Technical Paper by M.K. Yegian and U. Kadakal

GEOSYNTHETIC INTERFACE BEHAVIOR UNDER DYNAMIC LOADING

ABSTRACT: The seismic stability of earth slopes, embankments, and landfills that incorporate geosynthetics has been receiving increased attention in geotechnical engineering practice. In the analysis of such structures, the dynamic interface shear properties play important role. The authors have been conducting research to understand the dynamic response of various geosynthetic-geosynthetic and geosynthetic-soil interfaces. This paper presents an overview of the research including: a description of the shaking table facility and the experimental setup developed; typical test results and discussions; and a description of a constitutive model for a geosynthetic-geosynthetic interface that can be used in wave propagation analysis of soil and landfill liner systems that incorporate geosynthetics.

KEYWORDS: Slip deformation, Geosynthetic liner, Shaking table test, Geomembrane, Geotextile, Instrumentation, Seismic response, Landfill.

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1 INTRODUCTION

During the past decade, the use of geosynthetics in civil engineering applications has experienced tremendous growth. Among the many different applications, geosynthetics are used for filtration, for soil strength improvement, and as impervious barriers. During the earlier applications of geosynthetics in civil engineering projects, the static shear strength properties of geosynthetic-soil and geosynthetic-geosynthetic interfaces were of major importance. Research in this area was rapidly advanced, and standardized testing procedures were developed to determine experimentally the static friction angles of geosynthetic interfaces. Static interface friction angles of commonly used geosynthetics are widely published in the peer-reviewed technical literature.

Geosynthetics are commonly used in municipal solid waste landfills. Typically, geomembranes are used as impervious barriers along the bottom and top of landfills. Starting in the early 1990s, the seismic response of landfills became of major importance to owners, design engineers, and local state and federal regulatory agencies. In fact, in 1993, the United States Environmental Protection Agency (USEPA 1992) required that new landfills, located in certain seismic impact zones, where there is more than 10% chance in 250 years that the peak ground acceleration may exceed 0.1g, be designed to withstand earthquake-induced ground motions. Since almost all new landfills incorporate geosynthetics as impervious barriers, the dynamic shear strength properties of these geosynthetic interfaces have become important.

For a number of years, the authors of the current paper have been conducting research focused on understanding the dynamic shear behavior of geosynthetic-geosynthetic and geosynthetic-soil interfaces (Yegian et al. 1995a,b). This research has evolved from developing an experimental test facility and setups, testing of geosynthetic interfaces, and understanding the dynamic behavior of interfaces, to modeling of such behavior in the seismic analysis of landfills incorporating geosynthetics. The current paper provides a description of a shaking table facility and data acquisition system that are used in the estimation of the dynamic interface shear strength of a smooth geomembrane-geotextile interfaces. Typical test results are included and discussions are presented that describe the interface behavior under cyclic, as well as earthquake excitations. Finally, a brief description of an analytical model is presented that simulates the earthquake response of landfills, or soil profiles, that incorporate geosynthetics.

2 SHAKING TABLE FACILITY

Figure 1 shows the shaking table facility utilized in the investigation of the dynamic interface shear behavior of geosynthetics. The table top is made of a 1.22 m $\times$ 1.83 m $\times$ 0.25 m aluminum plate that slides horizontally on pillar block bearings. A hydraulic actuator with a capacity of 49 kN drives the table with a stroke of $\pm$ 150 mm (peak-to-peak). The table motion is controlled by a controller unit (Figure 2) which sends a displacement-proportional electrical signal to the actuator. A built-in function generator is used for harmonic table excitations, while transient-type motions are provided by a personal computer-based data acquisition system. The "Labtech Notebook" data acquisition software is used along with a 16-bit resolution data acquisition card. Table mo-

Figure 1. Photograph of the shaking table setup.

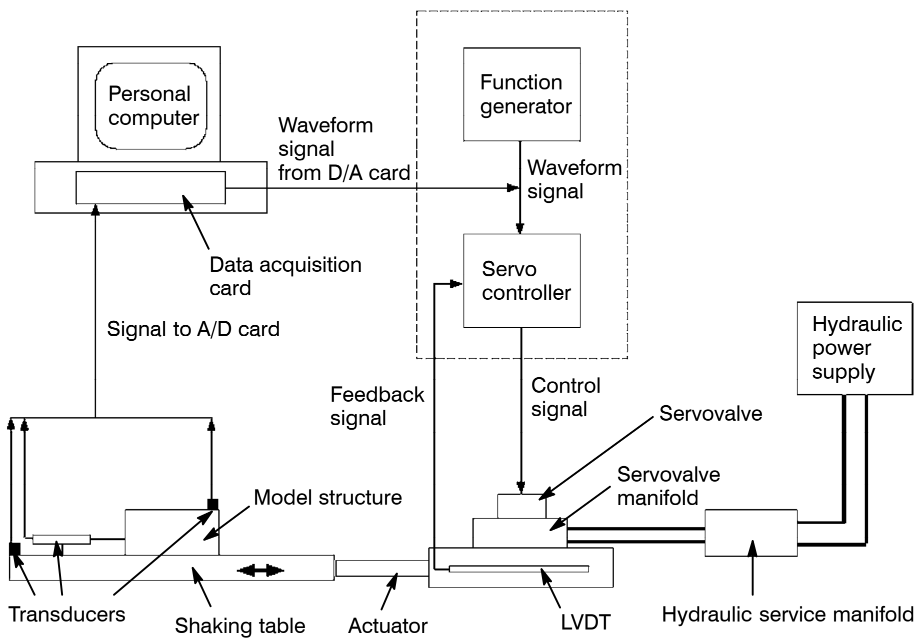

Figure 2. Schematic diagram of the shaking table setup.
Notes: D/A = digital/analog signal conversion; A/D = analog/digital signal conversion.

tion is monitored using an accelerometer and a linear variable displacement transducer (LVDT). The type of sensors used in the current research has varied.

