Use of EPS geofoam for seismic isolation of earth retaining structures: results of a FEM study

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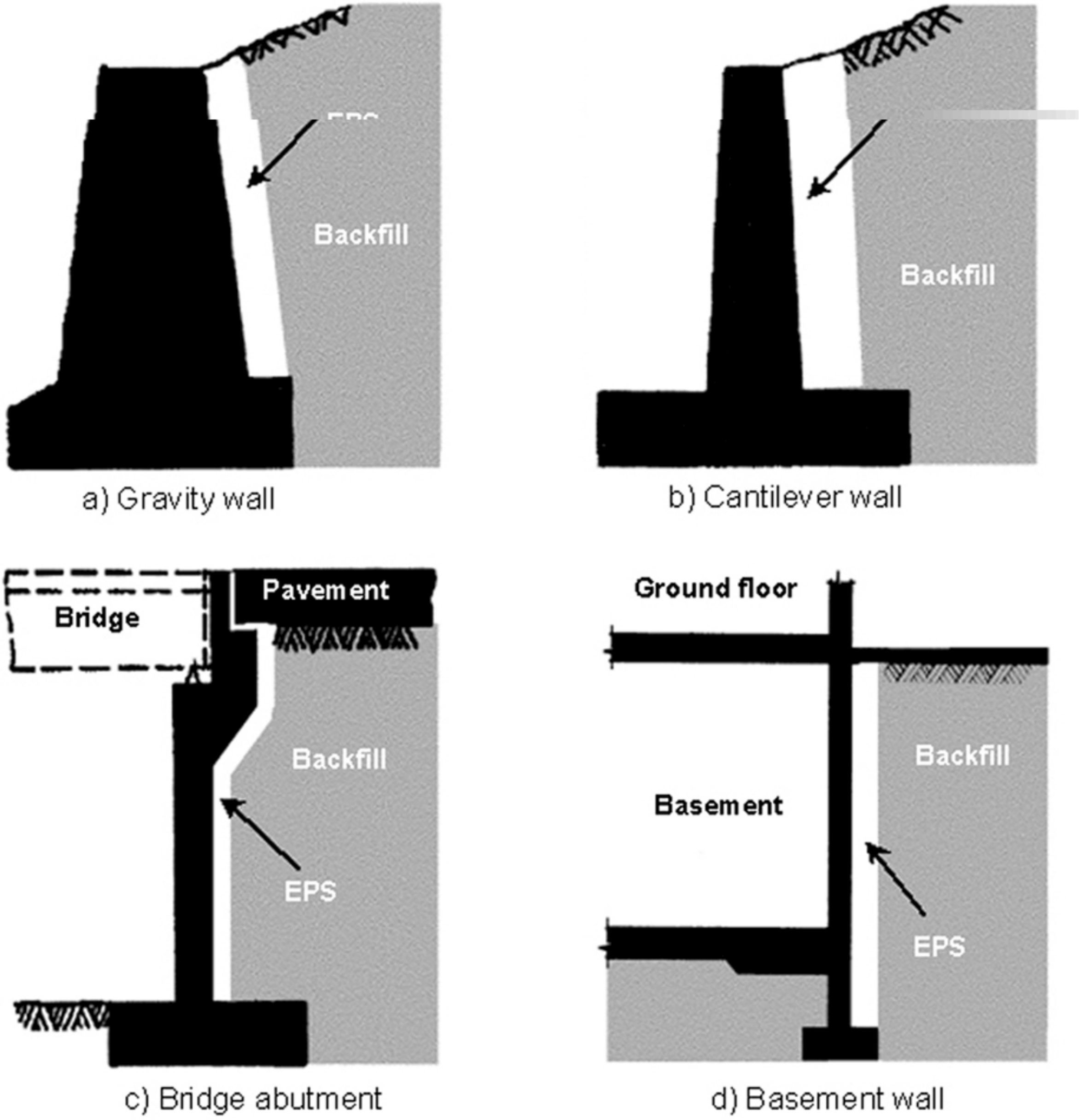
ABSTRACT: The results of a finite element study regarding the potential use of EPS geofoam as a seismic buffer behind earth retaining structures are presented. Parametric analyses were conducted for reinforced concrete cantilever-type retaining walls in which the backfill material and EPS geofoam were modeled as viscoelastic materials with strain-dependent values of shear modulus and damping ratio. The wall and retained soil systems were analyzed under horizontal earthquake excitations having maximum values of base acceleration ranging from 0.1g to 0.5g. It was found that the inclusion of an EPS geofoam layer between the back face of the wall and the backfill material greatly reduced (by more than 50%) the seismic earth pressures acting on the wall. This amount of reduction was found to depend mainly on the thickness of EPS layer and the stiffness of backfill material. The EPS layer thickness that is required to produce a desired amount of seismic earth pressure reduction can be estimated from a diagram prepared on the basis of the parametric analyses.

