DYNAMIC RESPONSE ANALYSIS PROCEDURE FOR LANDFILLS WITH GEOSYNTHETIC LINERS

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ABSTRACT: The dynamic response of geosynthetic interfaces commonly encountered in municipal solid waste landfills were investigated using a shaking table facility. The force-slip relationships for the tested interfaces showed almost rigid and then plastic deformation where the maximum shear force transmitted through the interface increases slightly with increasing slip. The force-slip relationships were modeled with equivalent stiffness and damping ratios. These equivalent parameters were established as a function of slip displacements to account for the nonlinear behavior of the interfaces. Using the equivalent stiffness and damping, the dynamic properties of an equivalent soil layer were established such that the dynamic response of the equivalent soil layer is similar to that of the geosynthetic interface it represents. The purpose of this representation was to allow the modeling of geosynthetic interfaces in wave propagation analysis, such as SHAKE analysis. The properties of the equivalent soil layer were validated by comparing the measured dynamic response of a rigid block placed on geosynthetics with that computed using the SHAKE program and the properties of the equivalent soil layer developed. A procedure for analysis of the dynamic response of landfills with geosynthetic liners is proposed.

INTRODUCTION

Contamination of subsurface environments has become a major concern for geotechnical and environmental engineers as well as state and federal regulatory agencies. The critical nature of hazardous waste necessitates its confinement and encapsulation within a very low permeability barrier, such as geosynthetic cover and bottom liner systems.

For the past few years, increased attention has been placed on the vulnerability of landfills to earthquake-induced deformations. In addition to the overall stability of the landfill waste, the cover and bottom liner systems that protect the surrounding soil and the ground water from potential contamination have to be designed to sustain a seismic event. In view of this environmental hazard, federal regulations (U.S. EPA 1992) have been formulated to address the problem of siting and designing a solid waste landfill within a seismically active zone.

Current seismic design of landfills is primarily based on the conventional earthquake engineering practice that is developed for earth dams and embankments. However, landfills contain components with properties that are still not easily defined. A typical municipal solid waste landfill contains a broad range of waste materials that have different engineering properties and are difficult to quantify. In addition, a municipal solid waste landfill incorporates geosynthetic liners. The geosynthetic industry is relatively new with a variety of new products introduced continuously, and the dynamic properties of geosynthetic materials are still under investigation. Also, there are only a few cases of modern landfills constructed with geosynthetics that have experienced a major seismic event. Thus, not many case history data are available for simulation and for validation of analytical and experimental results.

During the past few years, a number of investigators have been conducting research to improve the practice of seismic design of landfills. Kavazanjian (1994) measured in-situ shear wave velocities of landfill waste. Repetto et al. (1994) and Del Nero et al. (1995) investigated the effect of the waste on the dynamic response of landfills. Idriss et al. (1995) employed the finite-element method to investigate the seismic deformations of a landfill. Yegian et al. (1995) investigated the dynamic response of geosynthetic interfaces.

Seismic response analysis of a landfill that includes geosynthetic liners is quite a challenge. The problem can ideally be solved by using a general-purpose finite-element code that has the capability of considering material and geometric nonlinearities. However, such a solution requires well-defined material and interface properties and preparation of a detailed model that describes the geometry of the landfill. Often, in engineering practice, one-dimensional (1D) equivalent linear models (SHAKE) are preferred over two-dimensional (2D) nonlinear finite-element solutions. Several comparative studies (Bray et al. 1995, 1996; Idriss et al. 1995) also showed that 1D models provide similar results to 2D models under certain conditions. However, 1D equivalent linear solutions by SHAKE have a major drawback (i.e., inability to model friction interfaces). In current engineering practice, this problem is usually overcome by ignoring the geosynthetic liners during the seismic response calculations. Kavazanjian and Matasovic (1995) showed that ignoring the geosynthetics leads to overestimated accelerations in the landfill. Similarly Yegian and Harb (1995) experimentally demonstrated that under seismic excitations, along horizontal and inclined smooth geosynthetic interfaces, slip displacements occur that limit the acceleration transmitted through the interface. Hence, accelerations and shear stresses in a landfill cross section, calculated by ignoring slip along geosynthetic liners, may be overconservative if the analysis is of a new landfill. If the dynamic response analysis performed is of an existing landfill that has experienced an earthquake and if the purpose of the analysis is to back-figure landfill material properties or liner interface friction, ignoring the dynamic response of the geosynthetic liners may then lead to unconservative (overestimated) values of the waste material properties or liner friction coefficients. Hence, depending on the seismic acceleration, the dynamic response of a landfill may be significantly influenced by the presence of geosynthetic liners.

The estimations of earthquake-induced permanent deformations of a landfill and slip displacements along geosynthetic liners require the calculation of the average accelerations within the landfill. Typically, in engineering practice, a wave-propagation analysis is performed, and the shear stresses and accelerations within a landfill are calculated, considering an earthquake motion at the base of the landfill or its foundation

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soils. In such an analysis, it is imperative that the effect of the presence of geosynthetic liners are properly included. This paper presents an analysis approach and dynamic properties of geosynthetic interfaces that will permit the inclusion of the dynamic response of geosynthetic liners in wave-propagation analysis of landfills. An equivalent soil layer is described that replaces a geosynthetic liner in a SHAKE analysis. This layer behaves similar to a geosynthetic liner in limiting the shear stresses transmitted through the liner interface.

