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SLIP DISPLACEMENTS OF GEOSYNTHETIC SYSTEMS UNDER DYNAMIC EXCITATION

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ABSTRACT

The dynamic response of geosynthetic interfaces commonly used in Municipal Solid Waste Landfills (MSWL) are investigated using a shaking table facility. Geosynthetic interfaces placed horizontally and on inclined surfaces were tested to simulate bottom and cover liner systems. This paper primarily focuses on the research results related to the slip displacements induced under harmonic base excitation. Normalized plots are presented that can be used to estimate the maximum (peak-to-peak) slip along horizontally placed geosynthetic interfaces. In addition, plots of normalized permanent slip -per cycle of harmonic excitation- along geosynthetic interfaces placed on various slope inclinations are presented. Example calculations are included.

INTRODUCTION

One of the critical components of a MSWL is the geosynthetic system utilized as an impermeable barrier. Under earthquake excitation, it is imperative that the integrity of such a system, hence that of the landfill itself, is maintained. Therefore, understanding the dynamic response of geosynthetic interfaces is an important area for research. During the past few years, the authors have been investigating the behavior of geosynthetic interfaces under dynamic excitation

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using a shaking table facility. In this research program, the acceleration transmitted through various types of geosynthetic interfaces, as well as the slip displacements (hereafter referred to slip) developed along the interfaces have been investigated. Initial test results and observations have been reported by Yegian and Lahlaf (1991) and Yegian et al. (1995).

This paper presents results of shaking table tests performed on typical geosynthetic interfaces used in current practice for landfill design. The paper focuses primarily on the slip recorded along the interfaces tested. Normalized relationships are presented to predict slip under harmonic excitations. This research continues to evaluate slip along geosynthetic interfaces under earthquake excitations. The results from these tests will be published in the near future.

SHAKING TABLE FACILITY

Figure 1 shows a schematic drawing of the shaking table setup used in our research. The shaking table is powered by a hydraulic actuator that controls the horizontal displacement of the table. A geomembrane is fixed on the table upon which rests a plexiglass box used to hold soil or any other geosynthetic. Lead weights are added to increase the normal stress at the interface. The accelerations of the table and the box are measured by accelerometers. The relative displacement between the table and the box, hence slip along the interface, is measured by a Linear Variable Displacement Transducer (LVDT) as shown in Figure 1.

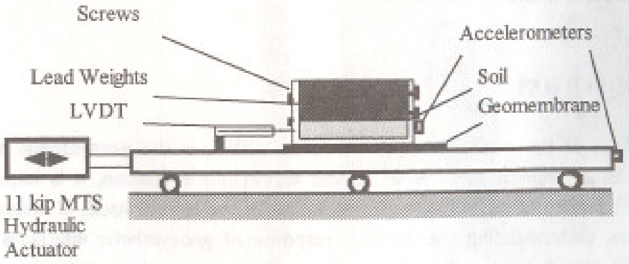

Figure 1. Schematic Diagram of the Test Setup for Investigating the Dynamic Shear Properties of Geomembrane / Soil Interface.

To simulate landfill side slope conditions in the experiments, an adjustable-slope table is bolted on the main horizontal shaking table as shown in Figure 2. Test results reported in this paper correspond to both, horizontally placed as well as sloping interfaces.

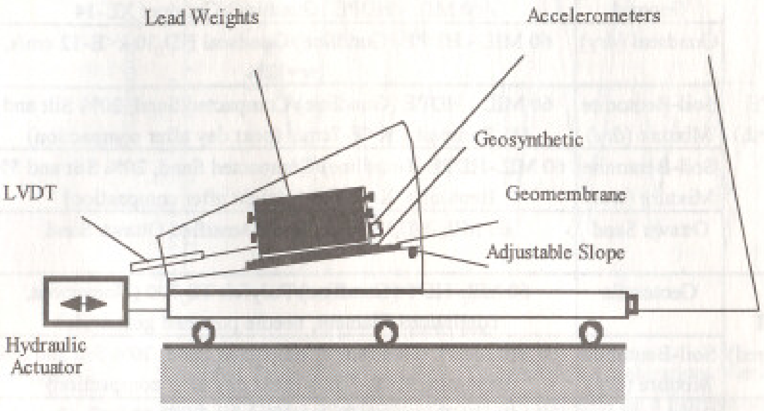

Figure 2. Schematic Diagram of the Test Setup for Investigating the Dynamic Shear Properties of Geosynthetic Interfaces on a Slope.

INTERFACES TESTED

In this paper, test results from three commonly used geomembranes are presented, namely: smooth HDPE, textured HDPE referred to as HDT, and PVC. Table 1 summarizes the various interfaces tested using these geomembranes.

As was stated earlier, the geosynthetic interfaces were tested horizontally as well as along inclined slopes. The test results for horizontally placed interfaces are presented first followed by the inclined interfaces.

Table 1. Summary of the Various Geosynthetic Interfaces Tested.

Interface		Description
HDPE (Smooth)	Geotextile	60 MIL - HDPE (Gundline)/Polyfelt TS 700 (Nonwoven, continuous filament, needle punched geotextile)
	Geogrid	60 MIL - HDPE (Gundline)/Gundnet XL-14
	Gundseal (dry)	60 MIL - HDPE (Gundline)/Gundseal HD 30 k<E-12 cm/s, w=12%
	Soil-Bentonite Mixture (dry)	60 MIL - HDPE (Gundline)/Compacted Sand, 20% Silt and 5% Bentonite, K<E-7cm/s (next day after compaction)
	Soil-Bentonite Mixture (wet)	60 MIL-HDPE (Gundline)/Compacted Sand, 20% Silt and 5% Bentonite, K<E-7cm/s (right after compaction)
	Ottawa Sand	60 MIL-HDPE (Gundline)/Densified Ottawa Sand
HDT (Textured)	Geotextile	60 MIL-HDT (Gundline)/Polyfelt TS 700 (Nonwoven, continuous filament, needle punched geotextile)
	Soil-Bentonite Mixture (dry)	60 MIL-HDT (Gundline)/Compacted Sand, 20% Silt and 5% Bentonite, K<E-7cm/s (next day after compaction)
PVCs	Gundseal (dry)	30 MIL-PVC smooth (Palco)/Gundseal HD 30 k<E-12 cm/s, w=12%
	Geotextile	30 MIL-PVC smooth (Palco)/Polyfelt TS 700 (Nonwoven, continuous filament, needle punched geotextile)
PVCr	Gundseal (dry)	30 MIL-PVC rough (Fisher)/Gundseal HD 30 k<1e-12 cm/s, w=12%
	Geotextile	30 MIL-PVC rough (Fisher)/Polyfelt TS 700 (Nonwoven, continuous filament, needle punched geotextile)