1 INTRODUCTION

Earth retaining structures (temporary or permanent) constitute an essential element of many civil engineering projects around the world. Permanent earth retaining structures are mainly reinforced concrete walls either of the gravity-type or of the cantilever-type. In many infrastructure projects earth retaining walls also operate as load bearing elements as in the case of bridge abutments and basement walls (Ouyang et al., 1991; Richards et al., 1996). In such structures the horizontal movement of the top of the wall is usually restrained. In a number of recent earthquakes extensive damages have been caused by failure of earth retaining structures (EERI 1989; Ishihara 1997). Thus in areas where strong earthquakes are likely to occur the earth retaining structures must be designed to be earthquake resistant.

The lateral earth pressures on retaining walls increase significantly as a result of earthquake motion (they may be tripled compared to the static pressures even for moderately sized earthquakes) and their earthquake resistant design may result in a highly increased cost. It would then be of great interest to examine methods for reducing the seismic earth pressures acting on earth retaining structures. In this paper a new approach for reducing the seismic earth pressures acting on reinforced concrete retaining walls is examined. This approach involves the installation of an expanded polysterene layer (which is called EPS geofoam when used in geotechnical applications) between the back face of the wall and the backfill material, as shown in Figure 1 (Inglish et al., 1996; Bathurst, Alfaro, 1997). This EPS geofoam layer is expected to operate as a seismic buffer by absorbing a part of the seismic energy and thus reducing the lateral earth pressures acting on the wall.

The analyses reported herein were conducted by using the Finite Element Method (FEM). It is known that the lateral earthquake pressures acting on retaining walls are usually estimated either by the quasi-static (or pseudodynamic) Mononobe-Okabe method or by the allowable permanent displacement method (Kramer, 1996). In cases of complex problems, however, the FEM offers the advantages of accurately modeling the geometry of the problem and the mechanical behavior and



a) Gravity wall

b) Cantilever wall

c) Bridge abutment

d) Basement wall

[redacted]

Figure 1. Earth retaining walls protected against seismic earth pressures by an EPS geofoam layer installed between the back face of wall and the backfill material.

properties of different materials. The above advantages of the FEM were utilized in the present study in which the behavior of a composite system (wall-EPS geofoam-backfill) had to be investigated under earthquake shaking.

2 EPS GEOFOAM: MATERIAL PROPERTIES

The generic term “geofoam” was proposed by Horvath (1992) to describe all rigid-plastic foams used in geotechnical applications. The majority of these applications, according to Horvath (1994), involve the use of expanded polysterene (EPS), which is usually utilized, in the form of molded blocks. This material is characterized by a very low unit weight (approximately 1/100 of the unit weight of soils), very high void ratios (e≈40 to 100) and high strength to unit weight ratios. EPS geofoam blocks are used today in many geotechnical applications including 1) thermal insulation, 2) lightweight fills, 3) compressible inclusions and 4) vibration damping.

The mechanical properties of EPS geofoam under dynamic/cyclic loading have been the subject of a few investigations in recent years. Athanasopoulos et al. (1999) have found that EPS geofoam behaves linearly in terms of stress-strain behavior for strains up to 0.1%. The nonlinear behavior becomes particularly pronounced, however, for strains greater than 1%. It has been also found that the EPS geofoam density affects only the dynamic moduli and not the damping ratio values whereas the value of Poisson's ratio, ν, is close to zero and may take negative values. The cyclic strain amplitude, γ_c, has a pronounced effect on the elastic moduli (E, G) and the damping ratio, D, of EPS geofoam in a way that is similar to the behavior of cohesive soil materials. Equations for G/G_o vs. γ_c and D vs. γ_c curves (G_o=shear modulus of low amplitude vibrations) for EPS geofoam have been reported by Athanasopoulos et al. (1999).