METHODOLOGY

The use of an analytical model that describes the dynamic behavior of a geosynthetic interface allows the flexibility of simulation for field conditions that cannot be easily reproduced in the laboratory. The analytical procedure developed is based on the representation of the geosynthetic interface shown in Fig. 1(a) by an equivalent spring and dashpot system as shown in Fig. 1(b). The geosynthetic interface acceleration versus slip displacement hysteresis loops obtained from shaking table tests was used to calculate the parameters (stiffness and damping ratio) of the equivalent system.

Roesset (1968) demonstrated that 1D wave-propagation analysis, such as the SHAKE analysis, through a soil profile is analogous to the analysis of a lumped mass multidegree-of-freedom system. The equivalent mass, stiffness, and damping of the system will depend on the soil layer thickness, soil modulus, and damping. Thus, the stiffness and dashpot representing the geosynthetic interface [Fig. 1(b)] can be used to describe an equivalent soil layer (Yegian and Harb 1996) that has dynamic properties similar to that of the geosynthetic interface considered [Fig. 1(c)]. This equivalent soil layer can then be introduced conveniently in the SHAKE analysis to represent the dynamic response of the geosynthetic interface. In the following sections, the details of the formulation of the properties of the equivalent soil layer and the validation of the model are presented for a geomembrane/geotextile interface. The properties of equivalent soil layers representing other geosynthetic interfaces are also presented in this paper.

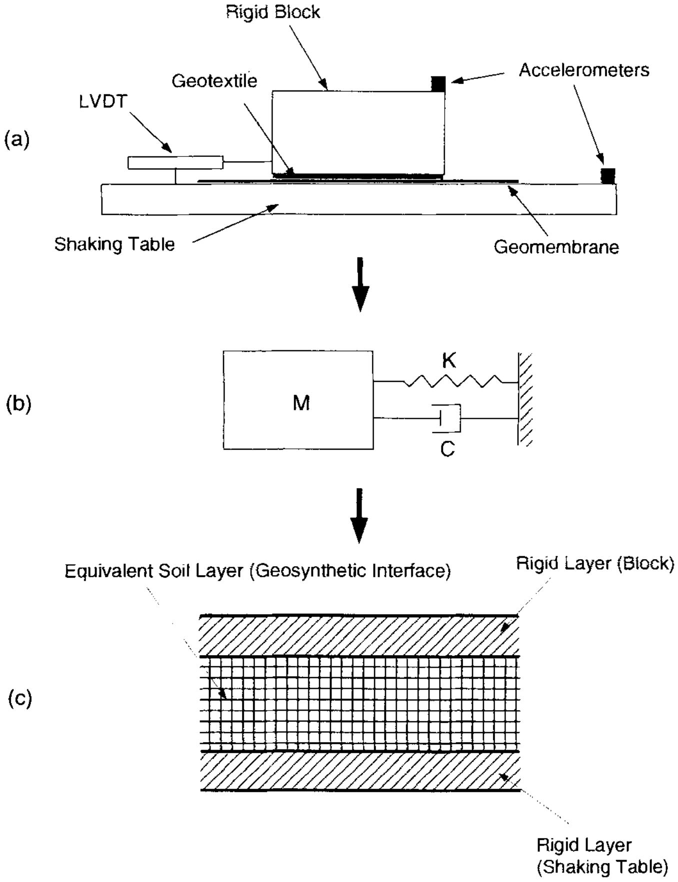

FIG. 1. Representation of Geosynthetic Interfaces by Equivalent Soil Layer: (a) Geosynthetic Interface on Shaking Table; (b) Equivalent Single-Degree-of-Freedom System; (c) Equivalent Soil Layer

EQUIVALENT STIFFNESS AND DAMPING

Fig. 2 shows typical shaking table test results on a smooth high-density polyethylene (HDPE) (Gundline 60 mil)/geotextile (Polyfelt TS 700) interface. The vertical axis shows the acceleration transmitted to a rigid block placed on the interface [Fig. 1(a)]. The horizontal axis represents the slip displacement recorded along the interface. It is noted that the peak transmitted acceleration multiplied by the mass of the block provides the shear force along the interface. This force acts in the direction opposite to the direction of the acceleration.

From Fig. 2, it is observed that the dynamic force-slip relationship for an HDPE/geotextile interface is nonlinear. At small base acceleration, and thus at small slip, almost rigid behavior is seen and the stiffness is very large. As the base acceleration is increased, the peak transmitted acceleration slightly increases and a stick-slip behavior is observed at the time of reversal of the block direction, exhibited as a sudden increase in transmitted acceleration. In the following section,

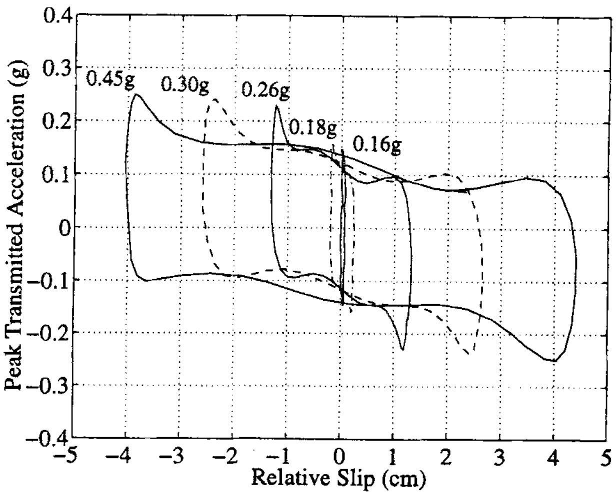

FIG. 2. Transmitted Acceleration versus Slip Hysteresis Loops at Various Base Accelerations for HDPE/Geotextile Interfaces

