EQUIVALENT LINEAR DYNAMIC RESPONSE ANALYSIS OF GEOSYNTHETICS LINED LANDFILLS

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ABSTRACT

U.S. federal regulations require that municipal solid-waste landfills located in seismic impact zones, which encompass nearly half of the continental United States, be designed to resist earthquake loading. To evaluate the seismic performance/deformation of the containment structures, the seismic response of the waste repository must be evaluated. Conventional site response analyses use 1-D wave propagation without consideration of the required composite liner system installed at the base of the waste that usually contains geosynthetics. This results in high levels of acceleration being propagated through the landfill. Yegian et. al (1998) proposed the use of an equivalent layer to account for the stiffness and damping characteristics of the liner.

This paper describes a parametric study of the response of geosynthetics lined landfills to seismic shaking using a one-dimensional equivalent linear wave propagation approach. The study focuses on the effects of a) the geosynthetics liner, b) ground motion frequency content, c) ground motion scaling, and d) thickness of the underlying soil. The paper raises issues relevant to engineers involved in the seismic design of landfills and in their assessment of their performance during a seismic event.

INTRODUCTION

U.S. federal regulations for new municipal solid-waste landfills (United States 1991) specify that new waste cells and the lateral expansion of existing cells shall not be located in seismic impact zones, unless all containment structures, including liners, leachate collection and removal systems and surface water control systems, are designed to resist the maximum horizontal acceleration (MHA) if the site is located in a seismic impact zone. A seismic impact zone is defined by the U.S. Environmental Protection Agency as areas with a 10% or greater probability that the maximum horizontal acceleration in lithified earth material will exceed 0.1g in 250 years. To evaluate the seismic performance of all containment structures, the seismic response

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of the waste repository must be evaluated. This is necessary to determine the permanent deformations within the soil foundation, bottom liner system, waste, and final cover system. These permanent movements could damage the liner system and possibly cause groundwater contamination and/or disrupt the function of the final cover or leachate and gas collection systems.

To estimate the permanent deformation of the liner and cover systems, the maximum horizontal acceleration induced by the design earthquake in the liner and cover systems must be known. To obtain these accelerations the MHA in the underlying bedrock is usually estimated from maps developed by the U.S. Geological Survey (Algermissen et al. 1990) and then a site response analysis is conducted to propagate this earthquake motion to the bottom liner and final cover systems. This propagation has become increasingly difficult because of the increased seismic hazard, especially in the central United States (FEMA 302, 1997) where the bedrock MHA can exceed 1.8g, the large depth of alluvial soil usually present under the landfill, and the high frequency of the earthquake motion. These factors usually result in large maximum horizontal accelerations being calculated at the bottom liner system.

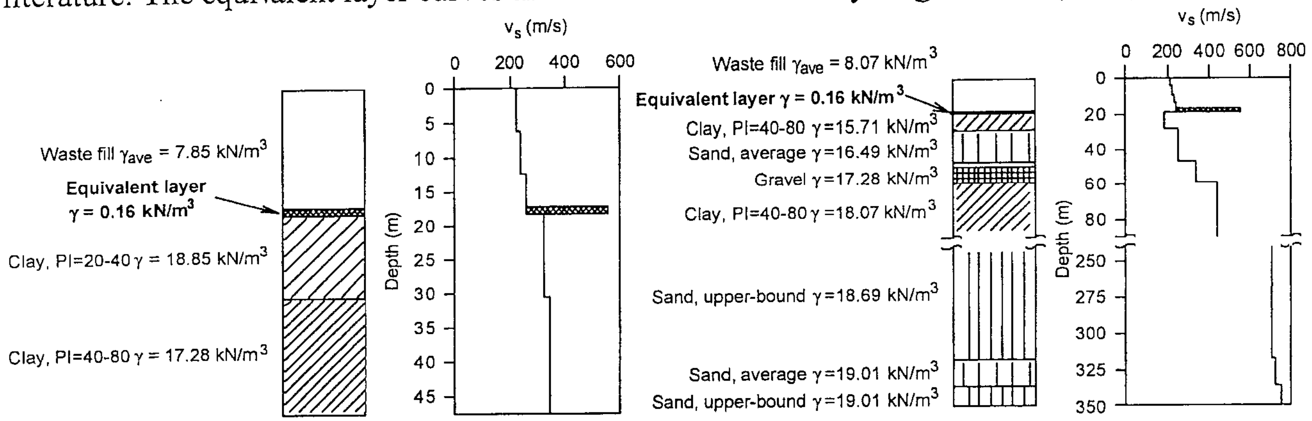
This paper presents a parametric study of the influence of a geosynthetic on propagation of ground motion through a landfill. The wave propagation problem is approximated as the 1-D vertical propagation of SH waves. This study evaluates the implications of the method proposed by Yegain and co-workers for evaluating the seismic response of landfills taking into account the effects of the geosynthetic liner layer.

DYNAMIC RESPONSE ANALYSIS

Many recent field case histories (Byrne et al. 1992, Stark et al. 1998, Seed et al. 1990, Stark 1999) suggest that geosynthetics, and in particular a geomembrane, can create a weak interface due to the low frictional resistance between it and another geosynthetic component or soil. This weak interface may not be beneficial for slope stability purposes but may be beneficial to the seismic response of the waste repository. The weak interfaces may not be able to transmit the seismic shear stresses and thus function as a base isolation system. The base isolation system reduces the magnitude of shear stress transmitted across the interface by undergoing shear displacement. Yegian et al. (1998) present a study of the dynamic response of geosynthetic interface in municipal solid waste. Laboratory tests are used to develop equivalent stiffness and damping properties of the interface. Yegian et. al. (1998) propose the use of these properties in the analysis of 1-D response of landfills using the equivalent linear method (e.g. SHAKE). This paper presents a parametric study of computed landfill response using the equivalent layer approach.

SOIL PROFILE AND PROPERTIES

Two soil/waste columns representative of landfills in southeast Missouri and northeast Arkansas are used in the parametric study and shown in Figure 1. The figure shows the unit weight used for the soil layers as well as the waste. The geosynthetic, a smooth HDPE/dry clay composite, is represented as a 1 m thick equivalent layer. The modulus degradation and damping curves for the layers are shown in Figure 2. The curves are based on those widely used in the literature. The equivalent layer curves are those recommended by Yegian et al. (1998).