3 FINITE ELEMENT ANALYSES AND RESULTS

The efficiency of EPS geofoam in isolating cantilever-type retaining walls against lateral earthquake pressures was investigated by conducting parametric analyses with the FEM code FLUSHPLUSH (1991). This code was used in association with purpose written pre- and post-processing graphical interfaces, which facilitate the input of data and the processing of output. In the FLUSHPLUS code the material behavior can be modeled as linearly elastic or viscoelastic with strain-dependent shear modulus and damping ratio values. Viscous dampers can be attached to the lateral boundaries of the finite element mesh to simulate infinite extent conditions of the mesh. The excitation is applied in the form of time histories of horizontal or vertical acceleration at the rigid (i.e. non-transmitting) base of the mesh.

The parametric analyses were conducted by studying the behavior of three cantilever-type retaining walls with a horizontal backfill and heights, H, equal to 3.30m, 4.80m and 7.0m. The walls were proportioned according to the rules commonly applied in the geotechnical engineering practice. The behavior of unprotected walls was compared to the behavior of walls with an EPS geofoam layer of thickness d (ranging from 0.2m to 0.8m), attached to the back face of the stem. The low-amplitude shear modulus of EPS geofoam, $G_{o,\ EPS}$ used in the analyses was varied from 2MPa to 5MPa (Athanasopoulos et al., 1999) whereas for the backfill material the values of $G_{o,\ backfill}$ ranged from 40MPa to 140MPa. The corresponding values of low amplitude shear wave velocity, V_{S0}, of the backfill material are 150m/sec to 280m/sec, which are reasonable values for such soil materials and have been used by other investigators (Veletsos, Younan, 1997). The excitations at the rigid base of the mesh were applied in the form of two horizontal motion accelerograms recorded during the Kalamata (1986) and Egion (1995) earthquakes. These accelerograms and corresponding acceleration response spectra (indicating predominant period values from 0.1 to 0.55sec) are shown in Figure 2. In the parametric analyses reported herein the intensity of base motion was varied by scaling the peak values, a, of both accelerograms to the values of 0.1g, 0.25g and 0.5g. It should be noted that in all analyses of the present study the wall back face was considered to be bonded to the backfill material. Although this assumption deviates from the actual field conditions, it does not affect significantly the validity of the results (Veletsos, Younan, 1997).

The finite element mesh used for the dynamic analyses of the 4.80m wall is shown in Figure 3a. The analyses were conducted by assuming elastic behavior for the retaining wall and equivalent linear viscoelastic behavior for the backfill material. The G_o vs. γ_c and D vs. γ_c curves were taken for the EPS geofoam from Athanasopoulos et al. (1999) and for the backfill material from Athanasopoulos et al. (1998) as shown in Figure 4. The values of material properties used in the finite element analyses were as follows:

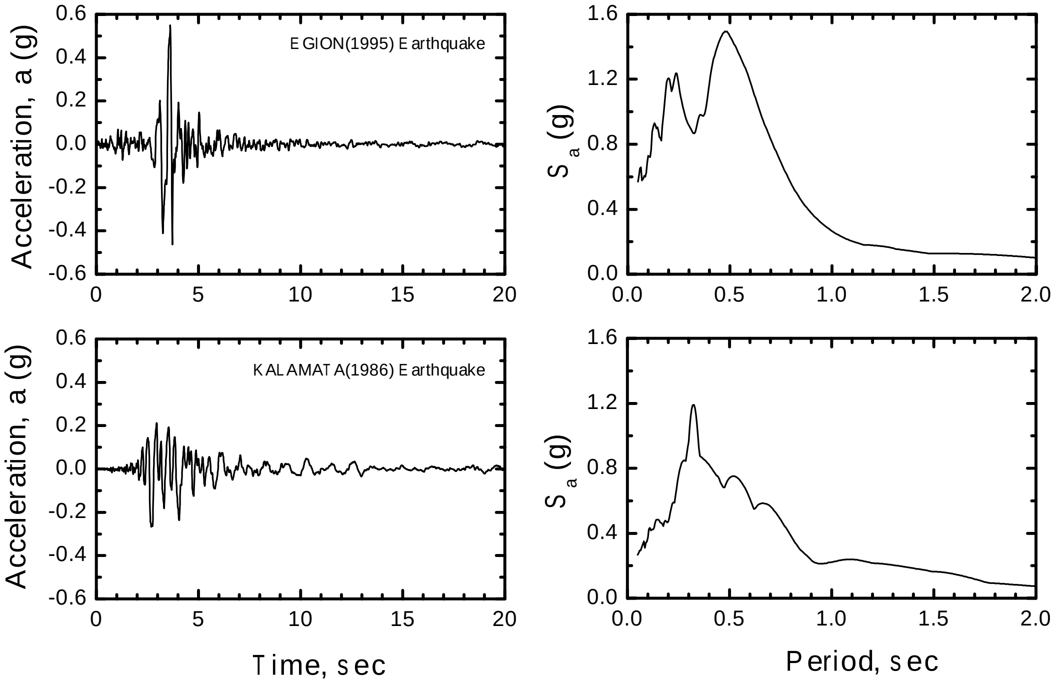


Figure 2. Time histories and corresponding response spectra of horizontal accelerations of two earthquakes that were used, after apropriate scaling, as input motion in the dynamic analyses of wall-geofoam-backfill systems

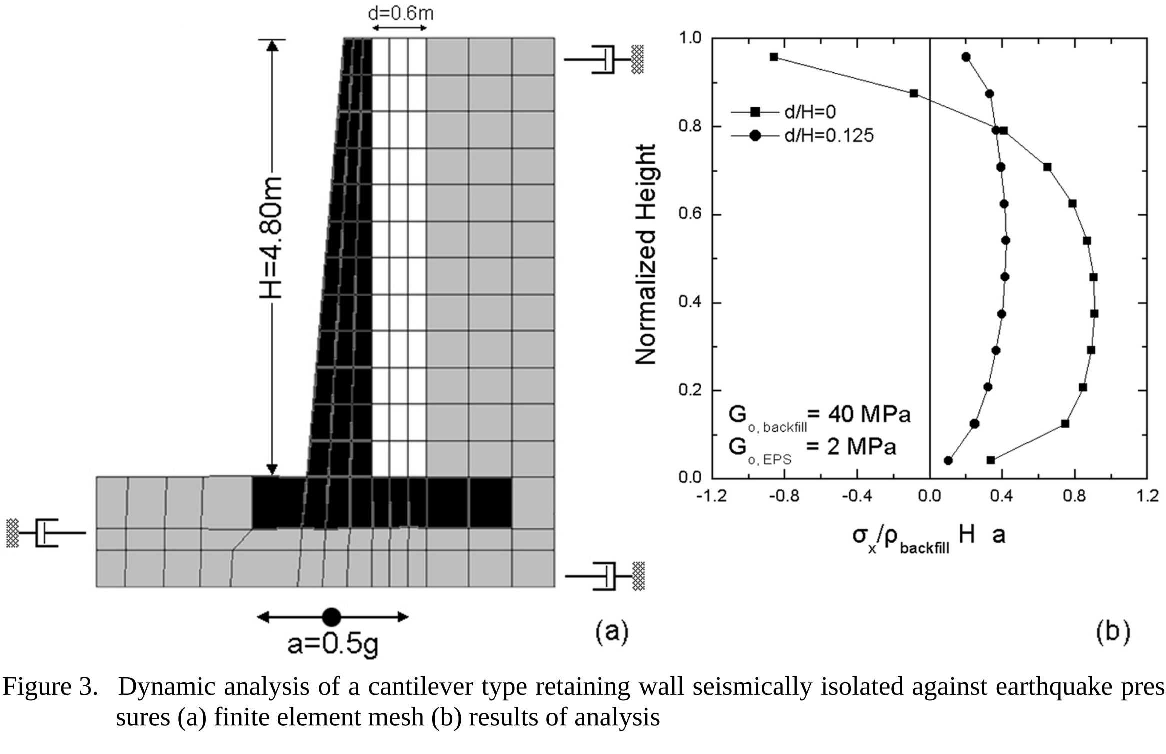


Figure 3. Dynamic analysis of a cantilever type retaining wall seismically isolated against earthquake pressures (a) finite element mesh (b) results of analysis