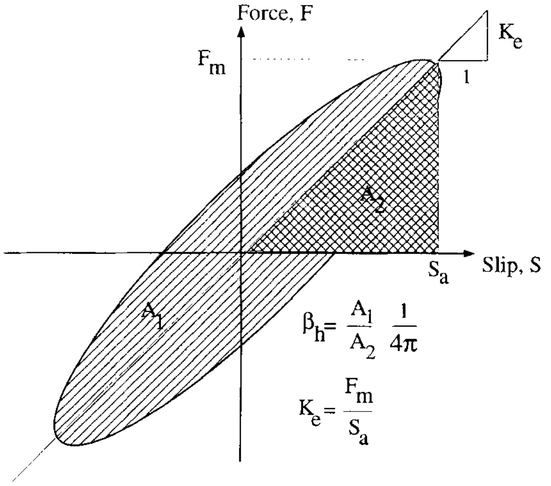

FIG. 3. Force-Slip Relationship that Allow Calculation of Equivalent Stiffness and Damping

the dynamic stiffness and damping ratio are retrieved from force-slip relationships.

An approximate approach for modeling the behavior of a geosynthetic interface is to consider the system behavior to be linearly elastic, with an equivalent stiffness that is dependent on slip amplitude. Fig. 3 shows the definitions of equivalent elastic stiffness and equivalent damping. The equivalent stiffness K_e (kN/cm) is defined as the slope of the line joining the two peaks of the force-slip hysteresis loop. Thus

$$K_e = \frac{F_m}{S_a} \tag{1}$$

where F_m = maximum shear force transmitted through the geosynthetic interface; and S_a = slip amplitude. The shear force F_m can be related to the maximum transmitted acceleration A_t as

$$F_m = MA_t = \frac{W}{g} A_t \tag{2}$$

where M and W = mass and weight of the sliding rigid block, respectively. Thus, combining (1) and (2) results in

$$K_e = \frac{WA_t}{gS_a} \tag{3}$$

From (3), it is seen that stiffness, defined as force per unit slip, is a function of the maximum transmitted acceleration A_t, slip amplitude S_a, and weight W (normal force).

To avoid working with normal force W, in finite-element analysis using interface elements, Desai et al. (1986) have defined stiffness as shear stress (force per unit contact area A_c of interface) per unit slip. Thus K (kN/cm^2/cm)

$$K = \frac{F_m/A_c}{S_a} \tag{4}$$

Substituting for F_m from (2) results

$$K = \frac{WA_t}{A_c g S_a} \tag{5}$$

Thus, the stiffness K (kN/cm^3) is expressed by

$$K = \frac{\sigma A_t}{gS_a} \tag{6}$$

or

$$\frac{K}{\sigma} = \frac{A_t}{gS_a} \tag{7}$$

where σ = normal stress acting on the interface; and K/σ = normalized stiffness (1/cm).

The force-displacement relationships obtained from the shaking table tests were utilized to establish the equation relating the normalized stiffness K/σ to slip amplitude S_a. Fig. 4 shows the experimental data for smooth HDPE/geotextile interfaces tested under 1, 2, and 5 Hz harmonic base motions. The normalized stiffness K/σ were obtained from each hysteresis loop by dividing the maximum transmitted acceleration with the maximum slip observed.

A regression analysis of the data resulted in the following expression for K/σ:

$$\frac{K}{\sigma} = \frac{0.19}{S_a^{0.9}}; \quad R^2 = 0.98 \tag{8a,b}$$

The experimental data confirm the general form shown in (7). Eq. 7 is based on the assumption that the maximum transmitted acceleration does not depend on the maximum slip. In fact, the experimental data showed that the maximum transmitted acceleration increases slightly with increase in base acceleration and, hence, with increase in slip. For this reason, in (8), the exponent of slip S_a is different from unity.

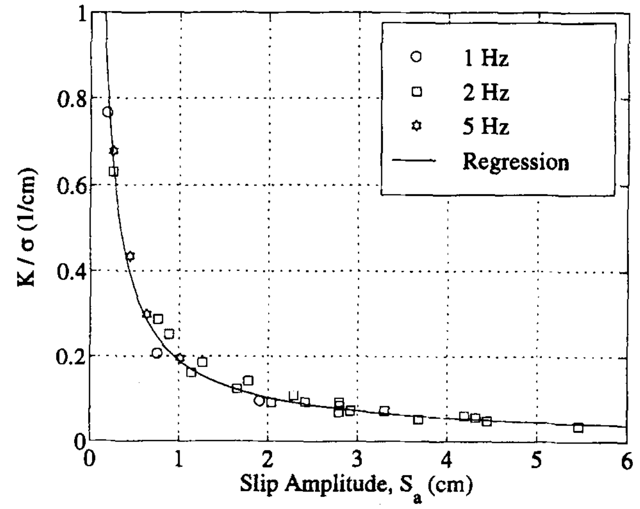

FIG. 4. Regression Line Fitted to Experimental Data for K/σ versus Slip Amplitude S_a for HDPE/Geotextile Interface

As shown in Fig. 3, the hysteretic damping ratio β_h can be obtained by

$$\beta_h = \frac{A_1}{A_2}\frac{1}{4\pi} \tag{9}$$

where A_1 = hysteretic loss of energy during one cycle of excitation; A_2 = elastic strain energy = $1/2K_e S_a^2$; K_e = equivalent elastic stiffness (kN/cm); and S_a = equivalent slip amplitude (cm).