3 EXPERIMENTAL SETUP AND INSTRUMENTATION

A 1.5 mm (60 mil) thick, smooth HDPE geomembrane manufactured by the National Seal Company and a heat-bonded nonwoven geotextile (Typar 3601) were used for the geosynthetic-geosynthetic interface tests reported in the current paper.

Two different setups were developed to test horizontal geosynthetic-geosynthetic and geosynthetic-soil interfaces. One setup was used for conducting cyclic, displacement-controlled tests on interfaces. The other setup was to measure the dynamic shear strength properties along an interface.

Figure 3 shows a schematic diagram of the experimental arrangement used in the measurement of the cyclic shear resistance of a geosynthetic-geosynthetic interface.

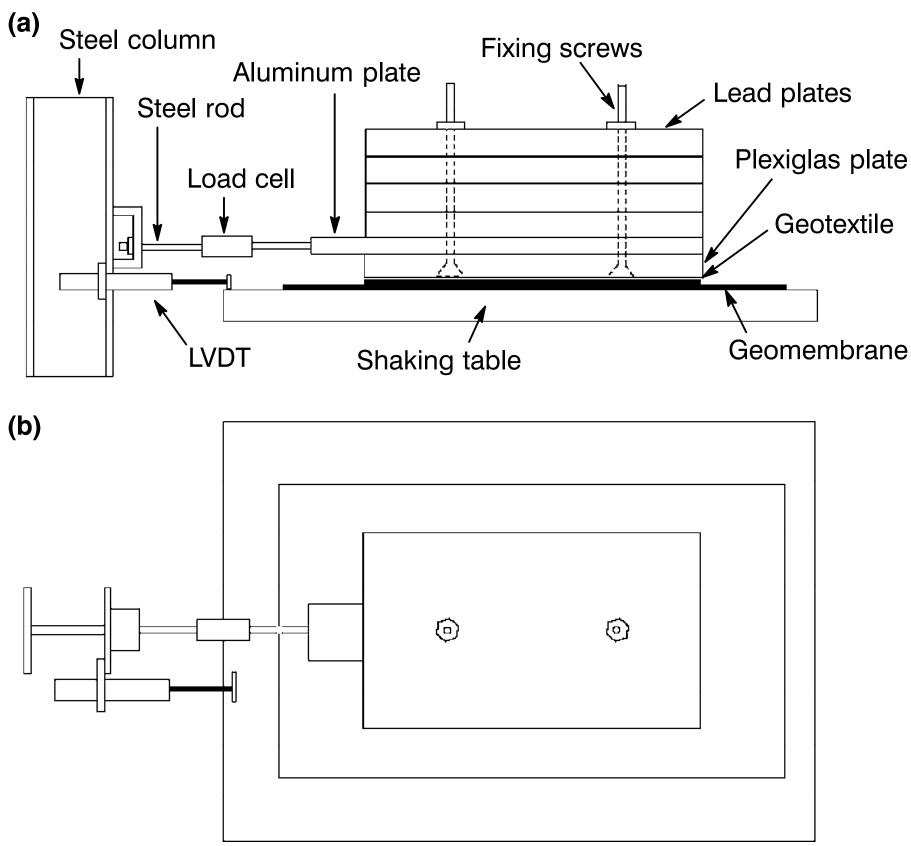

Figure 3. Schematic diagram of the cyclic load test for geosynthetic-geosynthetic interfaces: (a) side view; (b) plan view.

This setup consists of a Plexiglas plate (200 mm × 300 mm) connected to a steel column through a steel rod with a load cell attached. A large geosynthetic sheet (400 mm × 600 mm) is fastened on the shaking table using double-sided tape. Similarly, the other geosynthetic is fastened to the Plexiglas plate. Several lead plates are placed on the Plexiglas plate to provide the necessary normal stress. The steel column keeps the Plexiglas plate stationary while the shaking table moves, transferring the frictional force developed in the interface to the steel rod. This force is measured by the load cell. An LVDT is also attached between the table and the steel column and measures the corresponding displacements. The motion of the shaking table is generally selected to be a triangular pulse of variable frequency. The reason for selecting a triangular pulse is the fact that the friction coefficient is known to be a function of velocity (Oden and Martins 1985). Sinusoidal excitations are generally used to identify the force-displacement (or stress-strain) behavior of dynamic systems and interfaces; however, frictional interfaces possess properties that are highly dependent on sliding velocities (Oden and Martins 1985). These properties include friction coefficients and stick-slip amplitudes and frequencies. Therefore, triangular excitation is more appropriate to apply because it results in constant sliding velocities. Table excitation consists of five full triangular cycles that are ±25 mm in amplitude. The sliding velocity is controlled by changing the frequency of the triangular table motion.

To simulate the dynamic loads induced through ground motions, a rigid block test setup was devised as shown in Figure 4. In this setup, the steel rod in the previous test is removed, allowing the block (lead and Plexiglas plates) to move freely with the motion of the shaking table. An accelerometer is attached to the block to measure the accelerations transmitted to the block. An LVDT and a relative velocity sensor are also attached to the block to measure the relative displacement and relative velocity of the block. The shaking table is excited by harmonic motions of variable amplitudes and frequencies. Typical tests are run with acceleration amplitudes varying between 0.1g and 1.0g, and for frequencies of 1, 2, and 5 Hz. Similarly, the shaking table can also be excited by transient (earthquake) motions to simulate dynamic forces and slip induced by earthquake ground motions.

In both the cyclic displacement-controlled and the dynamic load test setups, the Plexiglas assembly can be replaced by a soil box that is designed to measure the dynamic frictional properties of geosynthetic-soil interfaces. This box (340 mm × 240 mm × 140 mm) is made of Plexiglas with its top and bottom open. In a typical test, the box is placed on a geosynthetic sheet fixed to the shaking table. A thin layer of soil is compacted and lead weights are placed on top of the soil to provide the necessary normal stress.