RESULTS OF HORIZONTALLY PLACED GEOSYNTHETIC INTERFACES

Figure 3 shows typical acceleration time records of the table (base acceleration) and that transmitted through an HDT geomembrane to the compacted soil-bentonite mixture described in Table 1 (transmitted acceleration). From this figure, it is observed that there is a limiting acceleration that the HDT/Soil-Bentonite interface can transmit. Because of this difference between the base and transmitted accelerations, a relative displacement, slip, is induced along this horizontally placed interface. Figure 4 shows the slip measured during the test on HDT/Soil-Bentonite interface of Figure 3.

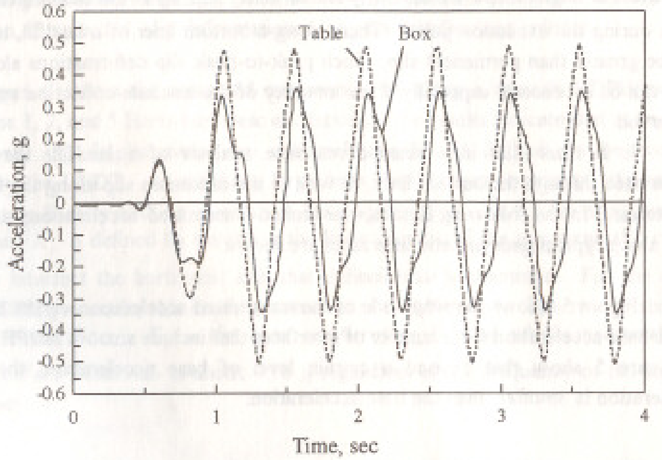

Figure 3. Recorded Table (Base) and Box (Transmitted) Accelerations Versus Time, for HDT / Soil-Bentonite Mixture Interface on a Horizontal Surface.

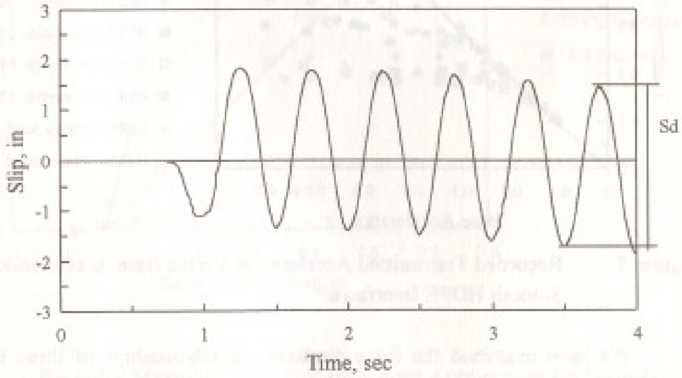

Figure 4. Recorded Slip Versus Time and Maximum (Peak-to-Peak) Slip, S_d for HDT/Soil-Bentonite Mixture Interface on a Horizontal Surface

The results shown in Figure 4 indicate that, along a horizontally placed geosynthetic interface, under harmonic excitation, although the permanent slip at the end of a cycle is negligible, a maximum (peak-to-peak) slip S_d of about 3 inches has taken place during the excitation pulse. Thus, along a bottom liner of a landfill, maximum slip can be greater than permanent slip. Such peak-to-peak slip deformations along a bottom liner can be a concern, especially if the integrity of the leachate collection system is to be preserved.

It is clear that in a seismic response analysis of a landfill, the acceleration transmitted through the bottom liner, as well as the maximum slip along the liner are both of interest. In the following figures, the limited transmitted accelerations and maximum slips along typical geosynthetic interfaces are shown.

Figure 5 shows the amplitude of the transmitted acceleration versus the amplitude of the base acceleration for a number of interfaces that include smooth HDPE. The results in Figure 5 show that beyond a certain level of base acceleration, the transmitted acceleration is *smaller* than the base acceleration.

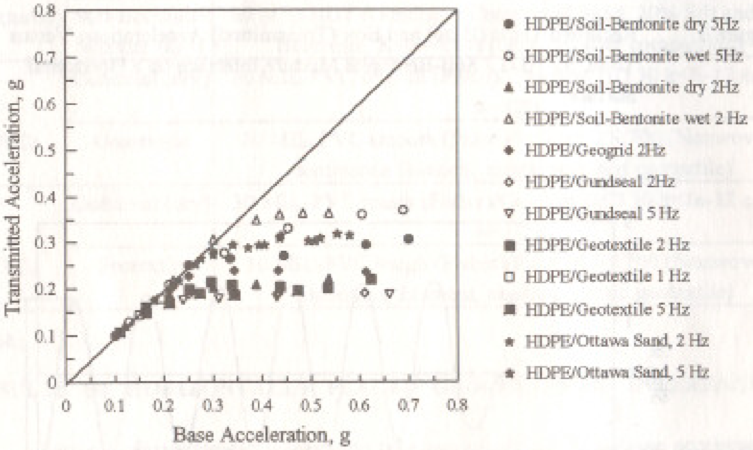

Figure 5. Recorded Transmitted Acceleration Versus Base Acceleration for Smooth HDPE Interfaces.

We have examined the force-displacement relationships of these interfaces and have concluded that the interface characteristic is not perfectly rigid-plastic, as is commonly assumed, but rather elasto-plastic. Because of this, even under small levels of base acceleration, very small slips were recorded. Thus, it is difficult to define a yield acceleration from the acceleration records such as shown in Figure 5. Traditionally, yield acceleration is commonly defined as the maximum acceleration that can be transmitted through the geosynthetic interface. Alternatively, the yield acceleration is defined as that acceleration, if exceeded, slip deformations along the interface are induced.