Calculations of β_h from the experimental force-slip relationships showed that the level of slip and the frequency of excitation have little influence on the value of β_h. This is indicative of a hysteretic behavior of the interface. Based on the experimental test results, the value of β_h for smooth HDPE/geotextile interface was computed to be 0.43.

EQUIVALENT SOIL LAYER

Fig. 1(a) shows the shaking table experimental setup in which a rigid box (or block) containing lead weight was placed on an HDPE/geotextile interface. The experimental test provided the dynamic responses of this box. The equivalent soil layer, when used in the computer program SHAKE, predicts the dynamic response of the box measured in the laboratory.

Fig. 1(c) shows the equivalent soil layer used to model the geosynthetic interface in SHAKE analysis. The top rigid soil layer represents the rigid box with the lead weights. The block has a cross-sectional area of 20 × 25 cm^2. With a total weight of 18 kg, the normal stress on the interface is 0.35 N/cm^2. Thus, maintaining the same normal stress as in the experiment, the thickness of the top rigid soil layer having a unit weight of 22 kN/m^3 is ~15 cm. The shear modulus of this rigid layer is assigned a very large value. Below this rigid layer is the equivalent soil layer representing the geosynthetic interface. This layer has a small unit weight of 0.16 kN/m^3 (1 pcf) and has a thickness of 1 m. The thickness is selected such that the period of this layer is much smaller than the period of the propagating wave, thus avoiding misleading resonance effects.

Roesset (1968) demonstrated that in the analysis of wave propagation using the lumped mass system the equivalent stiffness K of a sublayer can be obtained from the ratio of the shear modulus of the soil G and the sublayer thickness H. Thus, for the equivalent soil layer

$$K = \frac{G_e}{H_e} \tag{10}$$

in which K = geosynthetic interface stiffness in force per length per unit area; and G_e and H_e = shear modulus and thickness of the equivalent soil layer, respectively.

The stiffness K of a smooth HDPE/geotextile interface expressed as a function of the normal stress σ acting on the geosynthetic interface and the slip amplitude was given in (8). Thus, for a given normal stress σ and slip amplitude S_a, the stiffness of the geosynthetic can be calculated from (8). Using this value of K and (10), a combination of equivalent soil shear modulus G_e and thickness H_e can be calculated. The criterion used in defining the thickness H_e of the equivalent soil layer was that its period is <0.05 s, to avoid layer resonance in the dynamic response analysis. Thus

$$T_e = \frac{4H_e}{\sqrt{G_e/\rho}} \le 0.05 \text{ s} \tag{11}$$

Replacing G_e by K using (10)

$$T_e = \frac{4H_e}{\sqrt{KH_e/\rho}} \le 0.05 \text{ s} \tag{12}$$

For typical values of σ (larger than 5 N/cm^2) and S_a (smaller than 7.5 cm, HDPE/geotextile stiffness will be such that an equivalent soil thickness of $H_e \cong 1$ m (~3.5 ft) will meet the requirement of (10). Thus, it is recommended that in SHAKE analysis, the thickness of the equivalent soil layer representing the geosynthetic interface be specified 1 m.

The modulus of the equivalent soil layer G_e can be obtained as a function of normal stress σ and slip amplitude S_a by combining (8) and (10)

$$\frac{G_e}{\sigma} = \frac{19.26}{S_a^{0.9}} \tag{13}$$

Eq. (13) provides the normalized (with respect to normal stress) modulus of an equivalent soil layer of 1 m that replaces a smooth HDPE/geotextile interface in SHAKE analysis.

The results from SHAKE analysis provide the transmitted acceleration (acceleration at the top of the equivalent soil layer), as well as the shear strain within the equivalent soil layer representing the geosynthetic interface. The slip amplitude S_a can be obtained from the computed average shear strain γ_e within the equivalent soil layer by

$$S_a = \gamma_e H_e \tag{14}$$

or

$$S_a \text{ (cm)} = \gamma_e \text{ (\%)} \tag{15}$$

where γ_e = equivalent shear strain in percent. Combining (13) and (15) yields

$$\frac{G_e}{\sigma} = \frac{19.26}{\gamma_e^{0.9} \text{ (\%)}} \tag{16}$$

Fig. 5 shows the normalized G_e/σ modulus as a function of the equivalent shear strain γ_e (%) for the same experimental data shown in Fig. 4. Also, for comparison, (16) is plotted in Fig. 5 together with the experimental data. As expected, (16) is a good predictor of the data because it is based on (8), which was obtained by fitting the K versus S_a data from the experiments.

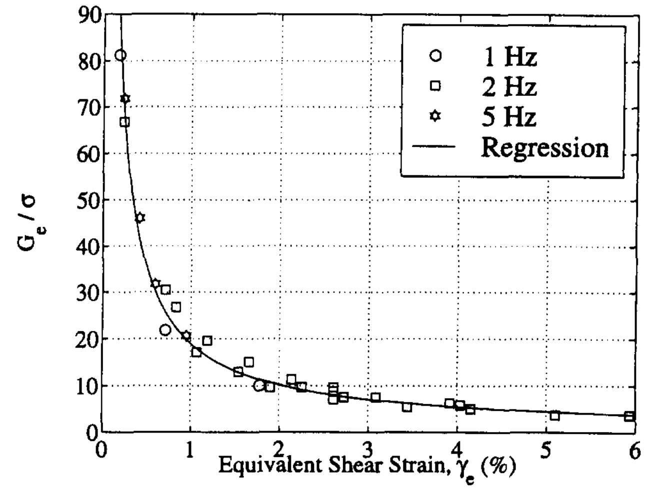

FIG. 5. Equivalent Shear Modulus Divided by Normal Stress σ versus Equivalent Shear Strain γ_e for 1-m-Thick Equivalent Soil Layer Representing HDPE/Geotextile Interface

