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SEISMIC ISOLATION OF EARTH-RETAINING STRUCTURES BY EPS GEOFOAM COMPRESSIBLE INCLUSIONS – DYNAMIC FE ANALYSES

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ABSTRACT

Results of numerical analyses (using the FEM) are presented for determining the response of earth retaining walls, seismically isolated by an EPS geofoam compressible inclusion, to harmonic base excitation. In the first part of the investigation the dynamic properties of EPS were evaluated by a laboratory testing program (resonant column tests, bender element tests, cyclic and monotonic triaxial tests with local strain measuring transducers) on specimens of varying densities under isotropic confinement ranging from 0% to 60% of the compressive strength of the material. By combining the results of all tests empirical relations (and graphs) were developed providing values of Poisson's ratio, static and dynamic moduli of deformation and damping ratio as a function of EPS density (12 to 30kg/m^3), strain amplitude (10^{-6} to 10^{-1}) and isotropic confining pressure (0 to 100kPa). In the second part of the study (involving the numerical analyses) the isolation efficiency, A_r, of the inclusion (i.e. the percent reduction of the seismic thrust increment compared to the case without isolation) was examined as a function of inclusion shape, density and thickness, of wall flexibility and height and of intensity and frequency of base motion. The reliability of the method of analysis was first checked and verified by analyzing a reported case of physical model shaking table tests. Then, based on the results of the parametric analyses, a two-step tentative design procedure was proposed for EPS geofoam seismically isolated soil retaining structures.

Keywords: Earth retaining structures, seismic isolation, EPS geofoam

INTRODUCTION

Earth retaining structures are designed to safely resist the lateral pressures exerted by earth masses and constitute an important component of many civil engineering works. These structures may be of a number of types (e.g. reinforced concrete retaining walls -gravity or cantilevered-, bridge abutments or basement walls), Figure 1, and in earthquake prone areas they must be designed to withstand the seismic earth pressures in addition to the static ones. It is known that in the case of strong ground motion the combined earth pressures may be more than two times higher, compared to the static pressures. The appropriate design against the increased lateral loading results in a significant increase in the construction cost. For this reason a method for the seismic earth pressure reduction (or isolation) would therefore be particularly useful in the civil engineering profession and construction industry (for both new and existing structures).

In the last decade a new method for the seismic isolation of earth retaining structures has been proposed (Horvath, 1995; Inglis et al., 1996; Pelekis et al. 2000; Hazarika, 2001; Hazarika et al.,2001;

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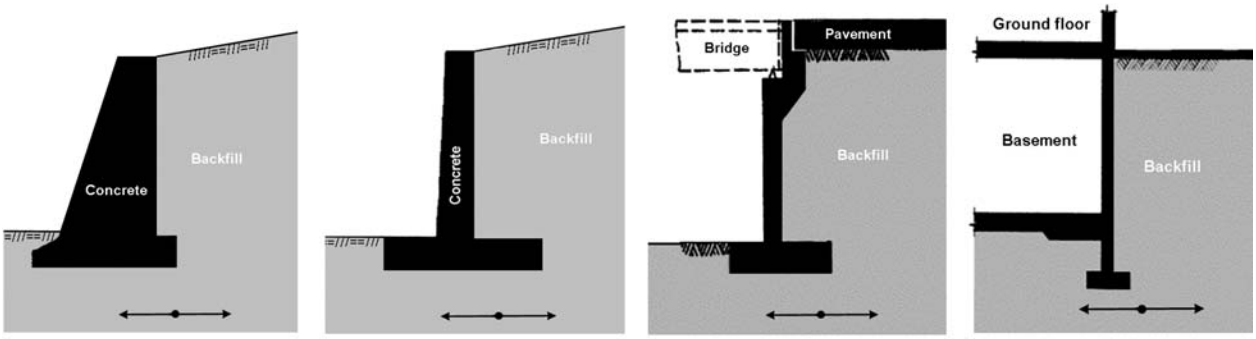