In earlier research on geosynthetic interfaces (Yegian et al. 1995a,b), the accelerations were measured with the commonly used piezoelectric accelerometers (B&K Type 4379 with a ±500g dynamic range and 0.1 to 2800 Hz frequency range). These accelerometers utilize a piezoelectric element that produces a charge proportional to base motions; hence, a piezoelectric accelerometer does not require an input current. However, the response of a piezoelectric accelerometer is inadequate in the low-frequency range. In other words, they are unable to measure constant accelerations (0 Hz frequency) typically experienced by a rigid block sliding freely on a smooth surface such as a smooth geomembrane. Therefore, a piezoelectric accelerometer, used in experiments where there is sliding, cannot measure the accelerations accurately. In the recent research performed by the authors of the current paper, capacitive-type accelerometers

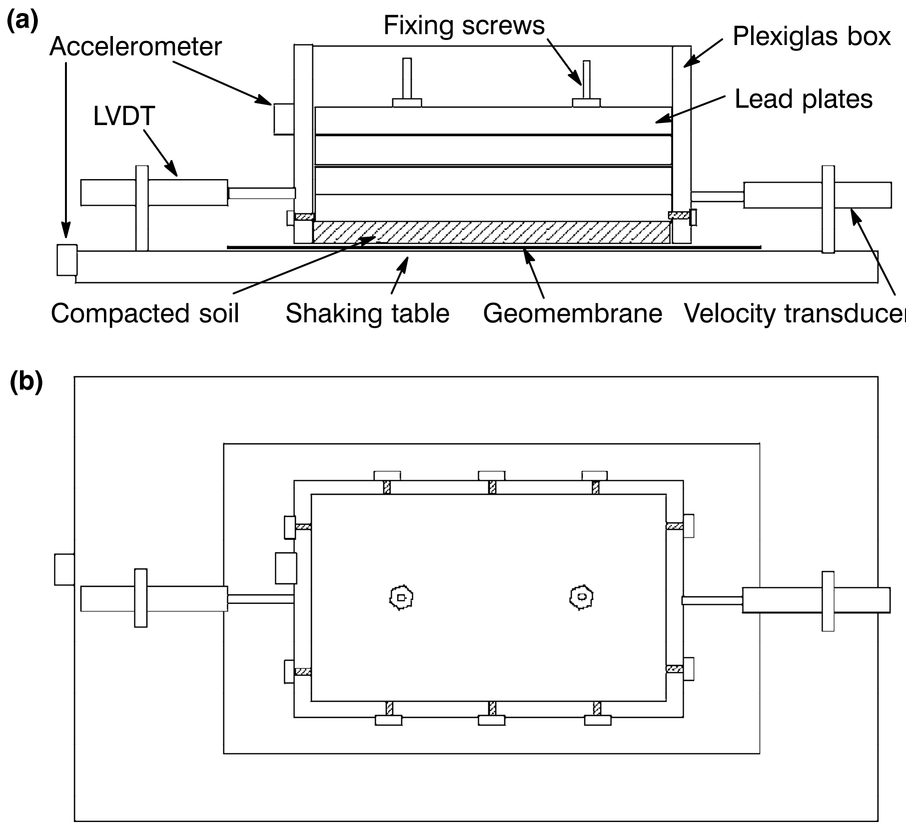

Figure 4. Schematic diagram of the rigid block test for geosynthetic-soil interfaces: (a) side view; (b) plan view.

(Kistler K-beam type with ± 2g dynamic range) have been used. The sensing element in a capacitive accelerometer was micromachined from a single silicon crystal and then electrostatically bonded to form a parallel plate capacitive device. The transducer is therefore sensitive to DC acceleration input that makes it ideal for measuring constant accelerations experienced in rigid block tests of geosynthetic interfaces, but requires an input voltage. Example test results are presented in Section 4 to illustrate the difference in the response measured by piezoelectric and capacitive accelerometers.

To demonstrate the inadequacy of using piezoelectric accelerometers, block accelerations measured with piezoelectric- and capacitive-type accelerometers are compared. It is noted in Figure 5 that capacitive accelerometers do capture the constant acceleration region during slip and the stick-slip behavior, but piezoelectric accelerometers distort the step-shaped trace leading to overestimated peak block accelerations.

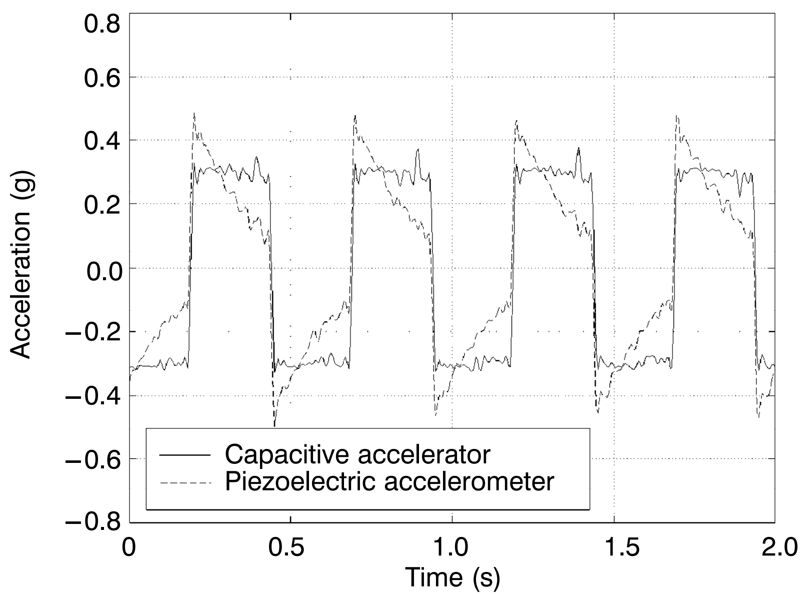

Figure 5. Comparison of typical block acceleration records measured by capacitive and piezoelectric accelerometers.