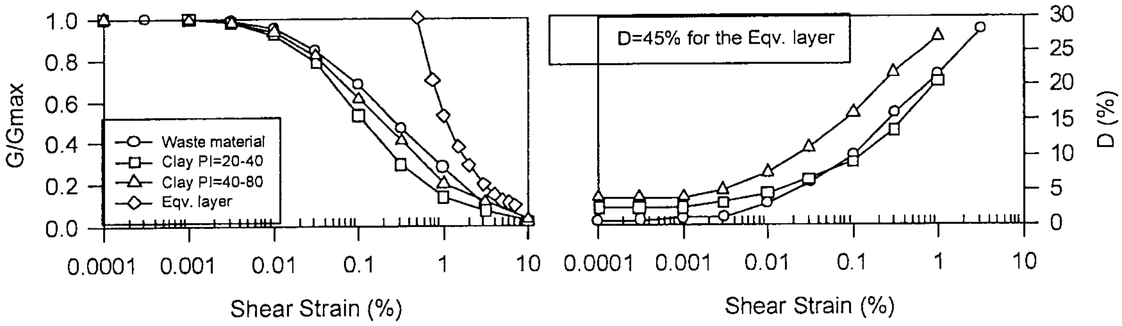


(a) shallow soil profile

(b) deep soil profile

Figure 1 Soil profiles used in analyses

(a) shallow soil profile



(b) deep soil profile

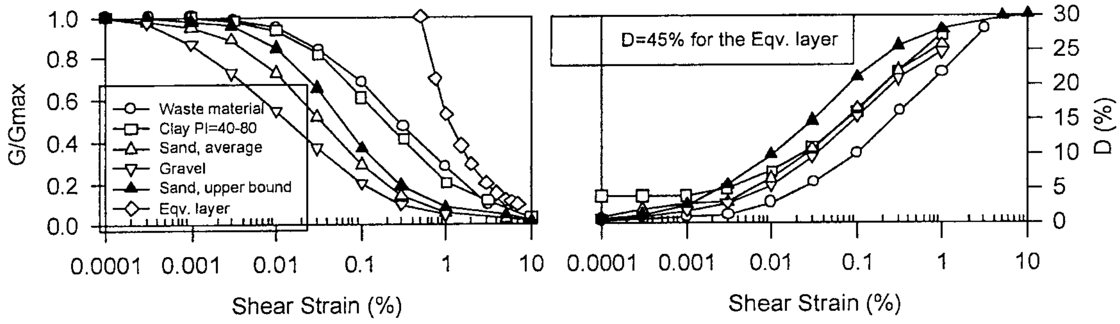


Figure 2 Modulus Degradation and Damping Curves used in the Numerical Analyses

INPUT GROUND MOTION

Four input ground motions are used in the analyses and presented in Table 1, Figure 3 and Figure 4. The recorded motions include Miramichi and Mexico City. The synthetic motions are the New Madrid (http://mae.ce.uiuc.edu) and Alameda motions. The Alameda motion was used in assessing the seismic vulnerability of two immersed tubes in the San Francisco Bay Area (Hashash et. al. 1998). The Miramichi and New Madrid Motions are representative of a Mid-Continent type earthquakes.

Table 1 lists significant parameters of the ground motion including the predominant period of the ground motion. M is the magnitude of the earthquake event. The motions have peak accelerations ranging between 0.1g and 0.76g. The motions have predominant periods ranging between 0.03 sec and 0.63 sec and have significantly different frequency content. Figure 4 presents the response spectra (5% damping) of the unscaled as well as motions scaled to 0.6g. The scaling only affects the amplitude of the ground motion but does not alter the frequency content. In the analyses, scaled and unscaled motions are used as input to the wave propagation analysis.

Table 1 Time histories used in the comparative analyses

Time history (outcrop)	Miramichi M=5.0, 1981, New Brunswick,	Mexico City M=8.1 1985	New Madrid 1000 year event	Alameda Retrofit Design Motion
Type	recorded	recorded	synthetic	synthetic
Duration (sec)	4.52	60.	18.48	48.
Peak acceleration (g)	0.3972	0.1051	0.2701	0.7598
Peak velocity (m/s)	0.0475	0.1154	0.1477	0.7411
Peak displacement (m)	0.0055	0.0378	0.1138	0.4207
Predominant period (sec)	0.03	0.63	0.04	0.2

PARAMETRIC STUDY

A series of 1-D wave propagation analyses are conducted using the soil profiles and ground motions described in previous paragraphs. The analyses are conducted using the equivalent linear method and the programs SHAKE and CyberQuake (software.brgm.fr). The study focused on a) the influence of the equivalent layer, b) the influence of the thickness of the underlying soil and c) the input ground motion on the waste fill response. The following is a description of the analysis results.

EFFECT OF EQUIVALENT LAYER ON WASTE RESPONSE

In this series of analyses the influence of the equivalent layer on the waste response is studied using the shallow soil profile and a waste deposit 17.5 m thick. Figure 5 plots the peak acceleration and strain profiles computed ignoring the influence of the geosynthetic layer. The waste fill experiences peak shear strains up to 0.3 % and large ground accelerations in the range of 0.4g to 1.0 g. Figure 6 presents a parallel set of analyses whereby the geosynthetic layer is modeled as an equivalent layer. Note however the different horizontal scales used. The analyses use the ground motions scaled to, peak ground acceleration, PGA=0.6g. The peak shear strains in the waste fill and the ground accelerations are significantly reduced above the equivalent layer compare to those in Figure 5. Shear strain levels in the equivalent layer are significantly larger than the overlying and underlying layers. Figure 7 shows profiles of acceleration and shear strain ratio profile. The figure shows that peak accelerations in the waste fill are nearly half those computed assuming no influence of the geosynthetic layer. The peak strain ratio profile shows a concentration of shear strains in the geosynthetic layer which experiences significant shearing and acts as a "base" isolation layer resulting is reduced shaking of the overlying waste fill layers.