Figure 1. Common types of earth retaining structures

Hazarika and Okuzono, 2004; Hazarika, 2005), which involves placing an EPS geofoam layer (as a compressible inclusion) between the back face of the wall and the backfill material, Figure 2. During earthquake loading, the major part of backfill seismic pressures is absorbed by the EPS layer. This layer acts as a buffer (due to its greater compressibility) and only a small portion is transferred to the retaining structure. It should be mentioned that this method of seismic isolation is an extension of the use of EPS compressible inclusions for reducing the static earth pressures acting on retaining walls, which was first examined by Partos and Kazaniwsky (1987). In subsequent years the subject was studied by several investigators by using experimental and analytical techniques (McGown et al., 1988; Horvath, 1991; Karpurapu and Bathurst, 1992; Horvath, 1997; Tsukamoto et al., 2001; Tsukamoto et al., 2002; Horvath, 2004).

The subject of the present study is 1) the systematic investigation of the effectiveness of an EPS geofoam compressible inclusion as a seismic isolator against lateral earthquake earth pressures, and 2) the development of a pertinent design methodology.

PROGRAM OF INVESTIGATION

In order to study systematically the effectiveness of EPS geofoam as a seismic compressible inclusion it is necessary to investigate a) the dynamic behavior of EPS as well as the behavior at the interface between EPS and backfill material (Athanasopoulos et al., 1999; Xenaki and Athanasopoulos, 2001) and b) the response of seismically isolated walls under varying seismic base excitations (Pelekis et al.,2000). Accordingly, in the present study two main directions of research were followed: 1) an experimental evaluation of the dynamic properties (moduli and damping ratios) of EPS (Xenaki, 2005) and 2) performance of a number of parametric response analyses of reinforced concrete retaining walls seismically isolated by EPS geofoam compressible inclusions (Stathopoulou, 2005; Nikolopoulou, 2006).

1. Experimental study

The dynamic properties of EPS geofoam (elastic moduli, damping ratios and Poisson ratio) in the present study were evaluated by conducting four types of tests (Xenaki, 2005):

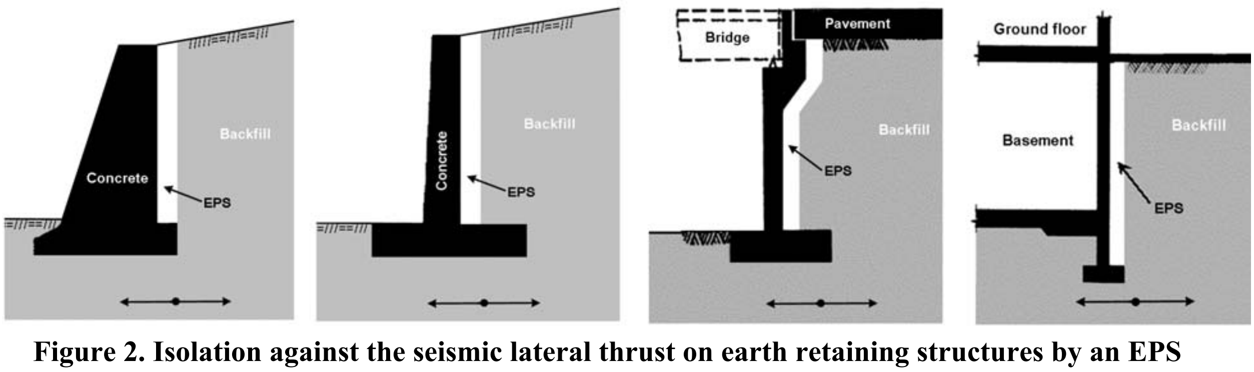

Figure 2. Isolation against the seismic lateral thrust on earth retaining structures by an EPS geofoam compressible inclusion

a. Monotonic (uniaxial and triaxial) tests

The tests were conducted in a GDS monotonic/cyclic triaxial testing system with a loading rate ranging from 1%/min to 2.5%/min, Figure 3. The confining pressure in these tests was varied from 0 to 60% of the EPS compressive strength. It was found that in this range of loading the rate of volumetric creep of the material becomes negligibly small after 15 min to 30 min following the load application. In these tests the maximum compressive strain was equal to 10%. Also, the reliable measurement of very small material strains was accomplished by using "Hall effect" type local-strain transducers, attached to the mid-height area of the test specimens (Clayton and Khatrush, 1989; Clayton et al., 1989).