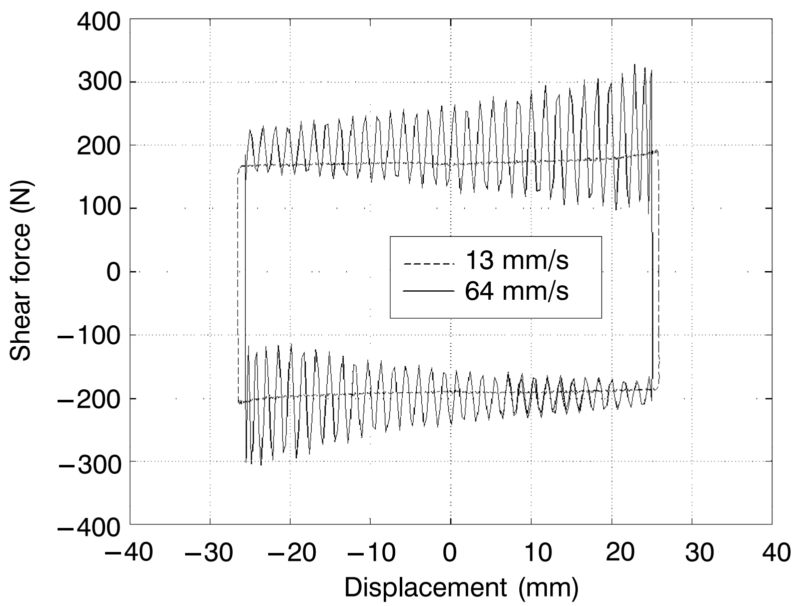

Figure 6. Typical force-displacement cycles obtained from cyclic load tests showing the stick-slip motion on a smooth HDPE geomembrane-nonwoven geotextile interface during displacement rates of 13 and 64 mm/s.

Note: The geomembrane and the geotextile are defined in Section 3.

4 TYPICAL TEST RESULTS

Figure 6 shows typical test results obtained from a cyclic load test on a smooth HDPE geomembrane-nonwoven geotextile interface. The normal force on the block was 712 N yielding a normal stress of 11.7 kN/m^2. The shear displacement was applied by the shaking table at displacement rates of 13 and 64 mm/s corresponding to frequencies of 0.13 and 0.63 Hz triangular excitation, respectively. Data was sampled at a rate of 200 Hz. The force-displacement relationship clearly shows a stick-slip behavior along the smooth geomembrane-nonwoven geotextile interface at a faster displacement rate, while a very smooth hysteresis loop was obtained for the displacement rate of 13 mm/s. The fluctuation in the shear force transmitted due to stick-slip behavior is a maximum when the the base displacement reverses. Because of this stick-slip behavior, the calculation of the cyclic friction angle is difficult.

Friction coefficients can be obtained from the cyclic load test results presented in Figure 6. The residual shear force can be approximately obtained from the graph as 170 N, for a velocity of 13 mm/s. The friction coefficient can then be calculated to be 0.24 by dividing the shear force (170 N) by the normal force (712 N). Similarly, a friction coefficient of 0.27 (= 190/712) can be calculated for a velocity of 64 mm/s. The slight difference between the friction coefficients indicates a velocity dependence. Static friction coefficients of approximately 0.2, obtained from direct shear tests on various HDPE geomembrane-nonwoven geotextile interfaces (Williams and Houlihan 1986; Mitchell et al. 1990), also support the velocity dependence phenomenon, because these tests are usually conducted at very low velocities (0.0004 mm/s).

Figure 7 shows typical shaking table test results for the rigid block setup and the smooth geomembrane-nonwoven geotextile interface. In this example, accelerations were measured with capacitive accelerometers. The results show that under a table acceleration of 0.6g, the transmitted acceleration to the block was limited to approximately 0.3g. This indicates that there is a limiting shear stress that can be transmitted through a geomembrane-geotextile interface. This limiting shear stress will limit the acceleration that is transmitted through the interface to the block. If the table acceleration exceeds this limiting yield acceleration, relative displacement (slip) will occur along the interface (Figure 7). The friction coefficient of the interface can be back-calculated from the measured transmitted accelerations. Assuming the interface material is perfectly rigid, the following equation of motion applies to the rigid block:

$$M\ddot{u} \pm Mg\mu = 0 \tag{1}$$

where: M = mass of the rigid block; $\ddot{u}$ = absolute acceleration of the rigid block; μ = friction coefficient; and g = acceleration due to gravity. Equation 1 indicates that the friction coefficient is equivalent to the absolute acceleration of the block. Therefore, measured transmitted accelerations of 0.3g correspond to a friction coefficient of 0.3. This value is also comparable to the friction coefficients of 0.24 and 0.27 obtained from cyclic load tests. Stick-slip motion is also observed on the sections of constant block acceleration (plateau sections of the curves in Figure 7) where sliding takes place.