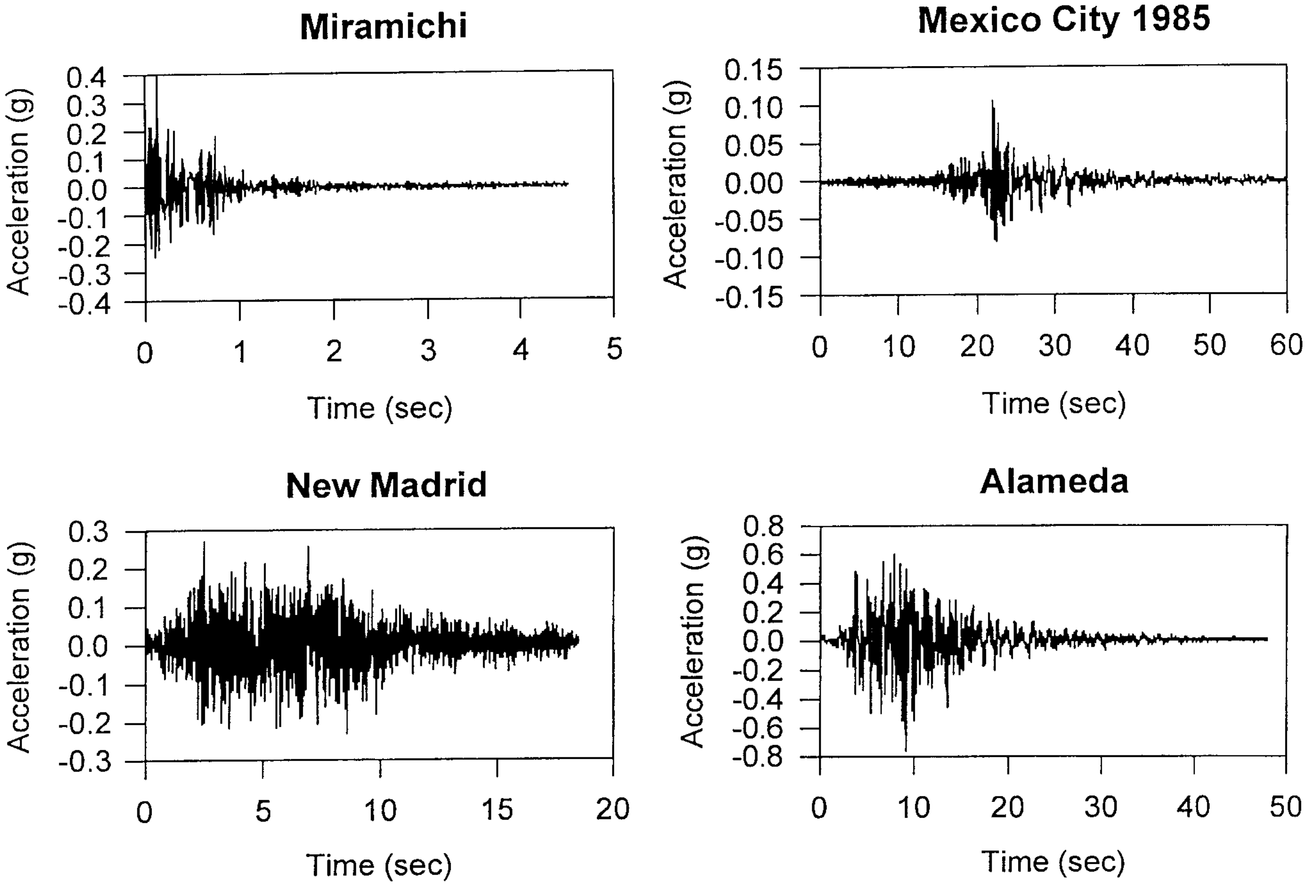


Figure 3 Time histories used in the comparative analyses

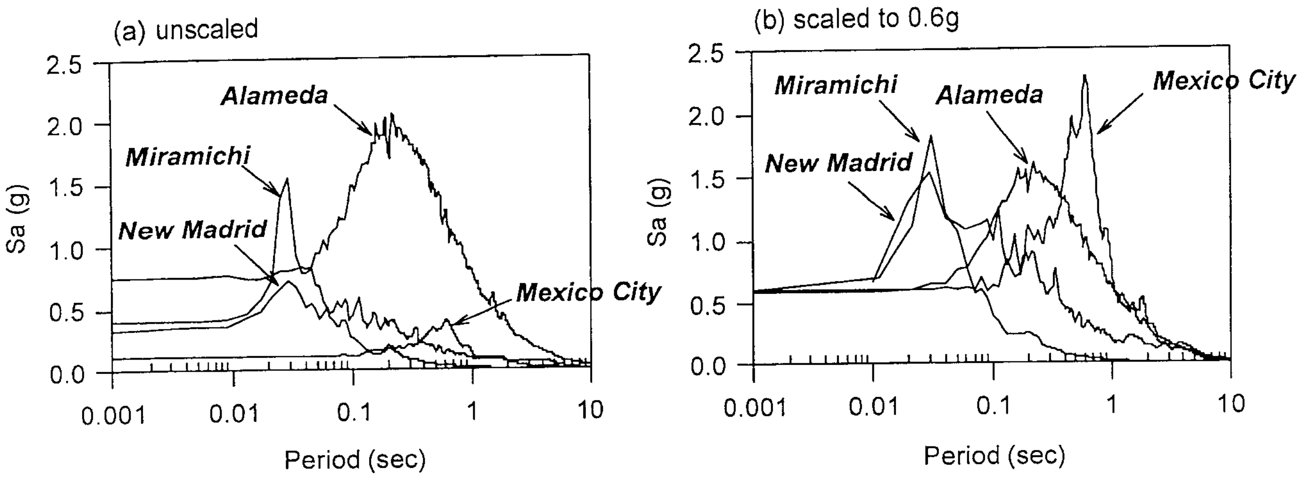


Figure 4 Acceleration spectra (5%) for the time histories used in the analyses

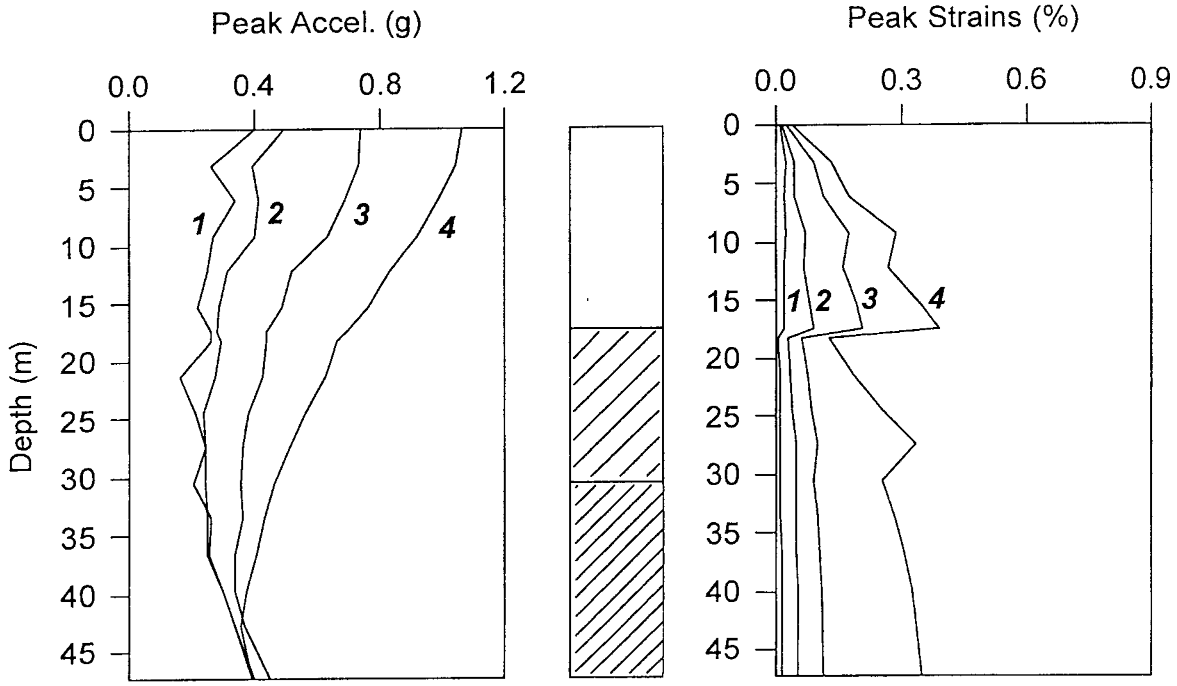