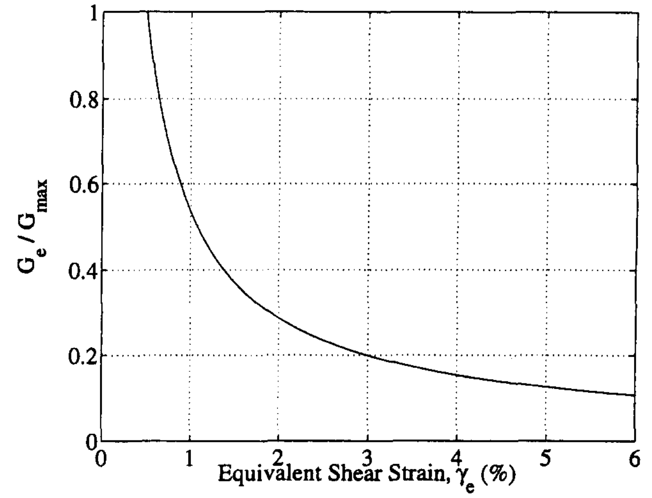

FIG. 6. Normalized Equivalent Shear Modulus versus Equivalent Shear Strain for 1-m-Thick Equivalent Soil Layer Representing HDPE/Geotextile Interface (G_{max} Is G_e at γ = 0.5%)

In SHAKE analysis, the strain dependency of shear modulus of soils is typically introduced by a normalized relationship which has an ordinate of G_e/G_{max}, where G_{max} is the modulus at small strain (typically for soil γ_e = 0.0001%), and G is the modulus at any other strain γ_e (%). Since G_e, the equivalent modulus of an HDPE/geotextile interface, increases asymptotically as equivalent shear strain decreases, it was decided to normalize the curve of Fig. 5 with a value of G_e at γ_e = 0.5%. The basis for selecting γ_e = 0.5% for normalization is that this value corresponds to a slip amplitude of

$$S_a = \gamma_e \text{ (\%)} = 0.5 \text{ cm}$$

At slips smaller than 0.5 cm, an HDPE/geotextile interface exhibits almost rigid behavior, and its dynamic response is very difficult to record accurately. Thus at S_a < 0.5 cm an HDPE/geotextile interface can be assumed infinitely stiff, for practical purposes.

Based on (16), the normalized equivalent shear modulus of an HDPE/geotextile interface can be derived as

$$\frac{G_e}{G_e\ (\gamma_e = 0.5\%)} = \frac{19.26}{\gamma_e^{0.9} \text{ (\%)}} \frac{0.5^{0.9}}{19.26} = \frac{0.536}{\gamma_e^{0.9} \text{ (\%)}} \tag{17}$$

Fig. 6 shows a plot of G_e/G_e (γ_e = 0.5%) as a function of γ_e (%). The plot of Fig. 6 can be used in SHAKE analysis together with the specific value of G_e (γ_e = 0.5%) = 36σ obtained from (16) for smooth HDPE/geotextile interface.

The damping ratio used for the equivalent soil layer representing HDPE/geotextile interface in SHAKE analysis was assigned the value of the hysteretic damping ratio (0.43) measured experimentally.

VALIDATION OF EQUIVALENT SOIL LAYER

To test the validity of the procedure for modeling a geosynthetic interface by an equivalent soil layer, analyses were performed using the SHAKE program and the model shown in Fig. 1. For each experimental case, the normalized modulus curve shown in Fig. 6 was used together with the value of the equivalent shear modulus G_e at equivalent shear strain of γ_e = 0.5%. For the HDPE/geotextile interface tested, this modulus was 120 N/cm^2 and was calculated using (16). The damping ratio used was β = 0.43. In each SHAKE analysis, the harmonic motion of the shaking table (base acceleration) was specified as the input motion.

To account for the dependency of the equivalent shear modulus (or stiffness) on shear strain (or slip), the iterative procedure built in the SHAKE program was followed. For each case, response calculations were repeated until the modulus used in calculating shear strain was compatible with the equivalent shear modulus-shear strain curve of Fig. 6. Slip along the geosynthetic interface was calculated from the shear strain within the equivalent soil layer, using (15).

Fig. 7 shows a comparison between the theoretically calculated (using SHAKE) and experimental slips. Fig. 8 shows a similar comparison between the calculated and experimentally measured transmitted accelerations as a function of the base acceleration. The results show good agreement indicating that the equivalent soil layer concept can provide, reasonably well, theoretical estimates of slip and transmitted accelerations using SHAKE analysis.