Figure 8 shows a second example of a test result obtained from a shaking table test on a smooth HDPE geomembrane-nonwoven geotextile interface. In this test, the capacitive type accelerometer was again used to demonstrate the stick-slip behavior of

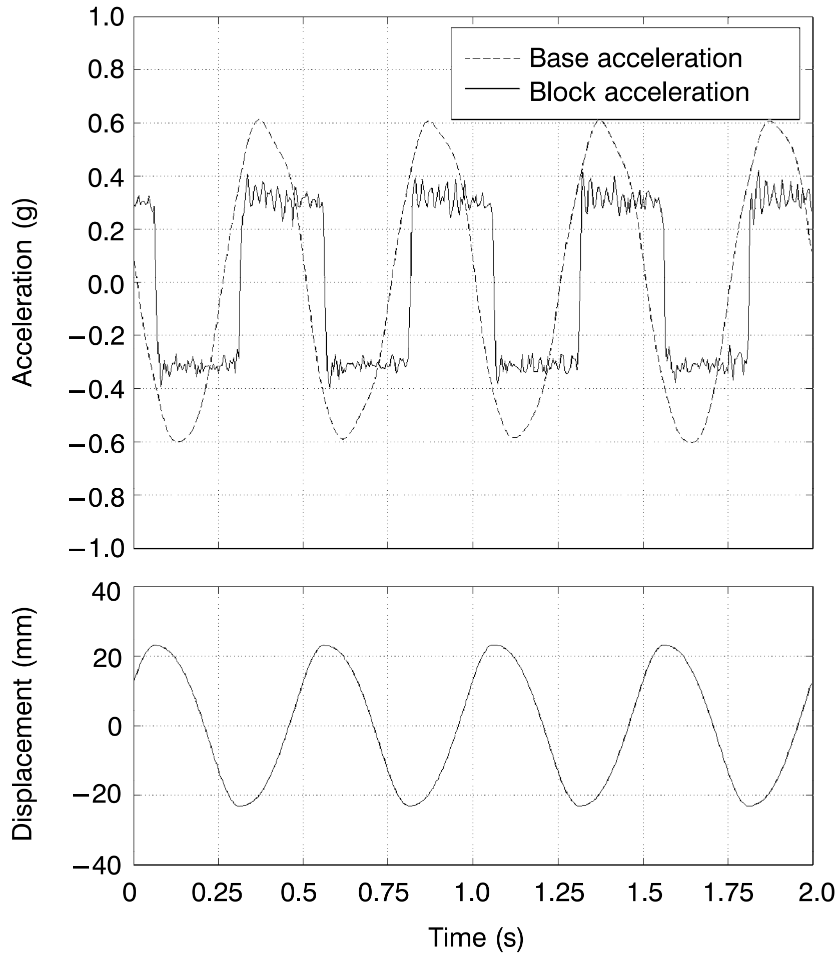

Figure 7. Typical rigid block test result with stick-slip motion under a sinusoidal base excitation of 2 Hz frequency and 0.6g acceleration for a smooth HDPE geomembrane-nonwoven geotextile interface.

the rigid block under dynamic loads, which is similar to that observed under a cyclic load. Again, the estimation of the yield acceleration (limiting acceleration transmitted through the interface) is difficult because of significant variation in the block accelerations during the time of slip.

A number of procedures were explored to determine the most reasonable method of estimating the yield acceleration, one of which was low-pass filtering of the data. A fourth order, low-pass Butterworth-type filter was employed at cut-off frequencies of 5 and 10 Hz. However, this procedure eliminated the stick-slip component: it distorted the block acceleration data by eliminating the high frequency harmonics in the step-shaped record. As Figure 8 shows, filtered records at 5 and 10 Hz result in overestimated

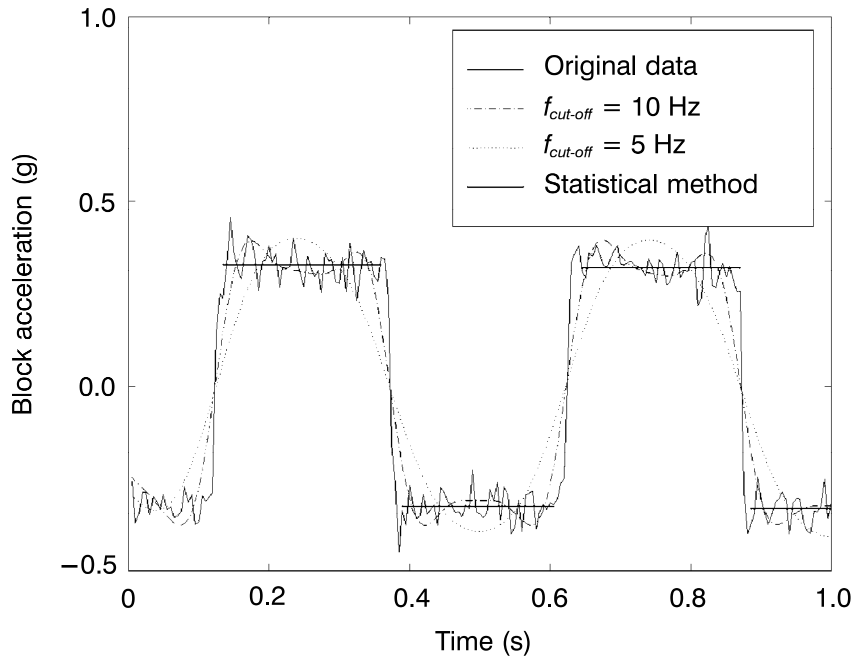

Figure 8. Effect of filtering on a typical acceleration record with stick-slip motion and the statistical method of estimating peak block accelerations for a smooth HDPE geomembrane-nonwoven geotextile interface.

Note: $f_{cut\text{-}off}$ = cut-off frequency used for fourth order, low-pass Butterworth-type filter.

peak transmitted accelerations. Alternatively, a statistical method was used in which the average acceleration and its standard deviation were calculated for each plateau region of the block acceleration trace. Then, the mean of all of the averages from all pulses was computed as the value of the maximum transmitted acceleration of the block. Figure 9 shows transmitted (block) acceleration versus base (shaking table) acceleration for the smooth geomembrane-nonwoven geotextile interface. Error bars in Figure 9 represent a ± 1 standard deviation in the estimation of the peak transmitted accelerations. The results for the tested interface show that appreciable slip occurs along the interface when the base acceleration exceeds 0.28g.