Figure 5 Shallow site without equivalent layer (Time history scaled to 0.6 g)
(1 – Miramichi; 2 – New Madrid; 3 – Alameda; 4 – Mexico City 1985)

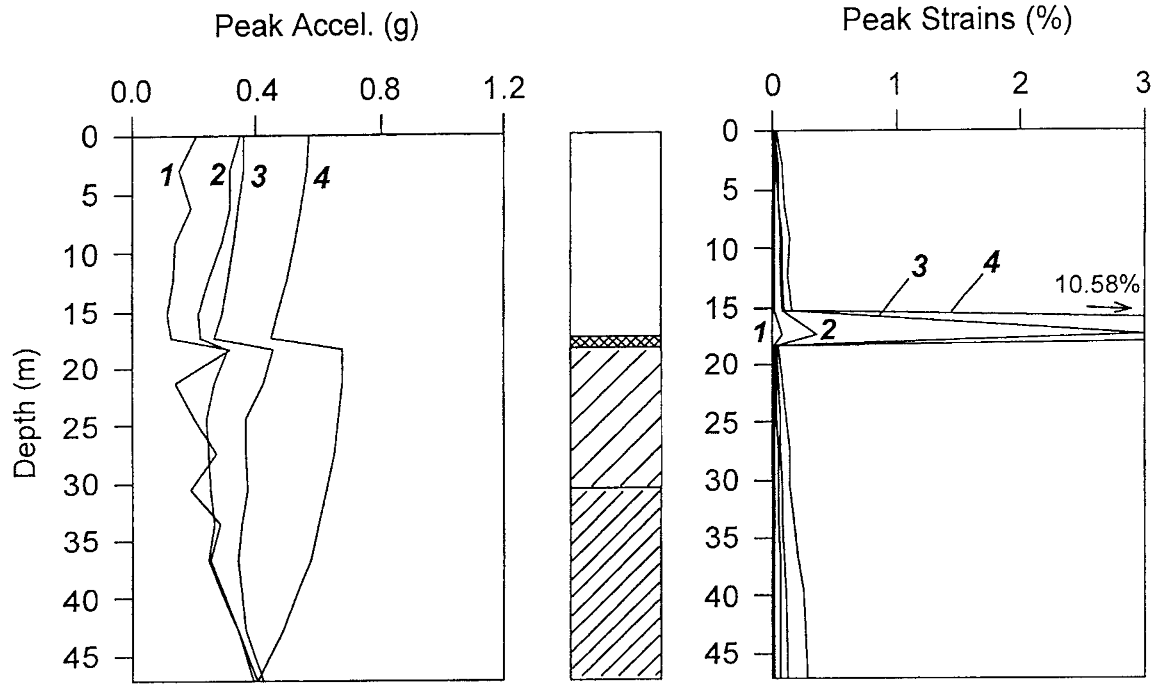
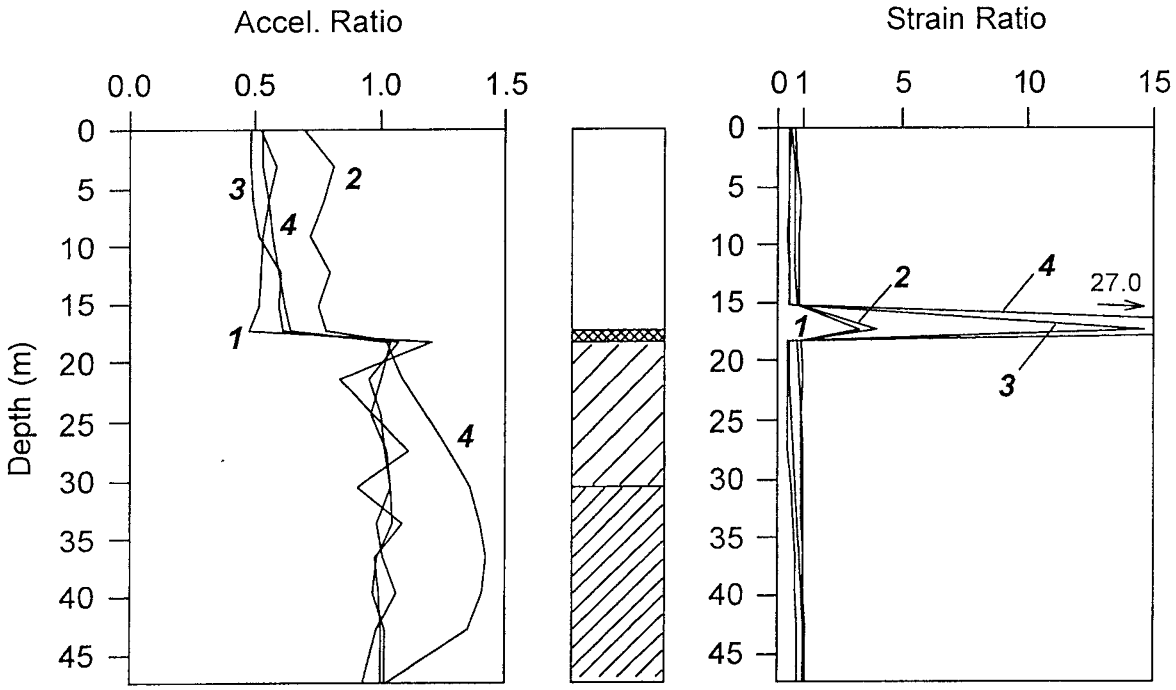