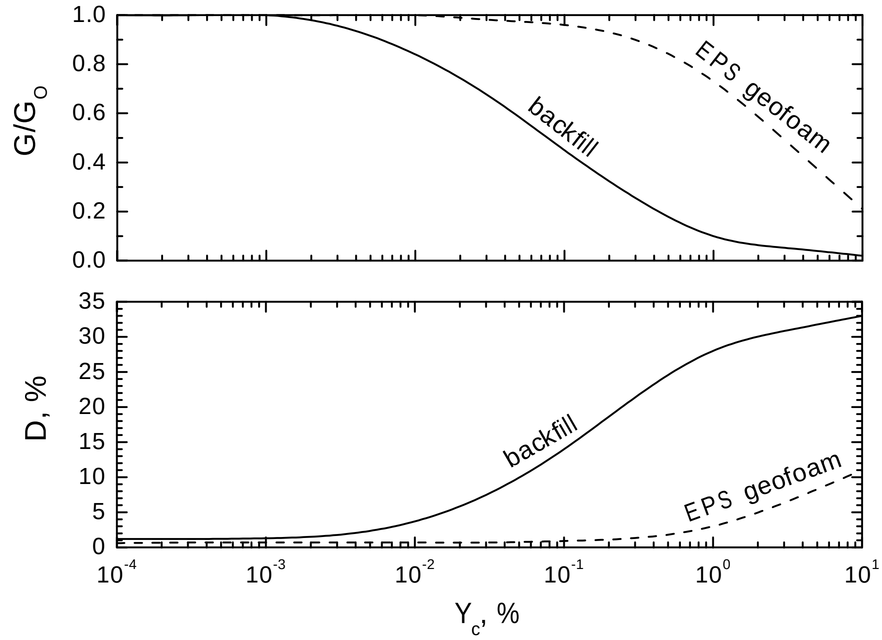


Figure 4. G/G_o vs. γ_c and D vs. γ_c curves used in the finite element analysis of the wall shown in Figure 3.

Retaining wall:	G_0 =10.0GPa,	γ=25.0kN/m^3	ν=0.2	(elastic)
EPS geofoam:	G_0 =2.0MPa,	γ=0.10kN/m^3	ν=0.0	(equivalent linear)
	=3.5MPa,	γ=0.15KN/m^3,	ν=0.0	
	=5.0MPa,	γ=0.20kN/m^3	ν=0.0	
Backfill:	G_0 =40MPa,	γ=17.0kN/m^3	ν=0.3	(equivalent linear)
	=80MPa,	γ=17.0KN/m^3,	ν=0.3	
	=140MPa,	γ=17.0kN/m^3	ν=0.3	

where: γ= unit weight of material

A typical example of the estimated distribution of maximum values of normal horizontal stresses, σ_x, (normalized with respect to “$\rho_{backfill}$ H a”) on the back face of the 4.80m wall is shown in Figure 3b for both the unprotected and the seismically isolated walls. In this example the base shaking intensity was a=0.5g and the EPS geofoam layer had a thickness of d=0.6m. It may be seen that the existence of a bond between wall back face and backfill results in tensile stresses at the top part of the wall. These stresses cannot be actually developed and would result in separation between wall-backfill. It should be kept in mind that the maximum values of seismic earth pressures plotted in Figure 3b, are not necessarily being developed simultaneously along the height of the wall.

It the diagram of Figure 3b the distribution of earth pressures on the unprotected wall has a form similar to the one derived by Veletsos, Younan (1997) on the basis of viscoelastic analyses of flexible walls. It is observed that the inclusion of the EPS geofoam layer results in a great reduction of seismic earth pressures. This reduction may be interpreted on the basis of Veletsos, Younan (1997) results which indicate a significant reduction of seismic earth pressures as the retaining walls became increasingly flexible. The diagram of Figure 3b, indicates that the value of σ_{xmax} is reduced by more than 50% in the case of 4.80m wall protected by an EPS geofoam layer under a strong base motion. The isolation efficiency can be described quantitatively by a Seismic Isolation Ratio $R=\sigma_{xmax(EPS)}/\sigma_{xmax}$. The value of R=0.43 in this case.

