MODELING GEOSYNTHETIC LINERS IN DYNAMIC RESPONSE ANALYSIS OF LANDFILLS

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ABSTRACT

Realistic analysis of the dynamic response of a landfill that has geosynthetic liners requires the proper modeling of the liner response within the landfill. The authors have conducted shaking table tests and have demonstrated that under dynamic excitations, slip displacements occur along smooth geosynthetic interfaces. Such slip along a geosynthetic bottom liner in a landfill can limit the accelerations transmitted to the landfill waste. Hence, in the estimation of the permanent deformations of a landfill waste and of slip displacements along geosynthetic cover and side slope liners, the effect of the presence of the bottom liner in the dynamic response of the landfill needs to be considered.

This paper describes a one-dimensional wave propagation analysis procedure that allows the modeling of slip along geosynthetic liners placed within a landfill. In this procedure, a geosynthetic interface is replaced by an "equivalent soil layer" of 1 m thickness. The dynamic properties of the equivalent soil layer are derived such that the response of the equivalent soil layer is in agreement with that of the interface as measured in shaking table tests. The paper presents the dynamic properties of equivalent soil layers representing various geosynthetic interfaces encountered in engineering practice. The results from an example study of a landfill cross section, is included to demonstrate the various steps of the procedure, and to illustrate the effect of the presence of geosynthetic bottom and cover liners on the dynamic response of the landfill waste.

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INTRODUCTION

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 groundwater from potential contamination, have to be designed to sustain seismic events. In view of this environmental hazard, federal regulations (EPA 1992) have been formulated to address the problem of siting and designing a solid waste landfill within a seismically active zone.

Earthquake ground motions when propagating through a landfill can induce permanent deformations of the waste fill, as well as, slip displacements along geosynthetic liners used as impervious barriers. Such potential deformations, if excessive, can compromise the integrity of a landfill.

The calculation of earthquake-induced permanent deformations of a landfill requires the investigation of the dynamic response of the landfill. Typically, in engineering practice, wave propagation analysis is performed to estimate the accelerations and shear stresses within the landfill that is experiencing a design level earthquake motion. In such an analysis, the presence of geosynthetic liners within the landfill cross section poses a significant challenge. Kavazanjian et al. (1991, 1995), Yegian et al. (1992), and Zimmi et al. (1994) have demonstrated that under dynamic excitations geosynthetic interfaces can transmit only limited shear stresses. Stresses larger than this limiting level will induce slip displacements along the geosynthetic interface. In current engineering practice, to simplify the dynamic analysis of a landfill, the presence of geosynthetic liners is generally ignored. This practice effectively assumes that there is no slip induced along the liners during a seismic event.

This paper presents a brief description of a model that can be used to represent the dynamic response of geosynthetic liners in one-dimensional wave propagation analysis of landfill cross sections. The paper also includes example applications of the dynamic response analysis procedure that incorporate geosynthetic liners. The results from these example analyses are discussed and conclusions are made regarding the effect of smooth geomembrane liners on the dynamic response of municipal solid waste landfills.

EQUIVALENT SOIL LAYER

The dynamic response calculation of a landfill is a difficult problem due to various factors including: the geometric irregularities, uncertainties in material properties of the landfill waste, and the nonlinear nature of the geosynthetic liner interfaces. A two-dimensional nonlinear dynamic analysis can accurately estimate the dynamic response of a landfill. Often, in current practice, a simplified analysis approach is followed due to the extreme effort and time required for a complicated two-dimensional analysis. Usually, the problem is simplified by using multiple one-dimensional wave propagation analysis in which the geosynthetic liners are ignored. Previously, Yegian et al. (1995), and Kavazanjian and Matasovic (1995) showed that slip deformations occur along a geosynthetic liner, limiting the accelerations transmitted to the landfill. Hence, an analysis ignoring the geosynthetic liners would produce overestimated response of the landfill. To allow the performance of one-dimensional dynamic response analysis of landfill cross sections that include geosynthetic liners, a model has been developed by (Yegian at al. 1996) that can represent the dynamic response of the liners in the analysis. Figure 1a shows a schematic diagram of a simple landfill profile consisting of a layer of waste fill, and cover and bottom geosynthetic liners. In Figure 1b, the same profile is shown except that the liners are replaced by equivalent soil layers that have identical dynamic response characteristics as the liner interfaces. The use of equivalent soil layers permits the dynamic response analysis of a landfill to be performed easily with the computer program SHAKE (Schnabel et al. 1972).