Figure 6 Shallow site with equivalent layer (Time history Scaled to 0.6 g)



$$\text{Accel.Ratio} = \frac{\text{Peak Accel.w eqv. layer}}{\text{Peak Accel.w/o eqv. layer}} \qquad \text{Strain Ratio} = \frac{\text{Peak Strain w eqv. layer}}{\text{Peak Strain w/o eqv. layer}}$$

Figure 7 Shallow site– ratios of peak accelerations and strains for profiles with equivalent layer versus profiles without equivalent Layer (Time history scaled to 0.6 g)

INFLUENCE OF SOIL COLUMN THICKNESS

A similar series of analyses was conducted using a deep soil profile with a total column thickness of 350 m. Figure 8 plots the peak acceleration and strain profiles computed ignoring the influence of the geosynthetic layer. The waste fill experiences peak shear strains up to 0.6 % and ground accelerations up to 0.3g. Figure 9 presents the same results computed whereby the geosynthetic layer is modeled as an equivalent layer. The peak shear strains in the waste fill and the ground accelerations are significantly reduced. Shear strain levels in the equivalent layer are significantly larger than the overlying and underlying layers. Figure 10 shows profiles of acceleration and shear strain ratio profile. The figure shows that except for TIME HISTORY 1, peak accelerations and strains in the waste fill are similar for analyses with and without the equivalent layer. Accelerations and to a limited extent strains computed in the analyses using the equivalent layer do not show the significant reduction that was observed in similar analyses using the shallow soil profile illustrated in Figure 7.

AMPLIFICATION OF PEAK GROUND ACCELERATION AND PERIOD CONTENT OF GROUND MOTION

Figure 11 is a summary plot of acceleration amplification factors for a suite of analyses. The analyses include soil profiles with (filled symbols) and without (open symbols) the equivalent layer. The analyses use the unscaled ground motions as well as ground motions scaled to 0.2g and 0.6 g. Amplification factors are plotted versus the dominant period of the ground motion.

Figure 11a shows the data for the shallow soil profile. The data shows that the presence of the equivalent layer consistently leads to lower amplification factors. The use of an equivalent layer will result therefore in lower seismic demand on the waste fill. Figure 11b shows the data for the deep soil column. The analyses show that the presence of the equivalent layer has minimal effects on the amplification factors for the deep soil profiles.

In both profiles the amplification factor shows strong dependence on the dominant period of the ground motion. The amplification factor increases as the dominant period increases and approaches the period of the deposit (site period). The dependence is true regardless of the scaling of the ground motion. Therefore, the frequency content of the input ground motion, which is expressed here in terms of the dominant period, has an important effect on the computed ground motion. The designer will have to carefully choose the input ground motion for a specific site. The ground motion has to have the appropriate frequency content compatible with the ground shaking level. Merely scaling the ground motion to desired peak ground acceleration may not always be suitable.