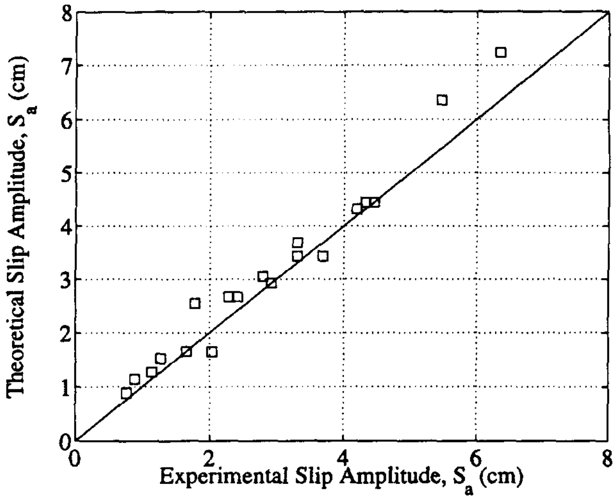

FIG. 7. Comparison between Experimental Slip Amplitudes and those Calculated Using Equivalent Soil Layer and SHAKE

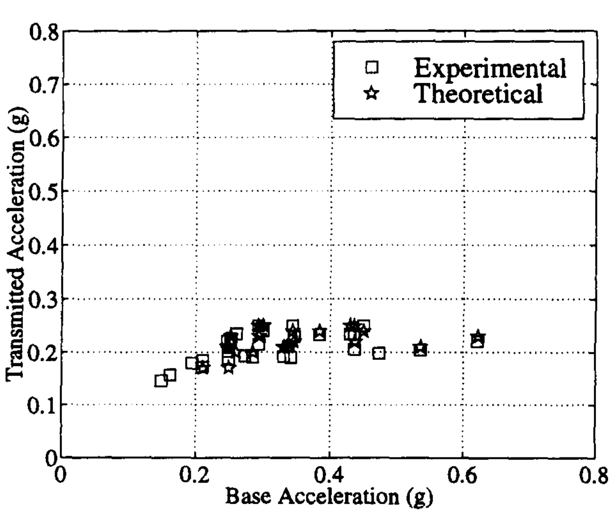

FIG. 8. Comparison between SHAKE and Experimental Transmitted Acceleration versus Base Acceleration

Further validation of the equivalent soil layer model was performed using recorded ground motions from a number of different earthquakes. For example, the Spitak record of the 1988 earthquake was scaled to a peak acceleration of 0.4g and used as base motion in shaking table tests. This base acceleration together with the transmitted acceleration (the acceleration of the box), for a smooth HDPE/geotextile interface, were measured in the laboratory, and are shown in Fig. 9. From Fig. 9, it can be noted that the box experiences a limited acceleration. The acceleration transmitted to the box varies from one pulse to another with a maximum value of 0.23g.

The same base motion, with peak acceleration of 0.4g, was used in a SHAKE analysis to calculate the acceleration transmitted to the box tested on the shaking table. The geosynthetic interface was modeled using the equivalent soil layer described earlier. The equivalent shear modulus, compatible with the equivalent shear strain, was obtained by using 2/3 of the calculated maximum shear strain within the equivalent soil layer. The transmitted acceleration time histories from the shaking table test and values calculated from SHAKE analysis are

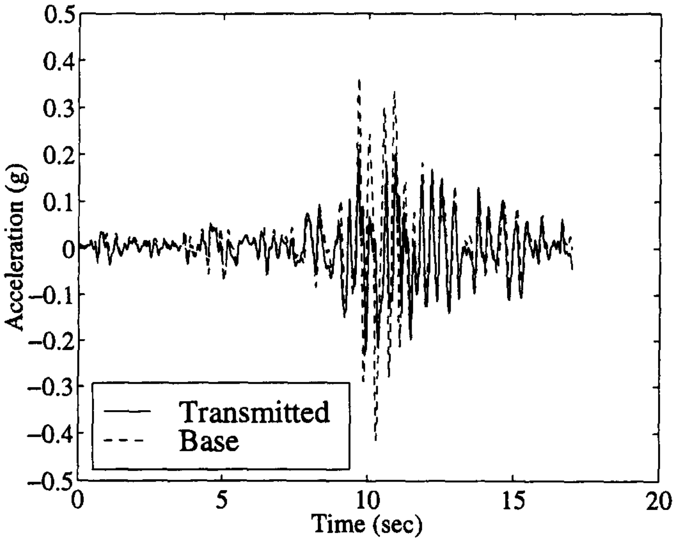

FIG. 9. Experimental Base and Transmitted Acceleration Time Histories for HDPE/Geotextile Interface Using Spitak, 1988 Earthquake Record Scaled to 0.4g

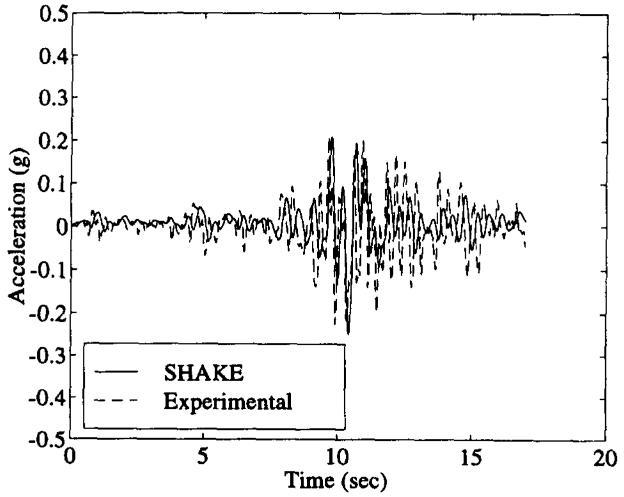

FIG. 10. Comparison between Experimental and SHAKE Calculated Transmitted Acceleration Time Histories for Spitak, 1988 Earthquake Record Scaled to 0.4g