The dynamic properties of an equivalent soil layer representing a geosynthetic interface were developed from the measurement of the response of the interface in shaking table tests. Initially, the force-displacement hysteresis curves of an interface were measured using the shaking table. The hysteresis loops were then used to obtain equivalent springs and dashpot coefficients. These equivalent parameters were then used to describe an equivalent soil layer that had response characteristics similar to that of the geosynthetic interface it represented. The validity of the equivalent soil layer model and its parameters, were confirmed by comparing the response of a rigid block placed on the interface and tested experimentally, with its response calculated analytically using the equivalent soil layer and the SHAKE program.

Yegian et al. (1998) describe the details of the formulation of the dynamic properties of the equivalent soil layer for a geosynthetic interface. The layer has a thickness of 1 m with a unit weight of 0.16 kN/m^3 (1 pcf). For each interface tested, the equivalent shear modulus, G_e, at an equivalent shear strain, γ_e, of 0.5%, was normalized with respect to the vertical normal stress, σ, acting on the interface. Table 1 presents the G_e (γ_e=0.5%)/σ for the interfaces tested. In addition, for each interface, the equivalent shear modulus, G_e, was normalized with respect to G_e (γ_e=0.5%) and were plotted as a function of equivalent shear strain, γ_e, as shown in Figure 2. Clearly, the modulus of an equivalent soil layer replacing a geosynthetic interface depends on the type of geosynthetic. However, as shown in Figure 2, for the interfaces tested, the reduction in the equivalent modulus as a function of equivalent shear strain is very similar. In engineering practice, to obtain the modulus, G_e, versus shear strain, γ_e, of an equivalent soil layer representing one of the interfaces listed in Table 1, the curve shown in Figure 2 should be multiplied by the product of G_e(γ_e=0.5%)/σ from the Table 1 and the normal stress, σ, acting on the interface. Calculations of the damping ratio from experimental force-displacement relationships showed that the level of slip and frequency have little influence on the damping values. Therefore, based on the experimental results, an average damping value of 0.45 is recommended for all interfaces. This relatively large equivalent damping ratio describes the large dissipation of energy through friction along the interface.

EXAMPLE APPLICATIONS

Figure 3 shows a simple cross section of a landfill with cover and bottom geosynthetic liners. The dynamic response of this landfill profile was investigated by selecting a one-dimensional column as shown in Figure 3. The layer thickness and material properties of the landfill column are shown in Figure 4. In this landfill column, the geosynthetic liners (smooth HDPE geomembrane/geotextile) are replaced by equivalent soil layers. The equivalent shear modulus versus shear strain curves of the smooth HDPE/geotextile bottom and cover liners were obtained from Table 1 and Figure 2. For HDPE/geotextile, G_e (γ_e=0.5%)/σ of 36 was multiplied by the vertical normal stress acting on the bottom and cover liners. The resulting equivalent shear moduli at a shear strain of 0.5% were 8622 kN/m^2 and 210 kN/m^2 for the bottom and cover liners, respectively. The curve shown in Figure 2 was then multiplied by the values of G_e(γ_e=0.5%) to obtain the G_e versus γ_e curves for the bottom and cover liners.

Using the equivalent shear moduli of the two liners and a damping ratio of 0.45, as determined from shaking table tests, the dynamic response of the landfill column was performed using the SHAKE program. The earthquake motion from the 1988 Spitak, Armenia, earthquake was normalized to 0.1 g and 0.4 g and used as input at the base of the landfill. Figure 5 shows the computed peak accelerations (with and without considering the geosynthetic liners) as a function of depth when the input earthquake motion had a peak acceleration of 0.1 g. The results show that the presence of the geosynthetic bottom and cover liners has no discernible effect on the acceleration within the landfill. This is not surprising because shaking table tests by Yegian and Harb (1995) show that slip deformations along smooth HDPE geomembrane /geotextile interfaces occur only at accelerations larger than about 0.2 g. Hence, if landfill accelerations are less than 0.2 g, ignoring the presence of smooth HDPE geomembrane/geotextile liners in the dynamic analysis of a landfill is reasonable.