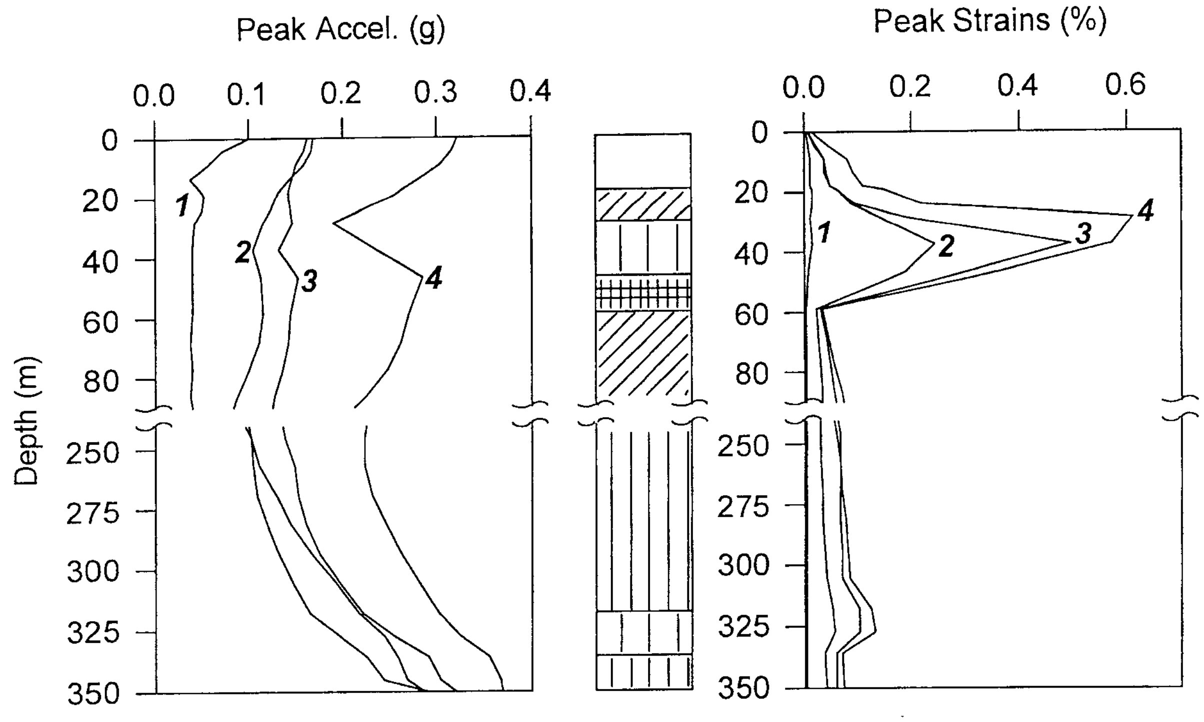


Figure 8 Deep site without equivalent layer (Time history scaled to 0.6 g)

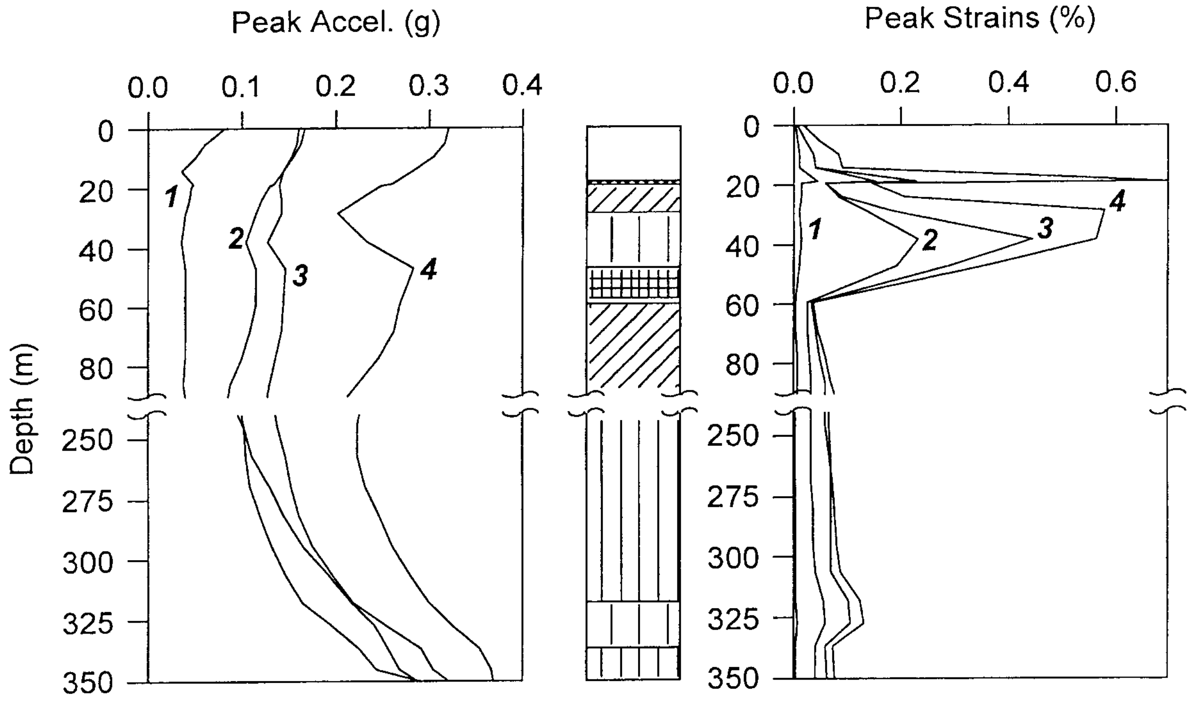


Figure 9 Deep site with equivalent layer (Time history scaled to 0.6 g)