b. Cyclic triaxial tests

These tests were conducted in the GDS testing system mentioned above, under controlled stress conditions and varying confining pressures and loading amplitudes. The rate of harmonic axial loading was approximately equal to 1%/min. Local strain measuring transducers were also used in these tests.

c. Resonant column tests (torsional)

These tests were conducted, in a "fixed-free" resonant column device, designed and fabricated by the senior author, Figure 4. The shear strains in these tests ranged from 10^{-6} to 10^{-3} whereas the loading frequency ranged from 35Hz to 70Hz (producing loading rates approximately equal to 6%/min). Due to the significant volumetric contraction of the EPS specimens under even small values of confining stress, (which resulted in a contact between magnet and coils) the resonant column testing was only conducted on unconfined specimens.

d. Bender element tests

These tests were conducted in a GDS bender-extender element testing system with wave frequencies

Figure 3. (a) The triaxial (cyclic/monotonic) loading system used in the laboratory program, (b) the local strain measuring transducers used in the triaxial tests on EPS specimens

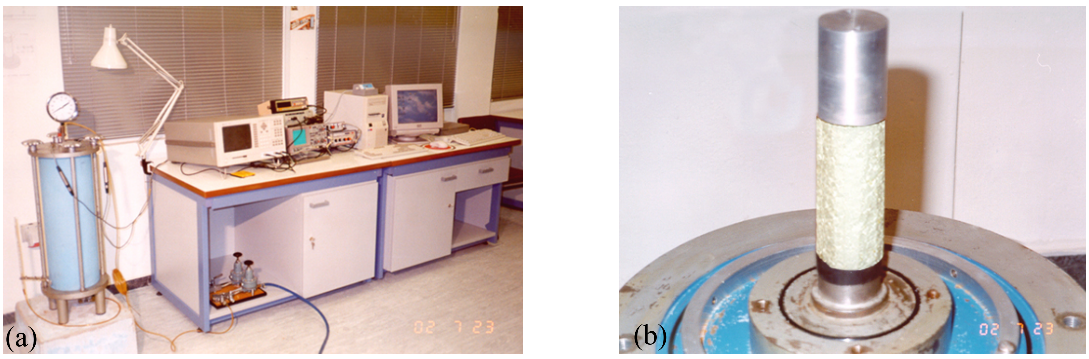

Figure 4. (a) The resonant column system used in the laboratory program, (b) cylindrical EPS specimen mounted to the pedestal of the resonant column device

Figure 5. The bender-extender system used in the laboratory program (a) the pedestal of the device with the insert element, (b) EPS specimen mounted in the testing system

ranging from 6.5kHz to 10kHz and vibration amplitude less than 10^{-6} (loading rate equal to 200%/min), Figure 5.

All specimens used in the experimental study were cylindrical with a height to diameter ratio equal to 2 and they were formed from EPS blocks having densities from $12kg/m^3$ to $30kg/m^3$. The final trimming of the specimens was accomplished by a sand paper, instead of a hot wire, to avoid any thermal disturbance of the surface of the specimens.

2. Numerical Analyses

The effectiveness of an EPS compressible inclusion as a seismic isolator in soil retaining structures was investigated in the present study, by performing numerical seismic response analyses. The response of vertical walls with horizontal backfill, under horizontal harmonic excitation of varying intensity and frequency was analysed. The dynamic analyses were conducted by the finite element code PLAXIS assuming non-linear material behavior for the backfill and the EPS material. Conventional walls, as well as walls seismically isolated with an EPS compressible inclusion, were analyzed.

In Figure 6a, the G/G_0 vs. γ_c curves used in the numerical analyses for the backfill material (average curve for sandy soils based on: Vucetic and Dobry, 1991; Stokoe et al., 2004; Hardin and Kalinski, 2005; Zhang et al., 2005) and the EPS compressible inclusion (Xenaki 2005), are shown. The two curves shown in Figure 6a, indicate that the behavior of EPS material remains approximately linear for strains almost two orders of magnitude greater compared to those of the backfill material.