Figure 6 shows peak accelerations, with and without geosynthetic liners, computed using an input motion scaled to 0.4 g. In this case, the bottom and cover geosynthetic liners play an important role in modifying the earthquake motion propagating through the landfill. For example, if the geosynthetic liners are ignored in the analysis, the acceleration at the base of the waste fill is 0.47 g. Including the liner responses by using equivalent soil layers reduces the acceleration at the base of the waste fill by a factor of 2, to about 0.21 g. Similarly, if the liners are ignored, the acceleration on top of the landfill is 0.58 g, and if the liners are included the landfill top acceleration is 0.28 g. Clearly, when the base acceleration is larger than 0.2 g, slip occurs along the geosynthetic liners thus limiting the accelerations transmitted through the liner interfaces. Ignoring this can unreasonably overestimate the landfill response.

Figure 7 summarizes the results of the dynamic analyses with and without considering the geosynthetic liners. The average acceleration of the waste fill is a parameter of importance in the calculation of the permanent deformations of the waste fill, and in the estimation of slip displacements along the side slope. In the example where the base acceleration is 0.4 g, if the liners are ignored, the average acceleration of the waste fill is about 0.46 g. When the liners are modeled in the dynamic response analysis of the landfill the average acceleration of the average acceleration of the waste is significantly reduced (0.3 g compared to 0.46 g). These values of the average accelerations of the waste fill were used to calculate slip displacements along the side slope of the example landfill. The procedure of Yegian and Harb (1995) was used for the calculation of the side slope slip, assuming that the side slope liner is a textured HDPE geomembrane/geotextile. The results again indicate that ignoring the dynamic response of the geosynthetic liners can lead to unrealistically large slip displacements (53 cm). Whereas, including the liner response the slip displacement on the slope is estimated to be less than 2.5 cm.

To investigate the effect of the landfill period and the period of the base rock motion on the deamplifying response of the geosynthetic liners, further analyses were made by varying the waste thickness of the landfill and using a rock motion record (the Corralitos record of the 1989 Loma Prieta earthquake).

Figure 8 summarizes the results of the dynamic response analyses performed using the SHAKE program and the equivalent soil layers representing the bottom and cover liners. The horizontal axis defines the ratio of the period of the landfill and the fundamental period of the base motion. The period of each landfill was obtained from the ratio of the response spectrum at the top of the landfill and the spectrum of the rock motion. The vertical axis in Figure 8 indicates the ratio of the landfill top acceleration, with geosynthetic liners, and the top accelerations without the liners. The results shown in Figure 8 demonstrate that the maximum reduction in the landfill top acceleration, because of the presence of the liners, is when the landfill is in resonance with the base rock motion. The magnitude of this reduction will depend on the peak acceleration of the base record. As shown in Figure 5, when the peak base acceleration is 0.1 g, there is no slippage along the bottom and cover liners; and the liners completely transmit the earthquake-induced shear stresses. For the example analyses presented in Figure 8 where the peak base acceleration is 0.5 g, the landfill top acceleration is reduced by a factor of about 0.3 in the landfill that comes in resonance with the base motion. The results from these example analyses clearly demonstrate that smooth geosynthetic liners can have significant deamplifying effect on the dynamic response of the landfill.

SUMMARY

To perform a realistic analysis of the seismic response of a landfill it is very important that geosynthetic liners are properly modeled. A procedure is described that can be used to perform dynamic response analysis of a landfill cross section that includes geosynthetic liners. An equivalent soil layer is briefly described that can be used in SHAKE analysis to model the dynamic response of geosynthetic liners placed in a landfill.

To assess the effect of bottom and cover geosynthetic liners upon the dynamic response of a landfill profile, example analyses were made using the SHAKE program and equivalent soil layers representing smooth HDPE geomembrane /geotextile liners. A typical landfill cross section was established and the thickness of the waste was varied to investigate the effect of the geosynthetic liners on landfills of different fundamental periods. Also, two rock motion records were used, one with longer period than the other, to evaluate the influence of the predominant period of the rock motion on the effect of the geosynthetic liners.