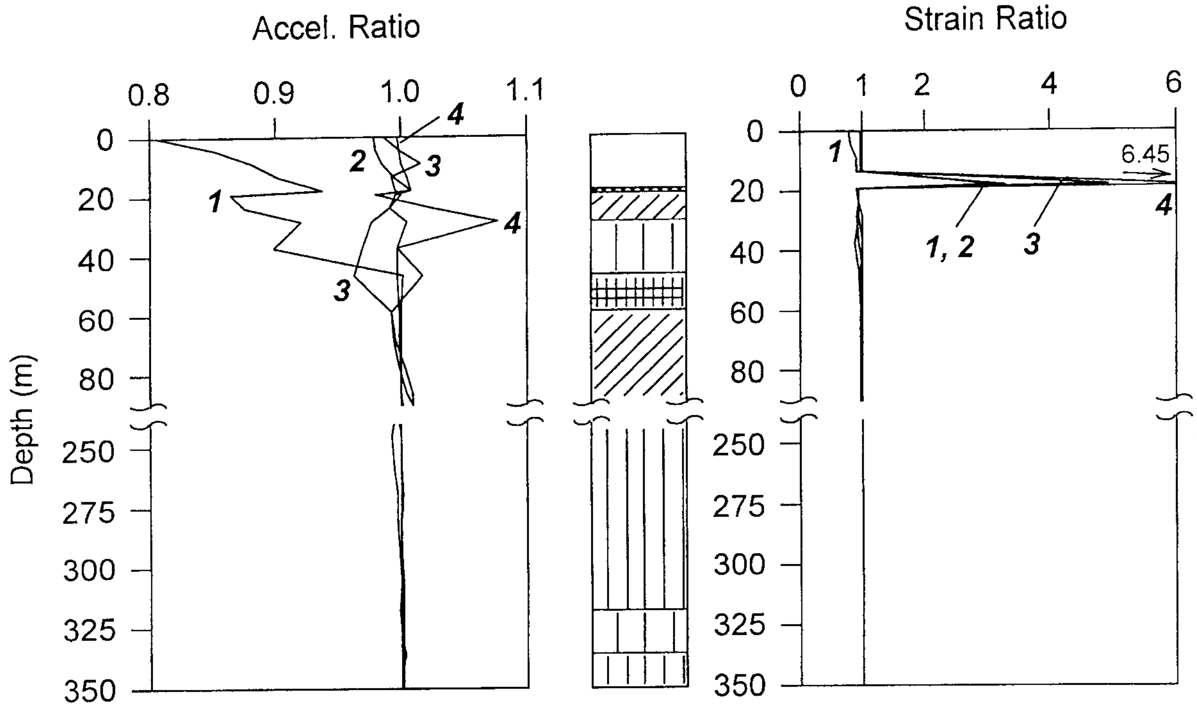


Figure 10 Deep site– ratios of peak accelerations and strains for cases with equivalent layer versus without equivalent Layer (Time history scaled to 0.6 g)

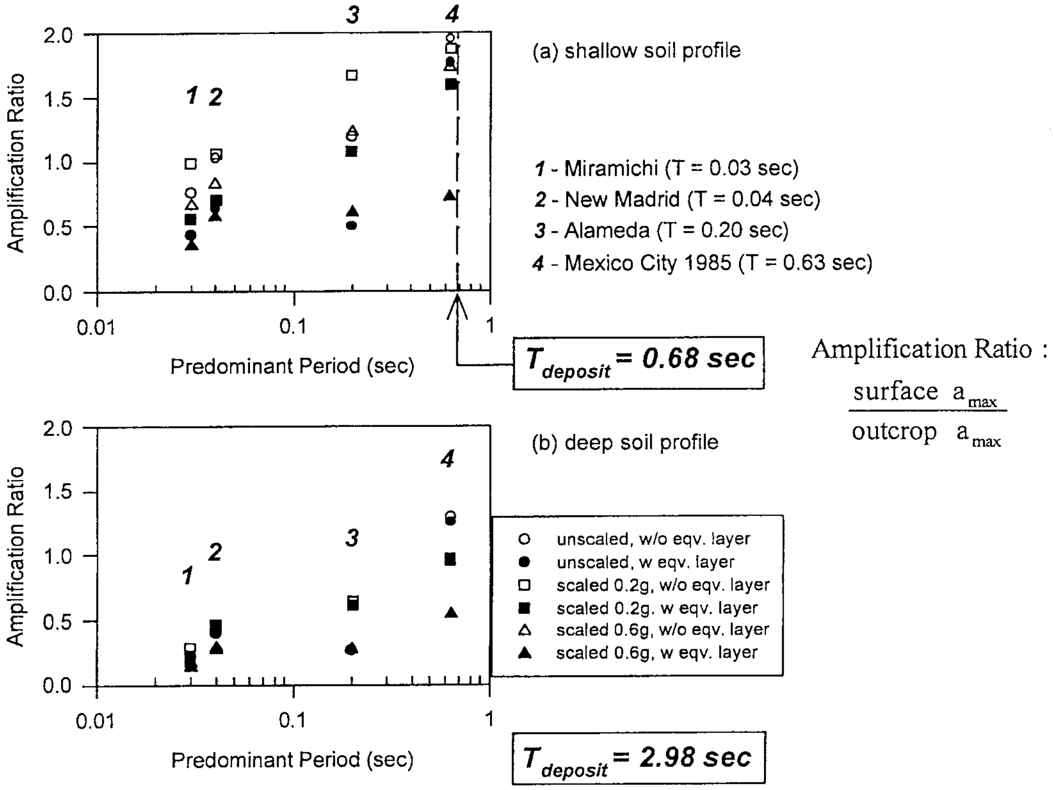


Figure 11 Influence of frequency content of time history on the amplification ratio

AMPLIFICATION/ATTENUATION OF GROUND MOTION

The results of the analyses are also plotted in Figure 12 in the form of surface peak ground acceleration versus rock site (input) peak ground acceleration. The figures also include empirical limits for sites with no landfills but with containing soft soils by Idriss (1990).

For the shallow soil profile, Figure 12a, the analyses using the unscaled ground motions (open and solid circles) fall within the limits of measured data. Analyses using Mexico City motion (#4) when scaled to 0.6 g give a surface acceleration that falls outside the measured data. This may indicate that it is inappropriate to scale that ground motion from the recorded value of 0.1g to 0.6 g without an adjustment of the ground motion frequency content.

For the deep soil profile, Figure 12b, the analyses show that all computed values fall at or below the median solid line proposed for empirical correlations. The analyses show greater attenuation of the ground motion than empirical correlations. It is likely that this analysis approach is inappropriate for deep soil profile. Recent work by Hashash et. al. (2000) shows that for deep soil deposits the dependence of modulus degradation and damping curves on confining pressures has a significant impact on site response analysis for deep soil depsoits (>50-100 m).

LINER DISPLACEMENTS

The slip along the liner has been computed using the following methods:

1- The rigid block (Newmark method) using the concept of yield acceleration.
2- The method proposed by Yegian et. al. (1988) using the concept of "maximum slip" or peak-to-peak slip, obtained by multiplying the computed maximum shear strain with the thickness of the equivalent soil layer.

Figure 13 plots the displacements using the Newmark versus the Yegian and Harb (1998). The rigid block method gives estimates of displacement that are much larger than those of Yegian et al. (1998) for analyses without the equivalent layer. The rigid block method computes larger displacement for analysis without the equivalent layer than for those with the equivalent layer, which is contrary to what would be expected. Similar results were obtained for analyses other time histories. The rigid block method is not recommended for use in analyses with the equivalent layer.

CONCLUSION

This paper presented a parametric study of landfill response using the procedure proposed by Yegian & co-workers. The analyses show that the use of the equivalent layer concept will reduce the computed acceleration in the waste fill and hence enhance stability estimates. The analyses show that the frequency content of the ground motion plays an important role in the amplification of the ground motion. Scaling of a ground motion to desired peak ground acceleration should also consider the frequency content of the ground motion.