Figure 10 shows similar shaking table test results obtained using a record from the 1994 Northridge Earthquake (Los Angeles University Hospital Grounds record, 95° component), scaled to 0.9g, to drive the shaking table. Again, it is noted that the smooth geomembrane-nonwoven geotextile interface transmits a limiting acceleration. The peak acceleration of the block resting on the geosynthetic interface is approximately 0.3g, which is much smaller than the peak acceleration of the base (0.9g). Using Equation 1 and a transmitted acceleration of 0.3g, the friction coefficient is estimated to be 0.3. Figure 10 also shows the measured slip along the interface tested under the earthquake excitation. It is noted that the maximum (peak-to-peak) slip induced along the interface is larger than the permanent slip measured at the end of the excitation. This observation has an important implication in practice. In seismic design of landfills, it

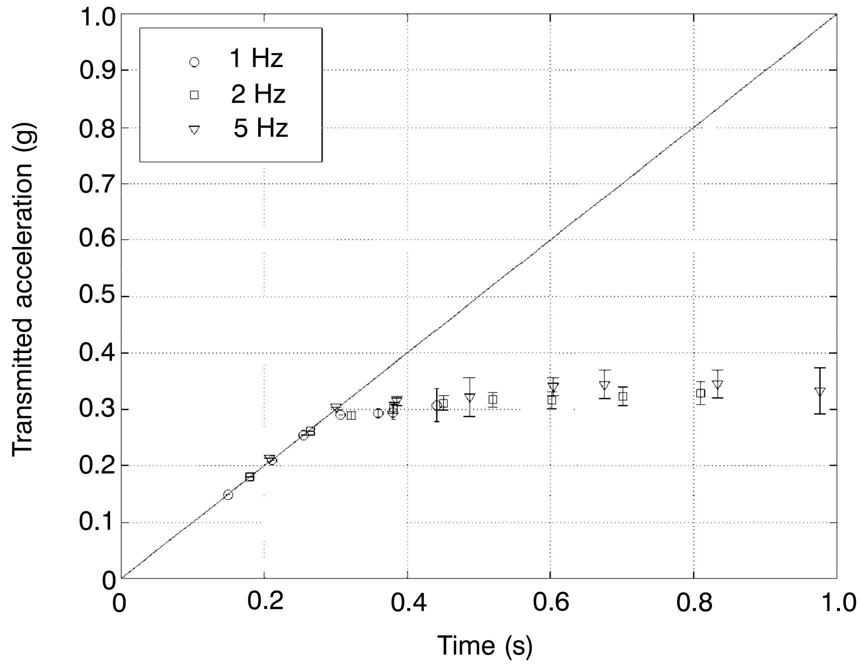

Figure 9. A typical rigid block test result of the transmitted acceleration versus base accelerations with error bars representing the ±1 standard deviation in the estimation of peak block accelerations for a smooth HDPE geomembrane-nonwoven geotextile interface.

is common practice to compute the permanent displacements along geosynthetic-geosynthetic interfaces using procedures developed for analysis of earthdams. Such procedures, when applied to horizontal geosynthetic-geosynthetic interfaces, will predict negligible permanent slip. Yet, the peak-to-peak slip, as shown in Figure 10, can be of significant magnitude depending on the earthquake record and the geosynthetic. Thus, for landfill liners, the maximum as well as the permanent slips should be computed to ensure the integrity of the liner and the leachate collection system.

The authors of the current paper are investigating the implications of stick-slip behavior on the yield acceleration and on the estimation of slip along geosynthetic-geosynthetic and geosynthetic-soil interfaces.

5 SEISMIC RESPONSE OF GEOSYNTHETIC INTERFACES

The experimental research results have demonstrated that smooth geosynthetic interfaces can modify earthquake motions propagating through soil or landfill waste profiles. In a conventional dynamic response analysis of a layered soil profile, a base rock motion was used and the accelerations at the top and within the profile were computed. The nonlinear soil behavior was approximately considered using equivalent linear