The results demonstrate that smooth HDPE geomembrane/geotextile liners significantly reduce the accelerations and shear stresses transmitted through the landfill profile, especially when the base acceleration exceeds 0.2 g. Ignoring these effects can result in unrealistic estimates of seismic accelerations, shear stresses and permanent deformations in a landfill. Also, the magnitude of the reduction in landfill acceleration and shear stresses due to the presence of geosynthetic liners will depend on the level of the peak acceleration of the base rock, and the ratio of the period of the landfill and the period of the base rock motion. The deamplifying effect of geosynthetic liners is maximum when the landfill cross section is in resonance with the base rock motion.

If in the seismic investigation of a landfill, a one-dimensional dynamic response analysis approach is deemed appropriate, the proposed equivalent soil layer can then easily be used to model in such analysis the previously ignored geosynthetic liners

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REFERENCES

EPA (1992). "Criteria for municipal solid waste landfills; Part 258," Title 40, U.S. Code of Federal Regulations, U.S. Environmental Protection Agency, Washington, D.C.

Kavazanjian, E.J., and Matasovic, N. (1995) "Seismic Analysis of Solid Waste Landfills", Geoenvironment 2000, Geotechnical Specialty Publication No.46, ASCE.

Kavazanjian, E.J. (1994). "SASW testing at solid waste landfill facilities," *Proc. NSF Workshop on Seismic Design of Solid Waste Landfills*, University of Southern California, Los Angeles, CA.

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, CA.

Yegian, M.K, Harb, J.N. and Kadakal, U. (1998). "Dynamic response analysis procedure for landfills with geosynthetic liners," *Journal of Geotechnical Engineering*, ASCE, submitted for publication.

Yegian, M.K. and Harb, J.N. (1996). "Dynamic response of geosynthetic interfaces," *Technical Report*, No.CEE-96-01. Department of Civil and Environmental Engineering, Northeastern University, Boston, MA.

Yegian, M.K. and Harb, J.N. (1995). "Slip displacements of geosynthetic systems under dynamic excitations," *Earthquake Design and performance of Solid Waste Landfills*, Geotechnical Specialty Publication, No.54, ASCE.

Yegian, M.K. and Lahlaf, A.M. (1992). "Dynamic interface shear properties of geomembrane and geotextiles," *Journal of Geotechnical Engineering*, ASCE, 118(5), 760-779.

Zimmie, T.F., De, A. and Mahmut, M.B. (1994). "Centrifuge modeling to study dynamic friction at geosynthetic interfaces," *Proc. Fifth Int. Conf. on Geotextiles, Geomembranes and Related Products*, Singapore.

Table 1. Equivalent Shear Moduli G_e ($\gamma_e = 0.5\%$)/σ for the Interfaces Tested

Interface	G_e ($\gamma_e = 0.5\%$)/σ
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

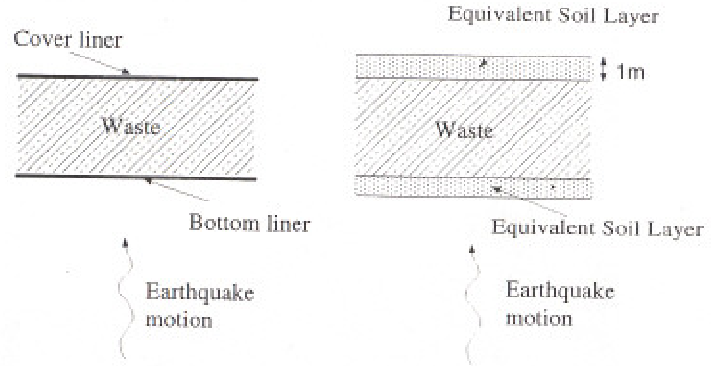


Figure 1. a) Waste Fill with Cover and Bottom Liners, b) Equivalent Soil Layers that Replace the Liners in Dynamic Response Analysis.