The paper did not address many important issues related to seismic design of landfills. These issues include a) appropriate mid-continent earthquake time histories to use in an analysis, b) relationship between computed displacement and anticipated damage to landfill liner, leachate collection system and cap systems, c) influence of non-linear response of the soil and waste. More research is required in the future to address these issues.

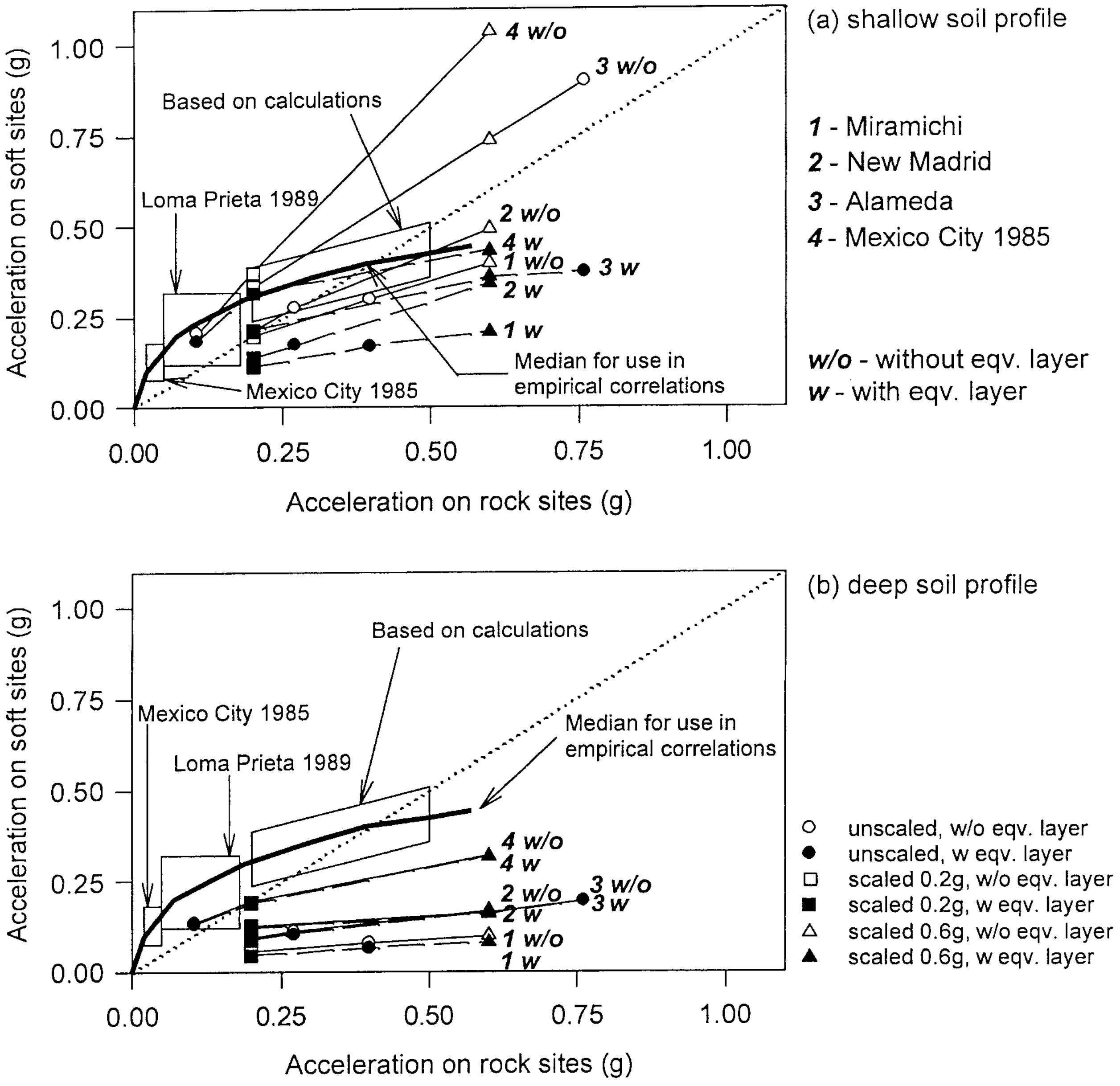


Figure 12 Relationship between peak acceleration on rock and soil surface (after Idriss, 1990)

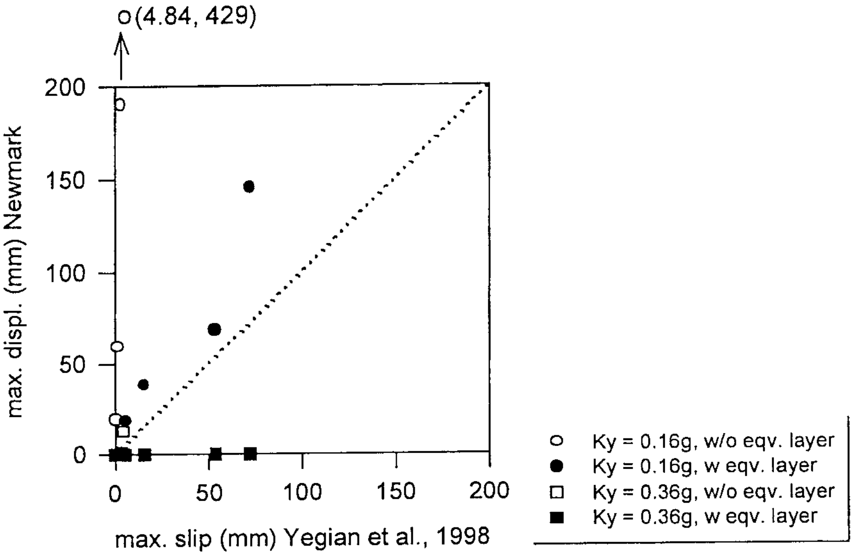


Figure 13 Correlations between displacements at the level of liner (equivalent layer) computed for the Alameda time history cases

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