In Figure 6b, an example of the finite element mesh used in the numerical analyses is shown, with a length ten times greater than the height of the wall. In these analyses the wall was modeled as a vertical elastic beam with finite rigidity. This beam was connected to a rigid base through a rotational

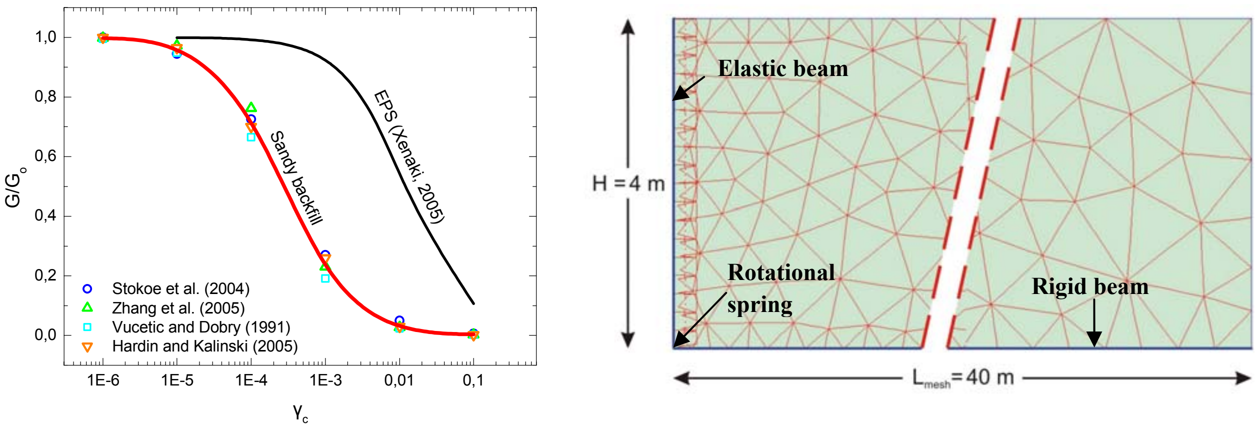

Figure 6. Finite element analyses (a) G/G_0-γ_c used in the analyses, (b) example of a finite element mesh

spring (the results of the present study were obtained for the case of a rigid connection). Veletsos and Young (1997) have shown that elastic models of soil retaining systems provide reliable estimates of soil thrust when the flexibility of the wall is taken into account The frequency of the base harmonic motion ranged from 0.5Hz to 20Hz.

The effectiveness of seismic isolation in the present study is quantified by the isolation efficiency, A_r, defined as the ratio (in percent) of seismic thrust reduction (due to isolation) to the earthquake thrust without isolation. Many parametric analyses were conducted to investigate the effect of the following parameters on the isolation efficiency: (a) shape, mean thickness and density of the compressible inclusion, (b) flexibility and height of the wall and (c) intensity and predominant frequency of the ground motion.

RESULTS

In this section the results are presented of the two parts of the present study i.e. of the experimental evaluation of EPS mechanical behavior and of the seismic response analyses of the reinforced concrete retaining walls.

A. Mechanical Behavior of EPS

The results of laboratory testing indicate that for stains less than 10^{-4} (0.01%) (small strains) the mechanical behavior of EPS geofoam is linear (i.e. independent of strain magnitude), whereas for strains ranging from 10^{-4} to 10^{-3} the behavior is approximately linear (i.e. the deviation from the linear behavior is less than 10%). For strains greater than 10^{-3} (0.1%) (large strains) the behavior is non-linear and the dependence of dynamic properties on strain should be taken into account.