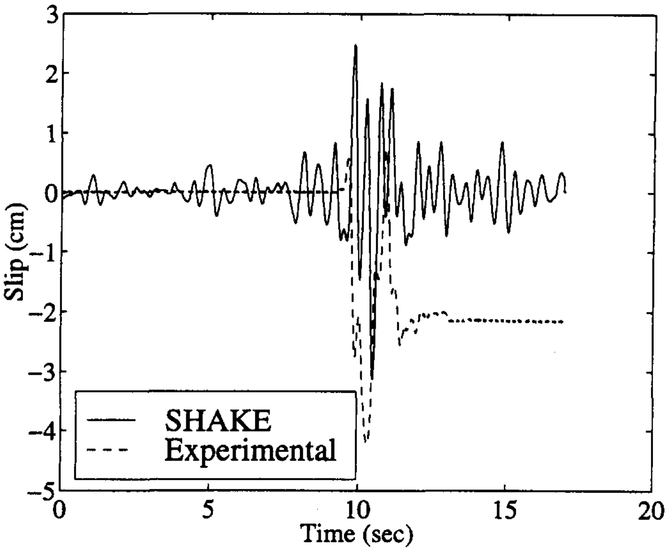

FIG. 11. Time History of Slip Calculated with SHAKE for HDPE/Geotextile Interface Using Spitak, 1988 Earthquake Record Scaled to 0.4*g* and that Measured in Shaking Table Test

compared in Fig. 10. A close match between the calculated and the measured transmitted accelerations is observed.

Fig. 11 shows the experimentally measured slip-time history of the horizontally placed box on an HDPE/geotextile interface. The slip was measured by a linear variable differential transducer (LVDT) fixed on the shaking table. The magnitude of the maximum slip (peak-to-peak) is ~5.0 cm; and the permanent slip is ~2.0 cm.

From SHAKE analysis, slip was obtained by multiplying the calculated strain within the equivalent soil layer by the thickness of the layer H_e. The calculated slip-time history, shown in Fig. 11, shows a peak-to-peak value of ~5.6 cm and is in reasonably good agreement with the experimental slip (5.0 cm), shown in Fig. 10. However, SHAKE analysis that uses linearly elastic properties for the equivalent soil layer cannot predict the permanent slip that occurred in the experiment. Yegian and Harb (1995) showed that along horizontally placed geosynthetic interfaces, permanent slips are negligible, whereas the maximum (peak-to-peak) slip can be as large as 15 cm. Hence, for horizontally placed geosynthetic liners, maximum slip, not permanent slip, is of concern. The equivalent soil layer model used in SHAKE analysis can provide reasonable estimates of this maximum slip.

The good agreements observed between the theoretically computed and experimentally measured transmitted accelerations and slips indicate that the equivalent soil layer described can be used in SHAKE analysis to represent a geosynthetic interface in the dynamic response analysis of landfills.

DYNAMIC PROPERTIES OF EQUIVALENT SOIL LAYERS FOR GEOSYNTHETIC INTERFACES

In the previous sections, the concept and validation of equivalent soil layer for a smooth HDPE/geotextile interface were presented. Similar shaking table tests were performed on other commonly used geosynthetic interfaces. The equivalent shear moduli G_e/σ of these interfaces were normalized by dividing by the G_e (γ_e = 0.5%)/σ of the corresponding interface. Table 1 lists the G_e (γ_e = 0.5%)/σ for each of the interfaces tested. Fig. 12 shows the normalized G_e/G_e (γ_e = 0.5%) for all the interfaces tested. Clearly, the modulus of the equivalent soil layer depends on the type of interface. However, for the interfaces tested, the reduction in the equivalent modulus as a function of slip amplitude is very similar. Thus, in practice, to obtain the modulus G_e/σ of an equivalent soil layer representing one of the interfaces listed in Table 1, the curve shown in Fig. 12 should be multiplied by the G_e (γ_e = 0.5%)/σ from Table 1. The damping ratio for the different interfaces did not vary appreciably, and an average value of 0.45 is recommended for all the interfaces.

TABLE 1. Equivalent Shear Moduli G_e (γ_e = 0.5%)/σ for Each Interface Tested

Interface (1)	G_e (γ_e = 0.5%)/σ (2)
HDPE/clay (dry)	47
HDPE/clay (wet)	63
Textured HDPE/clay (dry)	58
HDPE/geogrid	43
HDPE/Gundseal	35
HDPE/geotextile	36
HDPE/Ottawa sand	52
PVC/Gundseal	58
PVC/geotextile	57

Note: PVC = polyvinyl chloride.

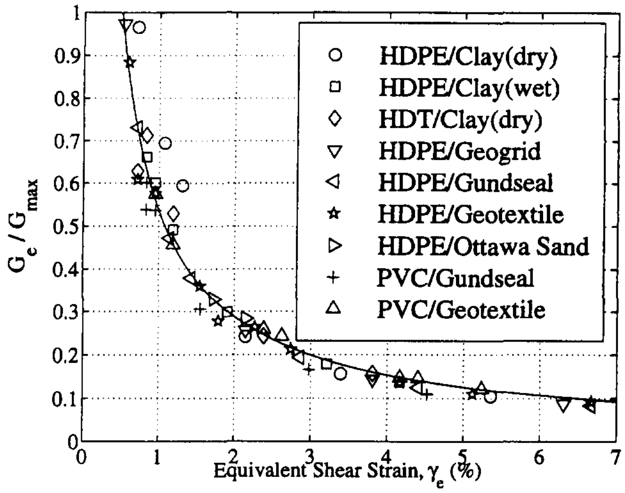

FIG. 12. Normalized Equivalent Shear Modulus versus Equivalent Shear Strain for Equivalent Soil Layer Representing Various Geosynthetic Interfaces (G_{max} Is G_e at γ = 0.5%). (PVC = Polyvinyl Chloride)