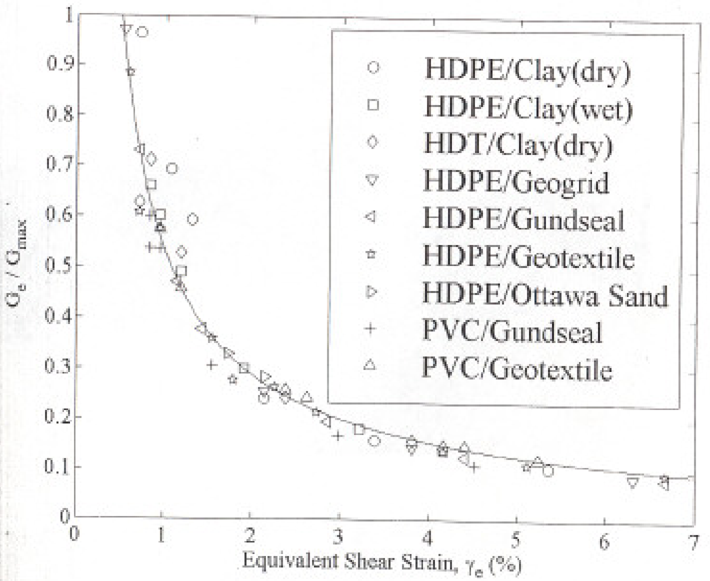


Figure 2. Normalized Equivalent Shear Modulus versus Equivalent Shear Strain for Equivalent Soil Layers Representing Various Geosynthetic Interfaces (G_{max} is G_e at γ_e = 0.5%).

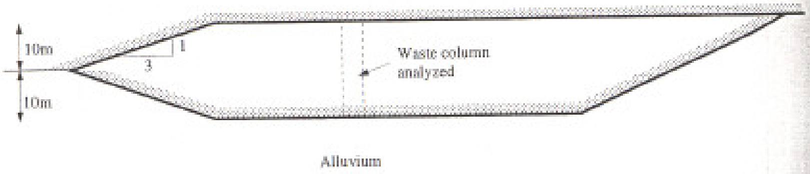
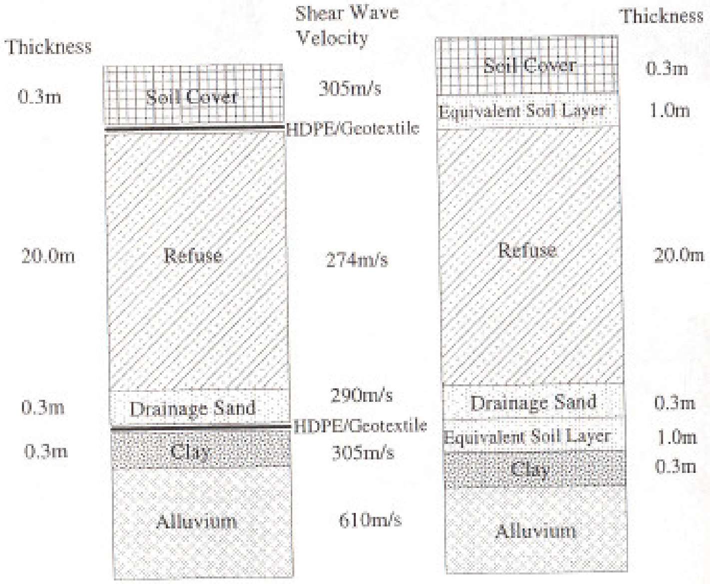


Figure 3. A Simple Landfill Cross Section Analyzed to Demonstrate the Effect of Geosynthetic Liners on Seismic Response.



(a) (b)

Figure 4. Soil/Waste Column Analyzed, a) Original Geosynthetic Liners, b) Equivalent Soil Layers Representing the Geosynthetic Liners.

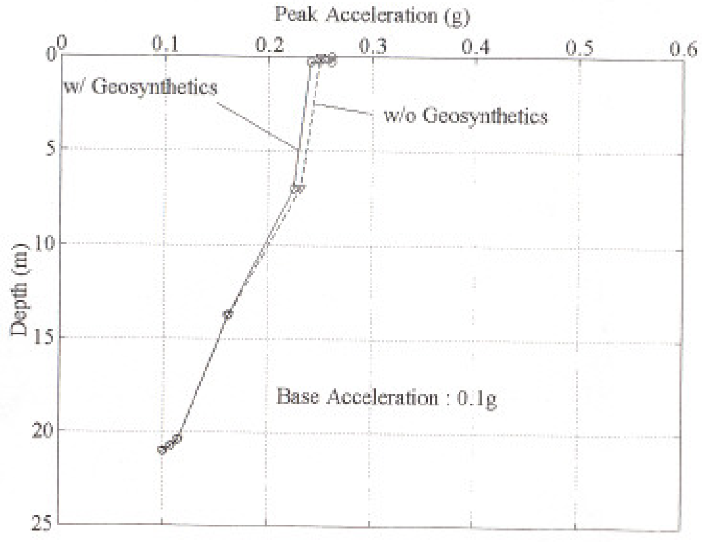


Figure 5. Peak Accelerations with Depth of Landfill Calculated with and without Geosynthetic Liners, and Base Acceleration of 0.1g.