Figure 6 shows the measured maximum slips along a smooth HDPE/geotextile interface for 1, 2, and 5 Hertz harmonic excitations. The results indicate that at small base accelerations, slip displacements are extremely small and difficult to be accurately recorded by the LVDT. At relatively large base accelerations, maximum slip increases approximately linearly with an increase in base acceleration. In this investigation, yield acceleration K_y is defined by extending the linear portion of the maximum slip curve to the left to intersect the horizontal axis that defines base acceleration. For the case of smooth HDPE/geotextile, this construction is shown in Figure 6. The results show that the yield acceleration, K_y *- the base acceleration beyond which measurable slip deformations are observed-* is about 0.16 g regardless of the frequency of the harmonic base motion.

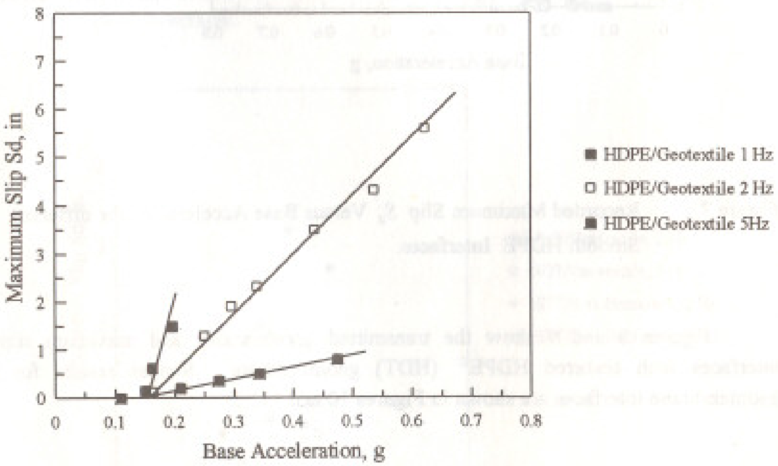

Figure 6. Recorded Maximum Slip S_d Versus Base Acceleration for Smooth HDPE/Geotextile Interfaces.

Figure 7 shows, for purposes of comparison, the maximum slips, S_d measured for different smooth HDPE interfaces and at different frequencies of excitation.

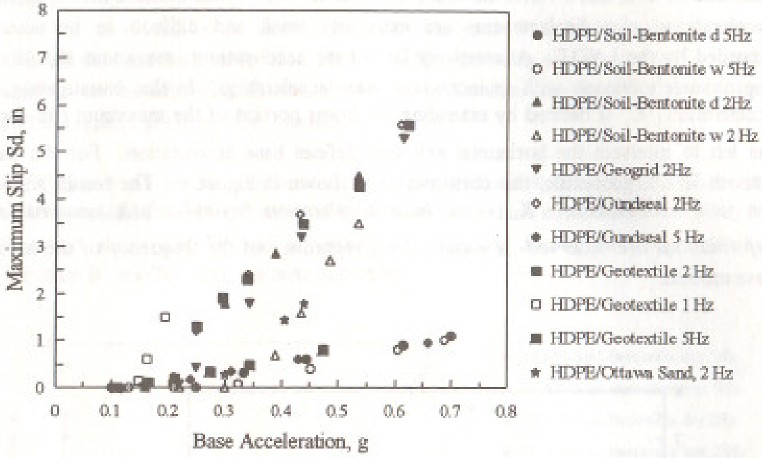

Figure 7. Recorded Maximum Slip S_d Versus Base Acceleration for different Smooth HDPE Interfaces.

Figures 8 and 9 show the transmitted accelerations and maximum slips for interfaces with textured HDPE (HDT) geomembrane. Similar results for PVC geomembrane interfaces are shown in Figures 10 and 11.

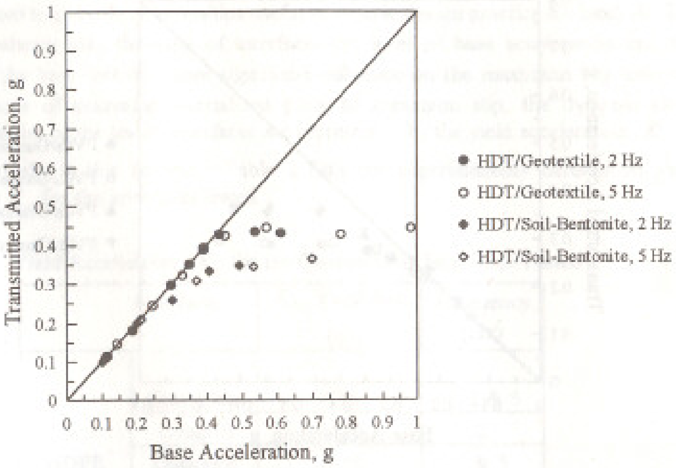

Figure 8. Recorded Transmitted Acceleration Versus Base Acceleration for HDT Interfaces.

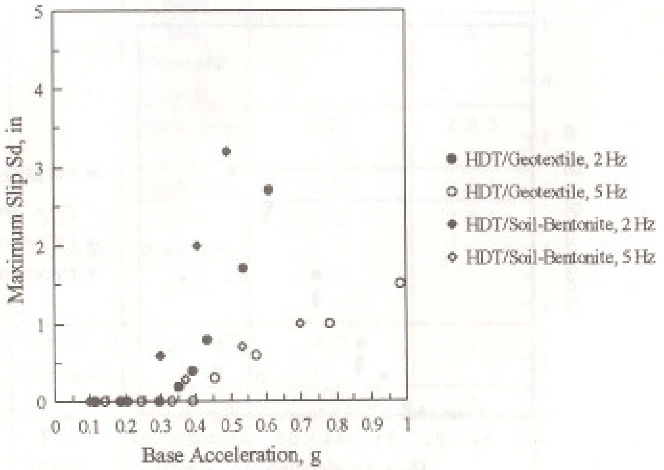

Figure 9. Recorded Maximum Slip, S_d Versus Base Acceleration for HDT Interfaces.