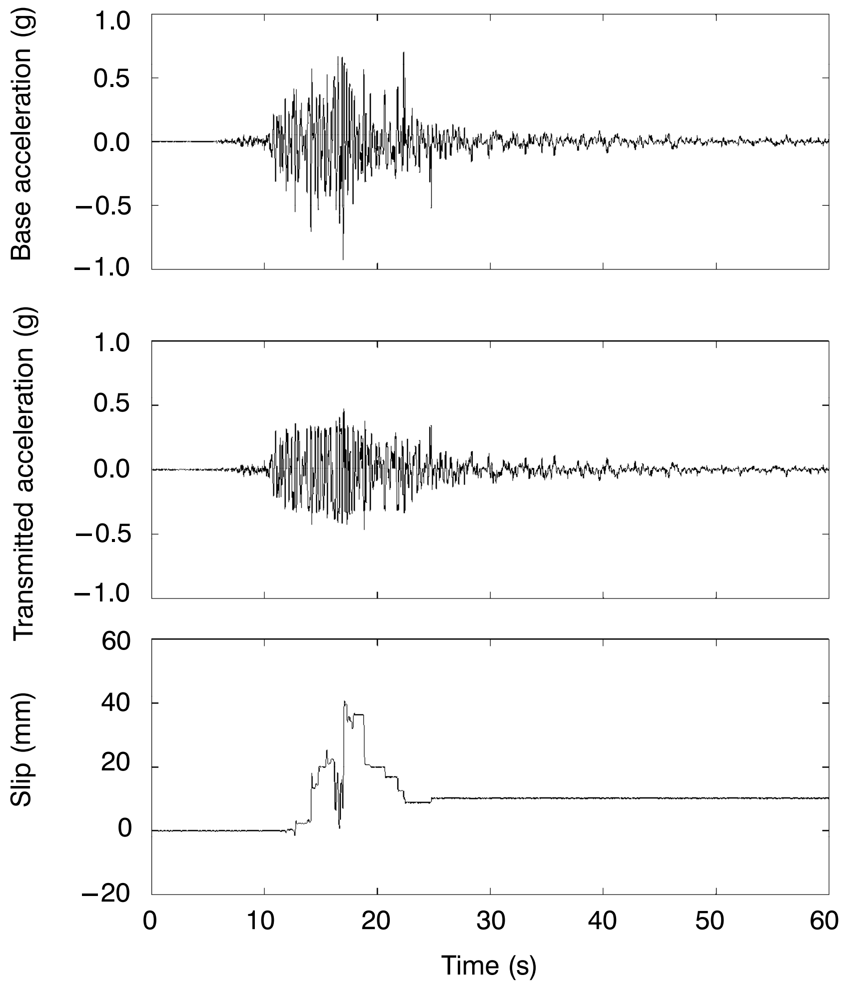

Figure 10. Test results of a rigid block on a smooth HDPE geomembrane-nonwoven geotextile interface under earthquake excitation (Northridge earthquake, Los Angeles University Hospital Grounds record scaled to 0.9g).

models. The computer program SHAKE (Schnabel et al. 1972) incorporates this equivalent linear soil behavior and calculates the response of a soil or waste profile to earthquake motions. The results from the shaking table tests on geosynthetic interfaces were utilized to develop an analytical model that can be used in dynamic response analysis of profiles that contain geosynthetic liner systems. The development of the analytical model is shown schematically in Figure 11 . The model is based on the concept that the nonlinear dynamic behavior of a geosynthetic-geosynthetic interface can be represented by an equivalent soil layer that has similar nonlinear dynamic behavior. The validity of the equivalent soil model was tested by comparing the measured geomembrane-geotextile interface responses from the shaking table test with the computed

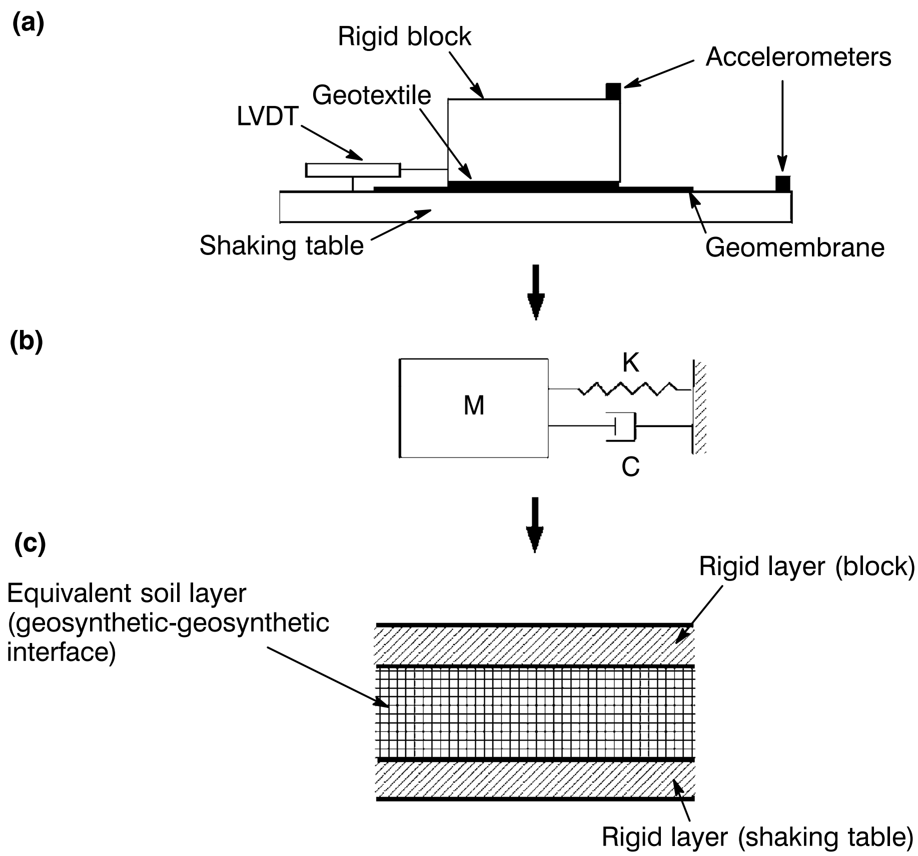

Figure 11. Schematic diagram of a single-degree-of-freedom system equivalent model: (a) experimental model of the interface; (b) theoretical model of the interface; (c) equivalent soil layer for the wave propagation analysis.

results using the model and the SHAKE computer program. The details of the derivation and validation of the equivalent soil model with application examples can be found in Yegian et al. (1998a,b).

Figure 12 shows the shear modulus versus shear strain of an equivalent soil layer that can be used to represent a smooth HDPE geomembrane-nonwoven geotextile interface in a wave propagation analysis. The computed acceleration at the top of the equivalent soil model is the acceleration transmitted through the interface, which is similar to that transmitted to the rigid block in the shaking table tests. The computed shear strains within the equivalent soil layer when multiplied by the thickness of the layer (1 m) will give an estimate of the slip that may occur along the geomembrane-geotextile interface during the earthquake excitation considered in the analysis.