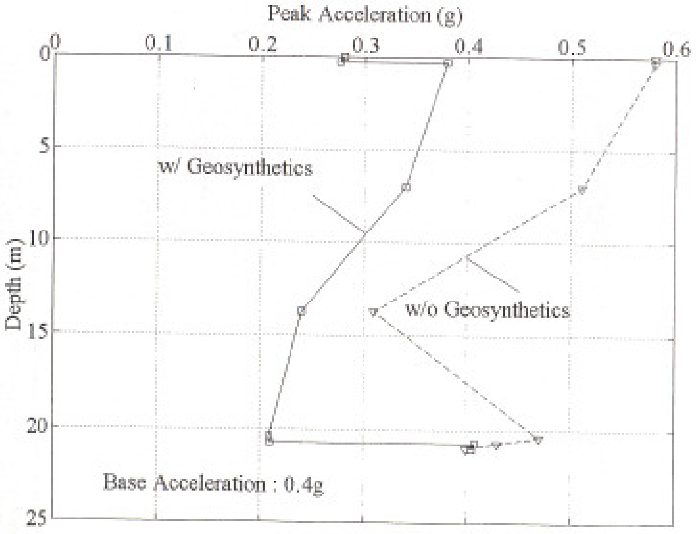


Figure 6. Peak Accelerations with Depth of Landfill Calculated with and without Geosynthetic Liners, and Base Acceleration of 0.4g.

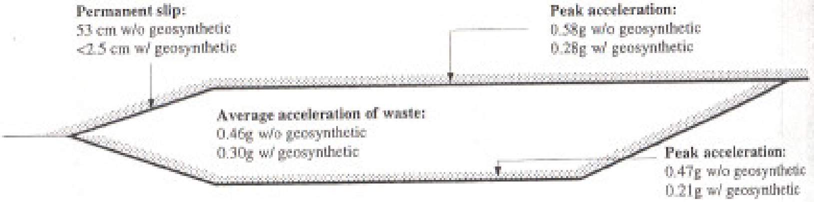


Figure 7. Results from Seismic Analysis of the Example Landfill Showing the Effect of Geosynthetic Liners on the Landfill Accelerations and Side Slope Slip Deformations.

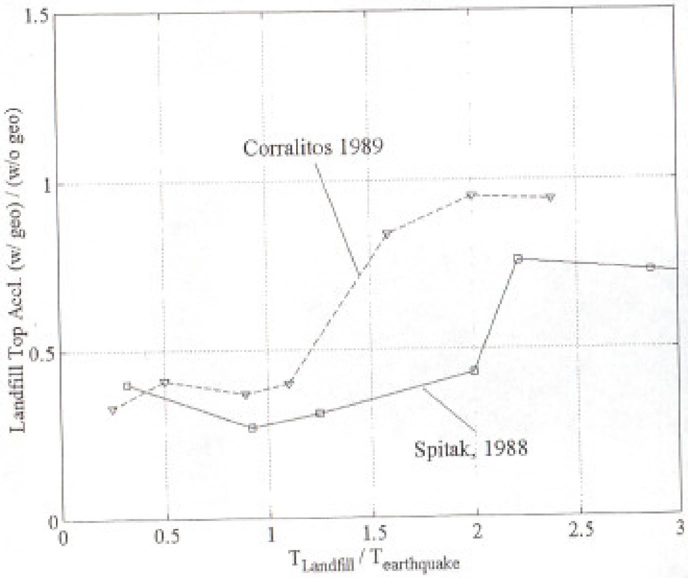


Figure 8. Comparison of Reduction in Landfill Top Acceleration due to Presence of Geosynthetic Liners for Spitak, 1988 and Corralitos, 1989 Records Scaled to 0.5g.