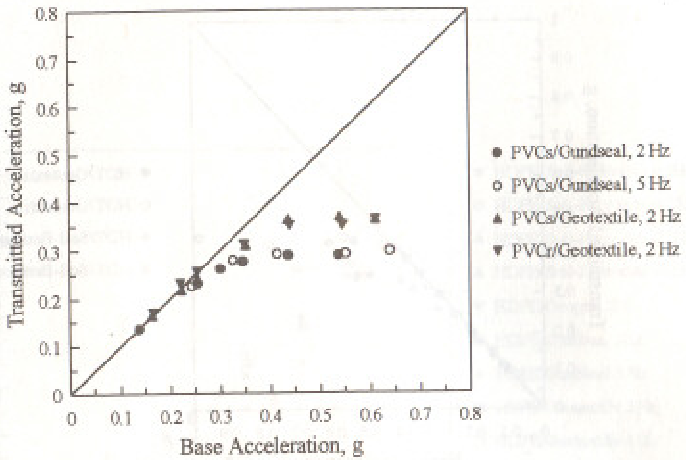

Figure 10. Recorded Transmitted Acceleration Versus Base Acceleration for PVC Interfaces.

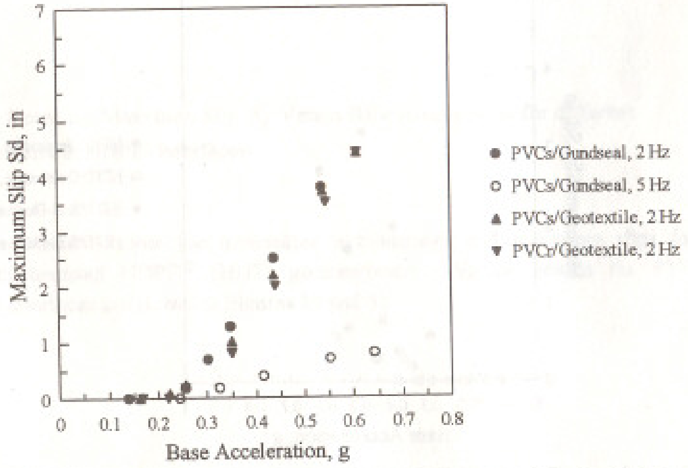

Figure 11. Recorded Maximum Slip, S_d Versus Base Acceleration for PVC Interfaces.

Application in Practice

The maximum slips S_d measured along horizontally placed geosynthetic interfaces were normalized to provide relationships useful in seismic design practice for landfills. The test results indicate that the type of interface, the level of base acceleration and the frequency of the base motion have significant influence on the maximum slip induced. For the purpose of preparing normalized plots of maximum slip, the dynamic shear strength properties of the tested interfaces are represented by the yield acceleration K_y as defined previously in this section. Table 2 lists the experimentally determined yield accelerations K_y for the interfaces tested.

Table 2 Yield Acceleration, K_y for the Geosynthetic Interfaces Tested

Interface		K_y, Yield Acc. (g)	Frequency (Hz)
HDPE (smooth)	Geotextile	0.16	1, 2 & 5
	Geogrid	0.20	2
	Gundseal (dry)	0.15	2 & 5
	Soil-Bentonite (dry)	0.18	2 & 5
	Soil-Bentonite (wet)	0.3	2 & 5
	Ottawa Sand	0.27	2 & 5
HDT (Textured)	Geotextile	0.36	2 & 5
	Soil-Bentonite (dry)	0.26	2 & 5
PVCs (Smooth)	Gundseal (dry)	0.23	2
	Geotextile	0.22	2
PVCr (Rough)	Gundseal (dry)	0.26	2
	Geotextile	0.23	2 & 5

Yegian et al. (1991), in their research on earthquake-induced permanent deformations of earth dams, defined a normalized relative displacement function as:

$$D_n = \frac{D_r}{K_a.T^2.N_{eq}} \qquad (1)$$

where D_n is the non-dimensional normalized relative displacement parameter, D_r is the relative displacement, K_a is the acceleration of a rigid support, T is the period of the base motion and N_{eq} is the equivalent number of uniform pulses of the motion. Following this approach, the maximum slips, S_d along the tested geosynthetics were normalized as in Equation 2

$$S_n = \frac{S_d}{K_a.T^2} \qquad (2)$$

where S_n is the normalized (non-dimensional) maximum slip, S_d is the actual measured maximum slip, K_a is the base acceleration, and T is the period of the base motion.

The maximum slips shown in Figures 6, 7, 9, and 11 were normalized using Equation 2 and then plotted in Figure 12, as a function of the ratio of K_y (from Table 2) and K_a. This plot shows a definite trend of the normalized slip, S_n decreasing with increasing K_y/K_a ratio. A regression analysis was performed on the data shown in Figure 12, which resulted in Equation 3.

$$S_n = \frac{S_d}{K_a.T^2} = 0.128 - 0.135\left(\frac{K_y}{K_a}\right) + 0.005\left(\frac{K_y}{K_a}\right)^2, \qquad r^2 = 0.95 \qquad (3)$$

Equation 3 can be used to estimate the mean value of maximum slip S_d along a geosynthetic interface. Example applications follow:

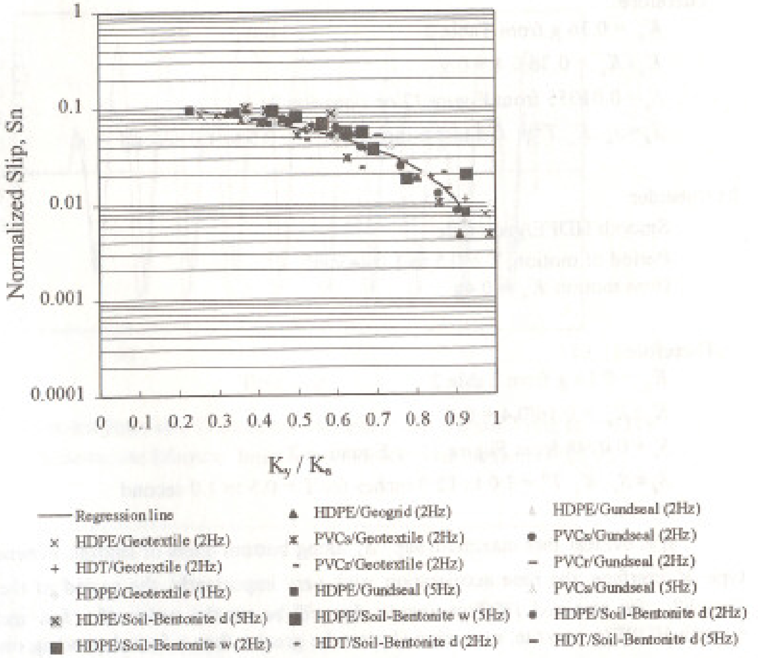

Figure 12. Normalized Slip, S_n Versus K_y/K_a for the Different Types of Geosynthetics Tested.

Examples (a) and (b)

a) Consider:

HDT/geotextile interface horizontally placed
Base motion $K_a = 0.4g$
Period of motion, T = 0.5 to 1.0 second

Therefore:

$K_y = 0.36$ g from Table 2

$K_y / K_a = 0.36/0.4 = 0.9$

$S_n = 0.01055$ from Figure 12 or Equation 2

$S_d = S_n . K_a . T^2 =$ 0.4 to 1.6 inches for T = 0.5 to 1.0 second

b) Consider:

Smooth HDPE/geotextile

Period of motion, T = 0.5 to 1.0 second

Base motion $K_a = 0.4$g

Therefore:

$K_y = 0.16$ g from Table 2

$K_y / K_a = 0.16/0.4 = 0.4$

$S_n = 0.0748$ from Figure 12 or Equation 2

$S_d = S_n . K_a . T^2 =$ 3.0 to 12.0 inches for T = 0.5 to 1.0 second

It is evident that maximum slip, S_d along bottom liners of landfills depends on the type of interface, the base acceleration, and, very importantly, the period of the motion. Typically, for textured HDT/geotextile slip will be on the order of a few inches. For smooth HDPE/geotextile, maximum slip can be greater than a foot depending on K_a and T. The implications of such slip on the integrity of the bottom liner and the leachate collection system is not yet well understood and await further research.

RESULTS ON INCLINED GEOSYNTHETIC INTERFACES

To evaluate the dynamic response of geosynthetic interfaces placed on side slopes of landfills, the experimental setup shown in Figure 2 was used. Figure 13 shows a typical acceleration record from a shaking table test on HDT /Soil-Bentonite interface placed on 4H:1V slope. Figure 14 shows the measured permanent slip along the interface as a function of time. It is evident from the record that the behavior of the inclined interface is more complex than a horizontal one. Depending on the interface and the level of base acceleration, slip occurred in both directions, down-slope, as well as up-slope.

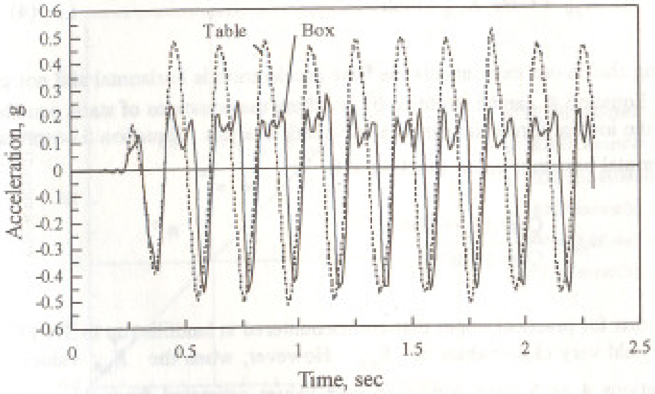

Figure 13. Recorded Base and Transmitted Accelerations Versus Time for HDT / Soil-Bentonite Mixture Interface on an Inclined Surface (4H:1V).

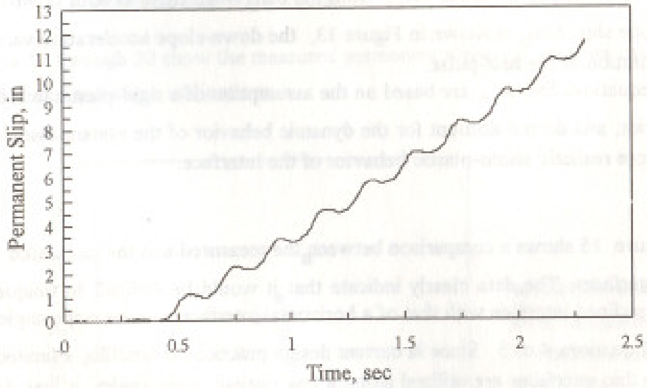

Figure 14. Recorded Permanent Slip Versus Time for HDT / Soil-Bentonite Mixture Interface on an Inclined Surface (4H:1V).

Difficulties were encountered in defining a single parameter K_y to describe the yield acceleration of the inclined interface. Newmark (1965) defined $K_{y,\theta}$ parallel to the slope as function of the yield acceleration on a horizontal plane, K_{yh} , and the slope inclination θ.

$$K_{y,\theta} = \mathrm{Cos}\theta . K_{y,h} \mp \mathrm{Sin}\theta \tag{4}$$

Considering that in our experiments the base acceleration is horizontal and not parallel to the slope, Equation 4 can be modified by rewriting the equations of static equilibrium and including the inertial forces similar to a Newmark analysis. Equation 5 expresses $K_{y,\theta}$ for a horizontal base motion, as function of θ.

$$K_{y\theta} = \frac{\mathrm{Cos}\theta . K_{y,h} \mp \mathrm{Sin}\theta}{\mathrm{Cos}\theta \pm \mathrm{Sin}\theta . K_{y,h}} \tag{5}$$

It is noted that for practical slopes that are encountered in landfills (up to 3H:1V), the two equations yield very close values of $K_{y,\theta}$. However, when the $K_{y,\theta}$ values calculated from Equations 4 or 5 were compared with values estimated from the measured data (using similar procedure as that described in the previous section), significant discrepancies were observed. The likely reasons for these discrepancies are:

1) It is very difficult to define $K_{y,\theta}$ from the data when there is both down-slope and up-slope slip. Also, as shown in Figure 13, the down-slope acceleration varies during the duration of the half-pulse.
2) The equations for $K_{y,\theta}$ are based on the assumption of a rigid-plastic interface shear behavior, and do not account for the dynamic behavior of the system associated with the more realistic elasto-plastic behavior of the interface.