For low-amplitude vibrations the experimental results indicate that the values of elastic moduli (G_o, E_o) of EPS increase with increasing density of material, ρ, and decrease with increasing mean confining pressure, σ_3. The low-amplitude value of Poisson ratio, v_o, depends mainly on confining pressure and decreases with increasing values of σ_3 (taking values from 0.30 to -0.05). Based on the experimental results, the following empirical equations are proposed for estimating the values of G_o (in MPa) and v_o as a function of material density, ρ:

$$G_{o(\sigma_3=0)} = 0.32\rho - 1.40 \quad (1)$$

$$v_{o(\sigma_3=0)} = 0.22 + 0.0033\rho \quad (2)$$

where ρ=EPS geofoam density (kg/m$^{3)}$

The experimental results of the present study also indicate that as the mean confining pressure applied to the material is increased, the values of G_0 and v_0 are reduced. The following empirical equations can be used to take into account the effect of σ_3:

$$\frac{G_{o(\sigma_3)}}{G_{o(\sigma_3=0)}} = 1.02 + 0.599\frac{\sigma_3}{\sigma_{c10}} - 1.41\left(\frac{\sigma_3}{\sigma_{c10}}\right)^2 \quad (3)$$

$$v_{0(\sigma_3)} = 0.25 - 0.33\frac{\sigma_3}{\sigma_{c10}} \quad (4)$$

where σ_{c10}=EPS compressive strength (kPa) from specimens with aspect ratio=2, σ_3=confining stress (kPa)

According to the experimental results of this study the value of σ_{c10} (in kPa) may be estimated from the following empirical equations:

$$\sigma_{c10} = 7.68\rho - 48.3 \qquad (5)$$

$$\frac{\sigma_{c10(\sigma_3)}}{\sigma_{c10(\sigma_{3=0})}} = 1.0 - 0.84\frac{\sigma_3}{\sigma_{c10}} \qquad (6)$$

where ρ=EPS geofoam density (kg/m^3)

The experimental results also indicate that the low-amplitude damping ratio, D_0, of EPS (for both the hydrostatic and deviatoric components of loading) takes low values and does not depend on material density. The value of D_0 increases somewhat with confining pressure and a mean value of D_0=1.70% is suggested for all low-amplitude vibration applications.

For high-amplitude vibrations the dynamic properties of EPS geofoam, in addition to material density and confining pressure, depend also on strain amplitude. More specifically, for increasing values of strain the elastic moduli decrease, the damping ratio increases whereas the Poisson ratio decreases markedly and may take negative values. A very interesting finding is that the EPS modulus of elasticity, E, in the range of intermediate to large strains (10^{-4} to 10^{-2}) also depends on the type of loading (monotonic vs. cyclic). More specifically, as shown in the diagrams of Figure 7a and Figure 7b, in the above mentioned strain range, the moduli obtained from cyclic loading are approximately 20% higher compared to the values from monotonic (i.e. static) loading. This behavior shows a remarkable similarity to the behavior of soils (Lo Presti et al., 1997; Pradhan and Ueno, 1998)

The modulus degradation curve of EPS geofoam was found to depend –although not significantly –on the material density, confining pressure and type of loading. As a first approximation these effects may be neglected and a unique relation (Eq.7) is proposed for practical applications (depicted as an equivalent G/G_0-γ_c curve in Figure 6a):

$$\frac{E}{E_o} = \frac{1}{1 + \frac{\varepsilon_c}{0.01}} \qquad (7)$$

Values of Poisson's ratio, v, -estimated from the measured axial and radial deformations of specimens- were obtained mainly from the monotonic triaxial tests, assuming an equivalent-linear material behavior. It was found that the value of v decreases with increasing confining pressure and axial strain whereas it is insensitive to the value of EPS density. Test results for the lowest and highest values of ρ are summarized in the diagrams of Figure 8, which indicate that for large strains and high confining pressures Poisson's ratio may take negative values (up to -0.30). This indicates that under such conditions, the EPS behaves as an "auxetic" material (Stavroulakis, 2004).