PROCEDURE FOR SEISMIC ANALYSIS OF LANDFILLS

Landfill cross sections can be of different shapes. Often in engineering practice, multiple 1D response analyses are performed to approximate the 2D response of a landfill. In such an analysis, equivalent linear material properties are typically used to describe nonlinear behavior. The procedure described herein is based on the utilization of SHAKE to solve for the dynamic response of a landfill cross section that contains geosynthetic liners. SHAKE analysis results can then be used to estimate the earthquake-induced slip deformations along the bottom and cover liner interfaces, as well as the permanent deformations of a critical mass of landfill waste. The following steps describe the procedure:

- Step 1: Prepare a 1D column representing the landfill cross section and the various materials present, including layers of foundation soil, clay liners, drainage layers, and the waste deposit. Identify the material properties of each layer according to the current practice in geotechnical earthquake engineering.
- Step 2: At each elevation where there is a geosynthetic liner, insert an equivalent soil layer (thickness of 1 m and unit weight of 0.16 kN/m^3), with equivalent slip-depen-

dent material properties as described in this paper. Select G_e ($\gamma_e = 0.5\%$)/σ for the interface from Table 1. Multiply this ratio by the overburden pressure at the elevation of the liner to obtain the shear modulus G_e ($\gamma_e = 0.5\%$) of the equivalent soil layer. Multiply the curve in Fig. 12 by G_e ($\gamma_e = 0.5\%$) of the liner and read the resulting values of G_e as a function of equivalent shear strain as input for SHAKE. Use a damping ratio of 0.45 for the equivalent soil layer and read as input for SHAKE.

- Step 3: Perform SHAKE analysis, iterating to ensure strain compatible moduli including the moduli of the equivalent soil layers. Use a factor of 2/3 to convert peak shear strains to equivalent cyclic shear strains.
- Step 4: The maximum slip along the horizontally placed liners (e.g., bottom and cover liners) are obtained by multiplying the computed maximum shear strains in the equivalent soil layers by the thickness of the layer (1 m). The acceleration record computed at the top of the equivalent soil layer representing the bottom liner will be the accelerations transmitted to the landfill. The acceleration record computed at the top of the equivalent soil layer for the cover liner will be the landfill top acceleration.
- Step 5: The accelerations computed within the landfill waste can be used to estimate the average acceleration of a critical mass of landfill $K_{\max}$. This value of $K_{\max}$, which will be influenced by the slip displacements along the liners, can then be used to calculate the permanent deformations of the landfill mass. A number of procedures are currently available that can provide this deformation. The calculation of the permanent deformations of a landfill mass is not within the scope of this paper.
- Step 6: The accelerations computed within the landfill mass, in the vicinity of the landfill slopes, can be used to calculate the average acceleration $K_{\max}$ of the landfill slope. Using this $K_{\max}$ and the slope inclination, the permanent slip along the cover liner on the slopes can be calculated according to the procedure described by Yegian and Harb (1995).

The proposed procedure should only be used when the geometry of the landfill justifies 1D analysis. The model permits the estimation of peak-to-peak displacements and not permanent displacements. Therefore, only horizontally placed or slightly sloped geosynthetic interfaces, such as bottom and cover liners, where peak-to-peak displacements are larger, can be modeled by the equivalent soil layer. However, the more important role of the equivalent soil layer is to allow the SHAKE program to model the property of the geosynthetic liners to absorb earthquake energy by transmitting accelerations limited to the friction coefficient at the interface. Therefore, it predicts the overall landfill response more accurately as opposed to current practice of simply ignoring the geosynthetic liners in a typical 1D SHAKE analysis.

SUMMARY AND CONCLUSIONS

Realistic analysis of the seismic performance of a landfill requires that the dynamic response of the geosynthetic liners be properly considered. A procedure is described that can be used to perform 1D dynamic response analysis of a landfill cross section that includes geosynthetic liners. In this procedure a geosynthetic liner is replaced by an equivalent soil layer that has characteristics that duplicate the liner interface response under dynamic loads. Shaking table test results on various geosynthetic interfaces were utilized to define the material properties of equivalent soil layers for each of the interfaces tested. Using these material properties, an equivalent soil layer can be used in a typical SHAKE analysis to include the dynamic response of geosynthetic liners in a landfill cross section. The equivalent soil layer can model the slip deformations that may occur along geosynthetic interfaces experiencing seismic excitation; such slip deformation can limit the accelerations transmitted through the interface to the landfill waste.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A_c = contact area of interface;
A_t = maximum transmitted acceleration;
A_1 = hysteretic loss of energy during one cycle of excitation;
A_2 = elastic strain energy;
F_m = maximum shear force transmitted through interface;
G = shear modulus;
G_e = shear modulus of equivalent soil layer;
$G_{\max}$ = shear modulus at small strains;
H = sublayer thickness;
H_e = thickness of equivalent layer;
K = stiffness;
K_e = equivalent stiffness;
$K_{\max}$ = average acceleration of critical mass of landfill;
M = mass;
S_a = slip amplitude;
T_e = period of equivalent soil layer;
W = weight;
β_h = hysteretic damping ratio;
γ_e = equivalent shear strain;
ρ = density; and
σ = normal stress.