Figure 15 shows a comparison between the measured and the calculated $K_{y,\theta}$ for selected interfaces. The data clearly indicate that it would be difficult to uniquely relate K_y for an inclined interface with that of a horizontal interface and the slope angle through the use of Equations 4 or 5. Since in current design practice for landfills, a limited number of geosyntethic interfaces are utilized along a few distinct slope angles, it was decided to present the test results in terms of normalized permanent slip as a function of typical slope angles, and for typical interfaces commonly used in landfills.

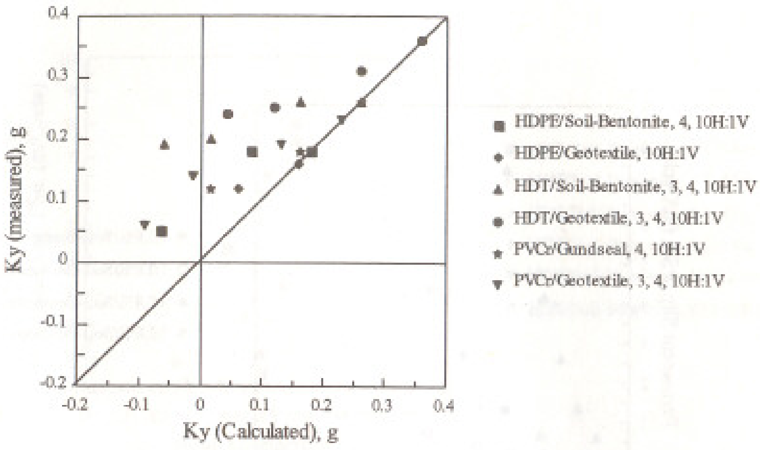

Figure 15. Comparison Between the Measured and Calculated K_y for Different Interfaces and slope angles.

Figures 16 through 20 show the measured permanent slips, PS_d (inches/cycle) for variety of interfaces and slope inclinations.

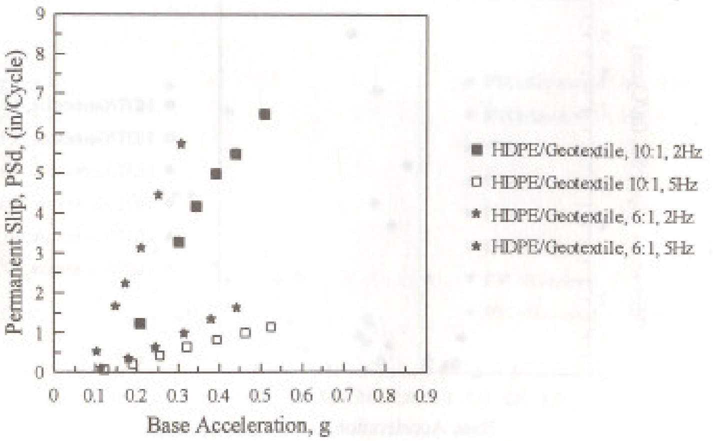

Figure 16. Permanent Slip per Cycle, PS_d Versus Base Acceleration for HDPE/Geotextile Interface

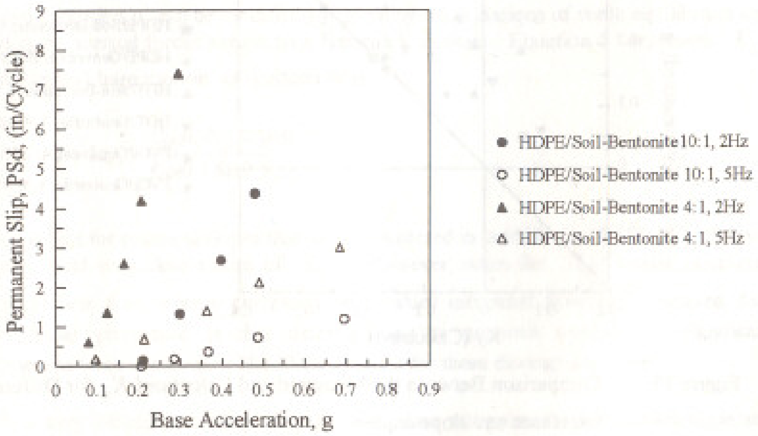

Figure 17. Permanent Slip per Cycle, PS_d, Versus Base Acceleration for HDPE/Soil-Bentonite dry Interface

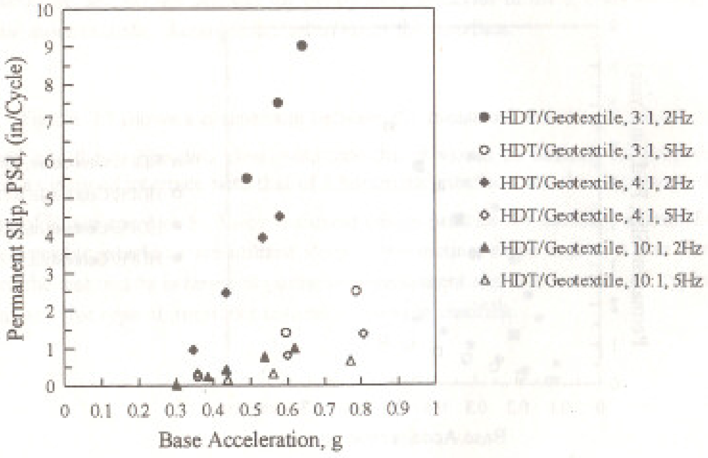

Figure 18. Permanent Slip per Cycle, PS_d, Versus Base Acceleration for HDT/Geotextile Interface