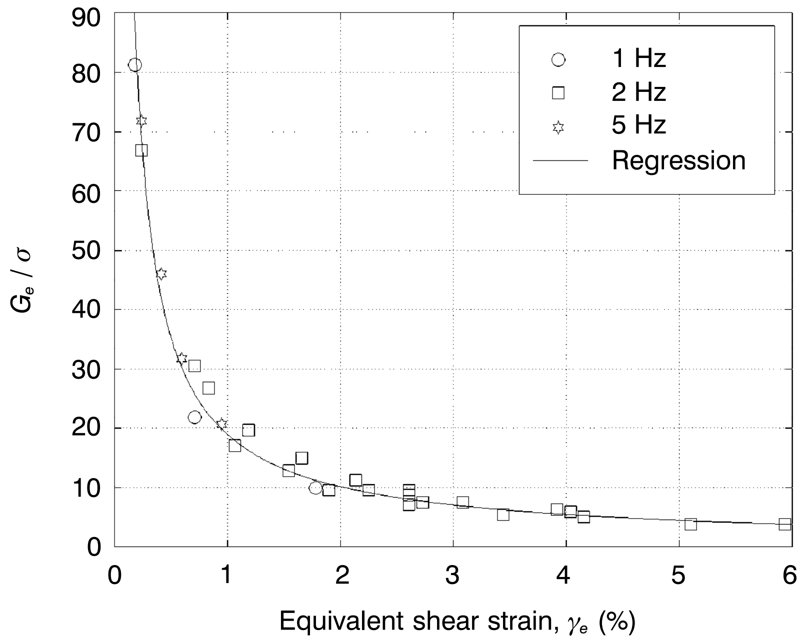

Figure 12. Equivalent shear modulus, G_e , divided by the normal stress, σ, versus the equivalent shear strain, γ_e , for a 1 m thick equivalent soil layer representing a smooth HDPE geomembrane-nonwoven geotextile interface.

6 CONCLUSIONS

A shaking table was utilized to test the frictional interface properties of a smooth HDPE geomembrane-nonwoven geotextile interface. Two test configurations were used, one for cyclic load tests, and the other for rigid block, dynamic load tests.

Cyclic load tests were performed to obtain the friction coefficients of the smooth geomembrane-nonwoven geotextile interface under constant displacement rates. The friction coefficients at displacement rates of 13 and 64 mm/s were calculated as 0.24 and 0.27, respectively. The difference between these values indicates that the friction coefficient increases with the sliding velocity.

Rigid block tests were used to simulate the dynamic loads induced in the smooth HDPE geomembrane-nonwoven geotextile interface during earthquakes. Tests can be run with harmonic base excitations as well as transient excitations. A friction coefficient of 0.28 was estimated from the harmonic rigid block tests for the smooth HDPE geomembrane-nonwoven geotextile interface for a table acceleration of 0.6g. Tests performed using an earthquake-type base excitation also resulted in a comparable friction coefficient of 0.3.

Accelerometer selection is an important issue with regard to measuring accelerations during rigid block tests. The authors of the current paper had previously performed experiments using piezoelectric accelerometers; however, this type of accelerometer was shown to be unable to accurately measure constant accelerations that were anticipated during sliding of a block. Therefore, capacitive accelerometers were utilized to accurately measure constant block accelerations that were used to estimate friction coefficients. The friction coefficients estimated from the capacitive accelerometers were in good agreement with friction coefficients obtained from cyclic load tests.

During the cyclic load tests, stick-slip behavior was observed in the form of high frequency fluctuations of the interface shear force. Similarly, stick-slip behavior was observed in the form of high frequency fluctuations of the block accelerations, during rigid block tests. The stick-slip component causes difficulties in estimating the shear forces and block accelerations that are used to estimate the friction coefficient of the interface. It was determined that low-pass filtering of the block acceleration distorts the data and leads to overestimation of block accelerations. A statistical method was utilized to estimate the transmitted accelerations measured from rigid block tests.

Under dynamic excitation, slip deformations occur along smooth geosynthetic-geosynthetic interfaces. Shaking table test results on geosynthetic-geosynthetic interfaces were utilized to develop and validate an equivalent soil layer that can model slip deformations along geosynthetic-geosynthetic interfaces in landfill liner systems. The model can be used by the SHAKE computer program to calculate the dynamic response of landfills that incorporate geosynthetic liner systems.

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REFERENCES

Mitchell, J.K., Seed, R.B. and Seed, H.B., 1990, “Kettleman Hills Waste Landfill Slope Failure. I: Liner-System Properties”, *Journal of Geotechnical Engineering*, Vol. 116, No. 4, pp. 647-668.

Oden, J.T. and Martins, J.A.C., 1985, “Models and Computational Methods for Dynamic Friction Phenomena”, *Computer Methods in Applied Mechanics and Engineering*, Vol. 52, Nos. 1-3, pp. 527-634.

Schnabel, P.B., Lysmer, J. and Seed, H.B., 1972, “*SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites*”, Report EERC-72/12, Earthquake Engineering Research Center, Berkeley, California, USA, 92 p.

USEPA, 1992, “*Criteria For Municipal Solid Waste Landfills: Part 258*”, Subtitle 40, U.S. Code of Federal Regulations, U.S. Environmental Protection Agency, Washington, DC, USA, 463 p.

Williams, N.D. and Houlihan, M., 1986, “Evaluation of Friction Coefficients Between Geomembranes, Geotextiles and Related Products”, *Proceedings of the Third International Conference on Geotextiles*, Vol. 3, Vienna, Austria, April 1986, pp. 891-896.

Yegian, M.K, Harb, J.N. and Kadakal, U., 1998, "Dynamic Response Analysis Procedure for Landfills with Geosynthetic Liners", *Journal of Geotechnical Engineering*, submitted for publication.

Yegian, M.K, Kadakal, U. and Harb, J.N., 1998, "Effect of Geosynthetic Liners on the Seismic Response of Landfills", *Journal of Geotechnical Engineering*, submitted for publication.

Yegian, M.K., Yee, Z.Y. and Harb, J.N., 1995a, "Response of Geosynthetics Under Earthquake Excitations", *Proceedings of Geosynthetics'95*, IFAI, Vol. 2, Nashville, Tennessee, USA, February 1995, pp. 677-689.

Yegian, M.K., Yee, Z.Y., and Harb, J.N., 1995b, "Seismic Response of Geosynthetic/Soil systems," *Geoenvironmental 2000*, Yalcin, B.A. and Daniel, D.E., Editors, Geotechnical Special Publication No. 46, ASCE, Vol. 2, proceedings of a specialty conference held in New Orleans, Louisiana, USA, February 1995, pp. 1113-1125.