By utilizing the results of all parametric analyses the diagram of Figure 5, was plotted in which the seismic isolation ratio, R, is shown as a function of a normalized value of EPS geofoam thickness, d/H. It observed that the isolation efficiency becomes significant for the stiffer backfill material whereas the intensity of motion does not affect significantly the value of R. In particular the EPS geofoam thickness has a pronounced effect on the seismic isolation ratio up to approximately d/H≈0.04 (for $G_{o,\ backfill}/G_{o,\ EPS}$=70) whereas for greater values of d/H the effect becomes less significant.

It should be noted that the dynamic earth pressures depicted in Figure 2 are incremental thrusts caused by the earthquake motion which are superimposed to the static earth pressures acting on the wall due to the gravity forces. According to the results of previous investigations (Horvath, 1995; Horvath, 1997; Negussey, 1998), the use of EPS geofoam behind retaining walls, also reduces the static earth pressures by functioning as a compressible inclusion and facilitating the development of fully active earth pressure conditions behind the wall.

4 CONCLUSIONS

Based on the parametric analyses of the present study it is concluded that the inclusion of an EPS geofoam layer of a small thickness and low density (γ≈0.10 to 0.20 kN/m^3) between the back face of cantilever-type retaining walls and the backfill material can result in a significant reduction (in excess of 50%) of the seismic earth pressures.

The EPS layer thickness that is required to produce a desired amount of seismic earth pressure reduction can be estimated from a diagram prepared on the basis of the parametric analyses.

Since the EPS geofoam is a compressible material, care should be taken when deciding the thickness of the protective EPS layer to take into account the thickness loss caused by the compression produced by static (due to gravity forces) lateral earth pressures.

The seismic isolation efficiency of EPS geofoam for gravity-type retaining walls and walls which are restrained against horizontal movement is expected to be greater than the one derived in the present study and research work on this subject is in progress.

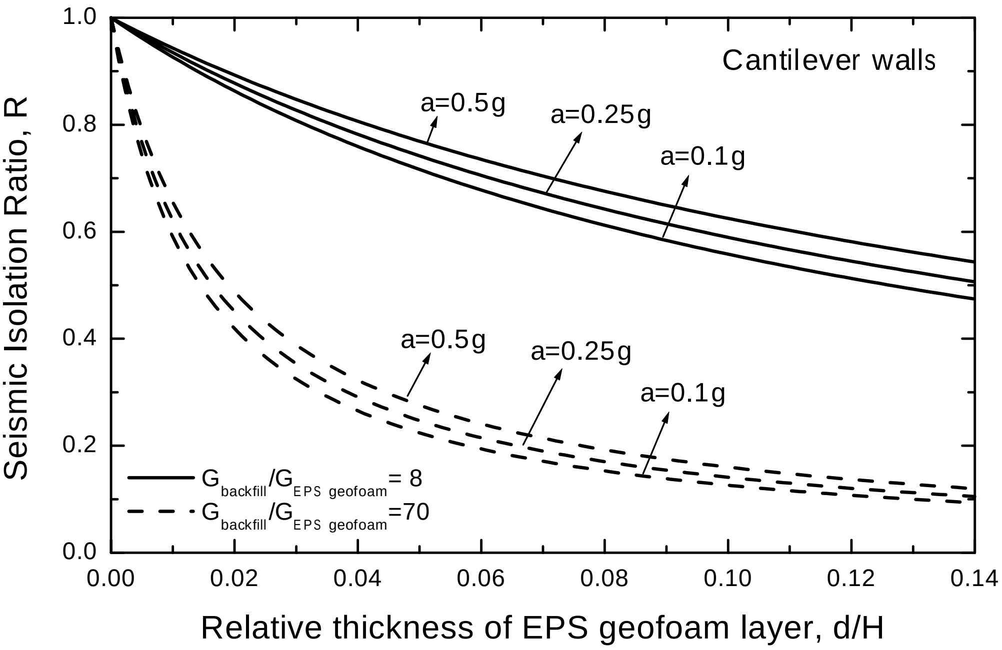


Figure 5. Effect of EPS geofoam layer thickness on the Seismic Isolation Ratio, R

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