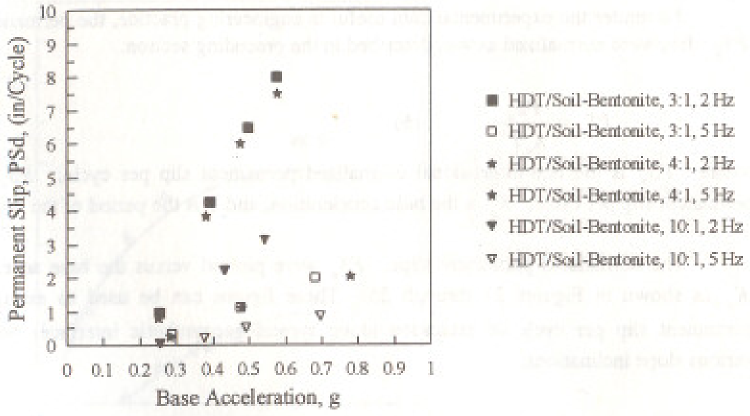

Figure 19. Permanent Slip per Cycle, PS_d, Versus Base Acceleration for HDT/Soil-Bentonite Mixture dry Interface

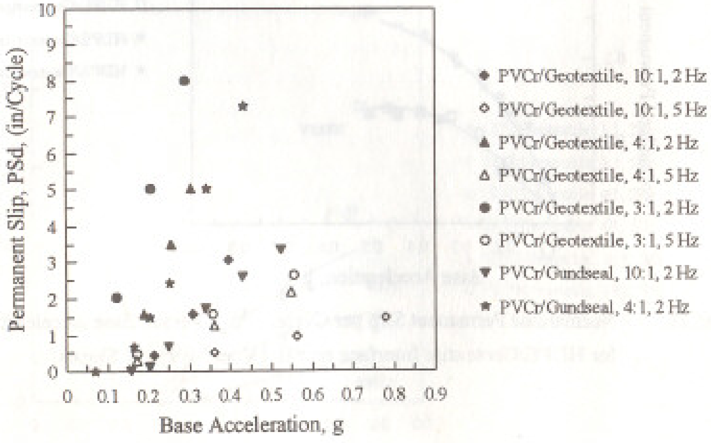

Figure 20. Permanent Slip per Cycle, PS_d, Versus Base Acceleration for PVC Interfaces.

Application in Practice

To render the experimental data useful in engineering practice, the permanent slip, PS_d, data were normalized as was described in the preceding section.

$$PS_n = \frac{PS_d}{K_a T^2} \qquad (6)$$

where PS_n is the non-dimensional normalized permanent slip per cycle, PS_d is the permanent slip per cycle, K_a is the base acceleration, and T is the period of the motion.

The normalized permanent slips, PS_n were plotted versus the base acceleration K_a as shown in Figures 21 through 25. These figures can be used to estimate the permanent slip per cycle of excitation along typical geosynthetic interfaces placed in various slope inclinations.

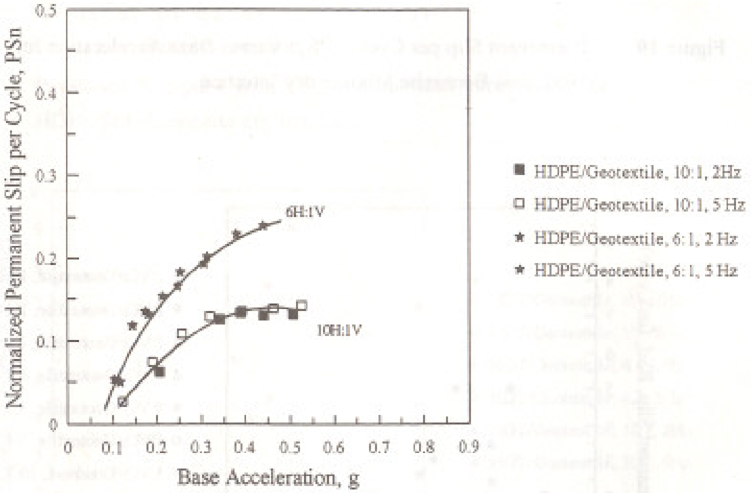

Figure 21. Normalized Permanent Slip per Cycle, PS_n, Versus Base Acceleration for HDPE/Geotextile Interface on 6H:1V and 10H:1V Slopes.

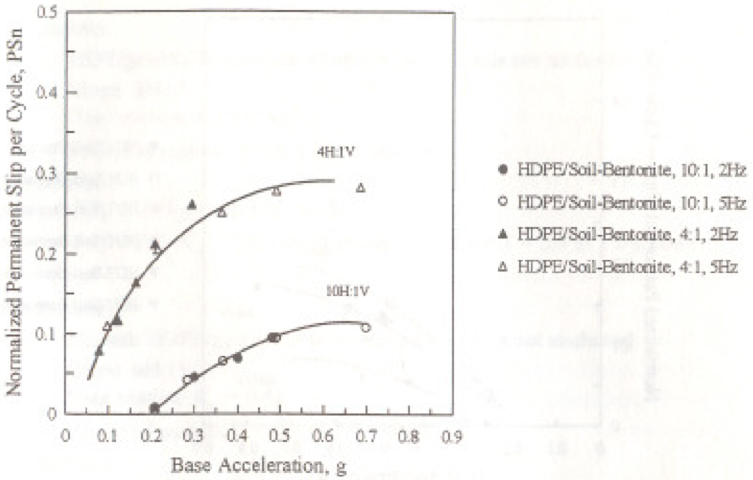

Figure 22. Normalized Permanent Slip per Cycle, PS_n, Versus Base Acceleration for HDPE/Soil-Bentonite Mixture Interface on 4H:1V and 10H:1V Slopes.

