along the interface between the two geosynthetics.

There is no significant difference between the dynamic interface friction angle measured at the onset of sliding from the shaking-table tests and those from static tests. Therefore, shaking-table tests can be adequately used to investigate both the dynamic and static interface properties of geosynthetics. Shaking-table tests also facilitate the use of large and representative samples of geosynthetics.

Once sliding is initiated along the geosynthetic interface, the shear stress transmitted slightly increases with increasing table acceleration. This increase in the shear stress, and thus in the dynamic interface angle of friction, for larger table accelerations could not be attributed to the table-motion frequency or normal stress. The reason for this increase needs to be further investigated.

The effect of submergence of the geosynthetics during the shaking-table tests was similar to that observed during the static tests. The interface angle of friction for the submerged condition was slightly but consistently smaller (by about 1°) than that for the dry condition.

The dynamic angle of friction for a smooth HDPE geomembrane-geomembrane interface can be as low as 7°. Such low frictional properties can make geosynthetics very appealing material for base isolation in seismic-hazard mitigation. To illustrate this concept, a geomembrane-geomembrane interface was used on the shaking table to isolate the base motion transmitted to slender models that had the tendency to topple. The test results indicate that models with a height-to-diameter ratio of up to 6 could not be toppled at table accelerations as high as 0.5 g at 2 Hz when placed on two layers of HDPE geomembrane.

The writers propose that this innovative application of geosynthetics be further explored. It is likely that new material products can be developed that can provide varying degrees of base isolation in the plane of the geosynthetics for different applications in earthquake hazard mitigation.

ACKNOWLEDGMENTS

The research reported in this paper was partially funded by the Stone and Webster Corporation and the National Science Foundation. The writers express their appreciation for this support. Gratitude is also extended to C. Ung and E. A. Marciano for their valuable comments and to M. Yassin and D. Whelpley for their assistance with the experimental setup.

APPENDIX I. REFERENCES

- Buckle, I. G., and Mayes, R. L. (1990). "Seismic isolation: History, application, and performance—a world view." *Earthquake Spectra*, 6(2), 161–202.
- Elgamal, A.-W. M., Scott, R. F., Succarieh, M. F., and Yan, L. (1990). "La Villita dam response during five earthquakes including permanent deformations." *J. Geotech. Engrg.*, ASCE 116(10), 1443–1462.
- Jacobson, P. N. (1980). "Translational behavior of gravity retaining walls during earthquakes." *M. E. Report 80/9*, University of Canterbury, Canterbury, New Zealand.
- Lai, C. S. (1979). "Behavior of retaining walls under seismic loadings." *M. E. Report 79/9*, University of Canterbury, Canterbury, New Zealand.
- Lahlaf, A. M. (1991). "Dynamic interface shear strength properties between geomembranes and geotextiles," PhD thesis, Graduate School of Northeastern University, Boston, Mass.
- Martin, J. P., Koerner, R. M., and Whitty, J. E. (1984). "Experimental friction evaluation of slippage between geomembranes, geotextiles, and soils." *Proc. Int. Conf. on Geomembranes*, Industrial Fabrics Association International, Denver, Colo., 191–196.
- Mayes, R. L., Jones, L. R., Kelly, T. E., and Button, M. R. (1984). "Design guidelines for base isolated buildings with energy dissipators." *Earthquake Spectra*, 1(1), 41–74.
- Mayes, R. L., Kelly, T. E., and Jones, L. R. (1990). "Seismic isolation: An economic alternative for seismic design and rehabilitation of buildings and bridges." *J. Boston Society of Civ. Engrs.*, 5(1), 7–30.
- Mitchell, J. K., Seed, R. B., and Seed, H. B. (1990). "Kettleman Hills waste landfill slope failure. I: Liner-system properties." *J. Geotech. Engrg.*, ASCE 116(4), 647–668.
- Miyamori, T., Iwai, S., and Makiuchi, K. (1986). "Frictional characteristics of non-woven fabrics." *Proc., 3rd Int. Conf. on Geotextiles*, Vienna, Austria, 701–705.
- Myles, B. (1982). "Assessment of soil fabric friction by means of shear." *Proc. 2nd Conf. on Geotextiles*, Las Vegas, Nev., 787–791.
- Negussey, D., Wijewickreme, W. K. D., and Vaid, Y. P. (1989). "Geomembrane interface friction." *Canadian Geotech. J.*, 26(Feb.), 165–169.
- Newmark, N. M. (1965). "Effects of earthquakes on dams and embankments." *Geotechnique*, London, England, 15(2), 139–160.
- O'Rourke, T. D., Druschel, S. J., and Netravali, A. N. (1990). "Shear strength characteristics of sand-polymer interfaces." *J. Geotech. Engrg.*, ASCE, 116(3), 451–469.
- Saxena, S. K., and Wong, Y. T. (1984). "Frictional characteristics of a geomembrane." *Proc. Int. Conf. on Geomembranes*, Denver, Colo., 187–190.
- Williams, N. D., and Houlihan, M. (1986). "Evaluation of friction coefficients between geomembranes, geotextiles and related products." *Proc., 3rd Int. Conf. on Geotextiles*, Vienna, Austria, 891–896.
- Yegian, M. K., and Lahlaf, A. M. (1992). "Discussion of 'Kettleman Hills waste landfill slope failure. I: Liner-system properties.'" *J. Geotech. Engrg.*, ASCE, 118(4), 643–645.