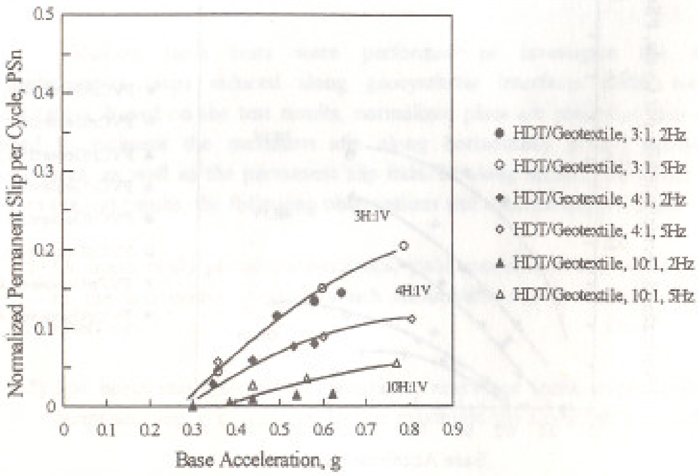

Figure 23. Normalized Permanent Slip per Cycle, PS_n, Versus Base Acceleration for HDT/Geotextile Interface.

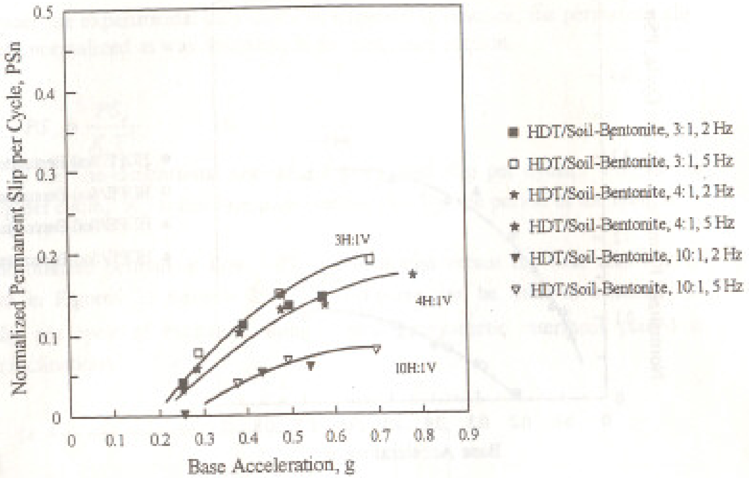

Figure 24. Normalized Permanent Slip per Cycle, PS_n, Versus Base Acceleration for HDT/Soil-Bentonite dry Interface.

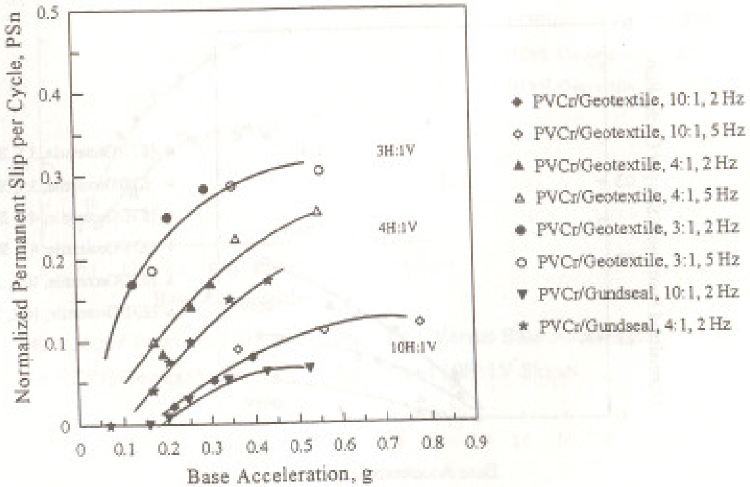

Figure 25. Normalized Permanent Slip per Cycle, PS_n, Versus Base Acceleration for PVC Interfaces.

Example applications follow:

a) Consider:

HDT/geotextile interface when the geotextile is not anchored
Slope 3H:1V
Base motion $K_a = 0.4g$
Period of motion, T = 0.5 to 1.0 second

Therefore:

$PS_n = 0.07$ g from Figure 23.
$PS_d = PS_n K_a T^2 = 2.7$ to 11 inches / cycle for T = 0.5 to 1.0 second

b) Consider:

Smooth HDPE/geotextile when the geotextile is not anchored
Slope 6H:1V
Base motion $K_a = 0.4g$
Period of motion, T = 0.5 to 1.0 second

Therefore:

$PS_n = 0.23$ from Figure 21.
$PS_d = PS_n K_a T^2 = 9$ to 36 inches / cycle for T = 0.5 to 1.0 second

SUMMARY

Shaking table tests were performed to investigate the relative displacements (slip) induced along geosynthetic interfaces under harmonic excitation. Based on the test results, normalized plots are presented that can be used to estimate the maximum slip along horizontally placed geosynthetic interfaces, as well as the permanent slip induced along inclined interfaces. Also, from the test results, the following observations and conclusions are made:

1) On horizontally placed geosynthetics, yield acceleration can best be defined as the acceleration beyond which measurable slip is induced along the interface.

2) For horizontal geosynthetic interfaces, maximum (peak-to-peak) slip, not permanent slip, is of concern. Hence, maximum slip along the bottom liner of

a landfill should be limited in design to ensure the integrity of the bottom leachate collection system.

3) Yield acceleration for inclined geosynthetic interfaces, calculated based on Newmark's equation are not in agreement with measured values from the shaking table tests. This discrepancy is attributed to elasto-plastic behavior of the interface as well as non-constant yield acceleration measured during slip in the down-slope direction. For this reason, it was deemed more appropriate to present normalized permanent slip as a function of base acceleration, (instead of K_y/K_a), for typical geosynthetic interfaces and, for side slope inclinations used in current landfill design practice.

4) The magnitude of slip along a geosynthetic interface depends on the square of the period of the base motion. Thus, the accuracy of predicted slip is heavily dependent on the accuracy of the period of the design base motion considered.

5) The normalized slip plots can be used in engineering practice by converting the earthquake ground and landfill waste motions to equivalent uniform motions according to Seed et al. (1975) procedure.

This research program continues to progress and the authors are currently investigating slip displacements induced under earthquake motions.

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