Finally, according to the test results, the damping ratio value of EPS is increased for large strains and furthermore it increases with increasing confining pressure and decreasing material density. However, the most important effect seems to be associated with the type of loading, with damping ratio values for compressive loading being about 4 times the corresponding values for shear loading. For practical

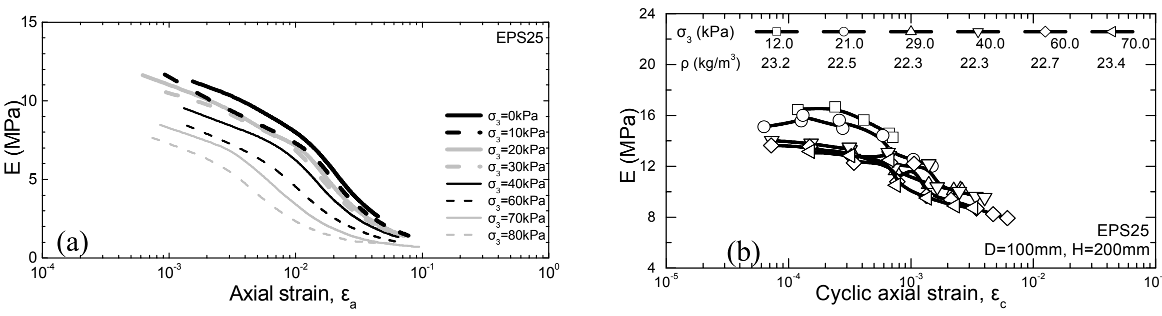

Figure 7. EPS geofoam modulus of elasticity as a function of strain and confining pressure, (a) from monotonic triaxial tests, (b) from cyclic triaxial tests

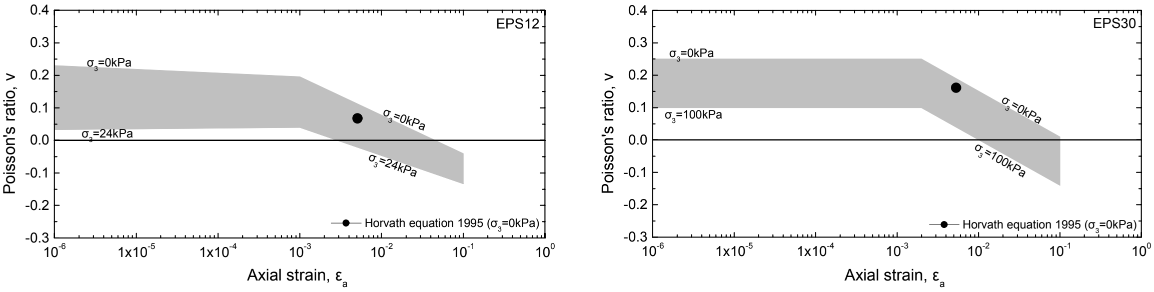

Figure 8. Poisson's ratio of EPS geofoam as a function of strain, confining pressure and density

applications involving large strains it is suggested to use the values of D≈3% and D≈14% for the deviatoric and hydrostatic component of loading, respectively.

B. Effectiveness of EPS Seismic Isolators

The reliability of the numerical method of analysis used in this part of the investigation was first checked by analyzing a published case of shaking table test on a small scale physical model of a retaining wall (Zarnani and Bathurst, 2005, Zarnani et al., 2005). In the diagrams of Figure 9, the results of a comparison are shown between the measured values of active seismic thrust on the wall vs. the estimated values obtained by using the code PLAXIS. The comparisons are shown for the case of non-isolated wall as well as for two cases of seismic isolation using EPS12 and EPS16. In all cases the agreement between measured and estimated response is satisfactory. The diagrams also include results estimated by using the code FLAC, which are also in general agreement with the experimental values.

Having obtained confidence with the modeling capability of the PLAXIS code, a series of parametric analyses were conducted to investigate the effect of several parameters on the effectiveness of EPS compressible inclusion as a seismic isolator. The results of these analyses are briefly discussed in the following sections.

a. Method of Analysis

A number of comparisons between the results of linear vs. non-linear finite element analyses showed that a non-linear analysis describes better the behavior of the system (wall-EPS buffer-backfill). Based also on the fact that the measured response of the physical model test, described in the previous section, was best modeled by implementing the non-linear behavior of EPS and soil material (Figure 9), it was decided to assume non-linear behavior of materials in all subsequent analyses.

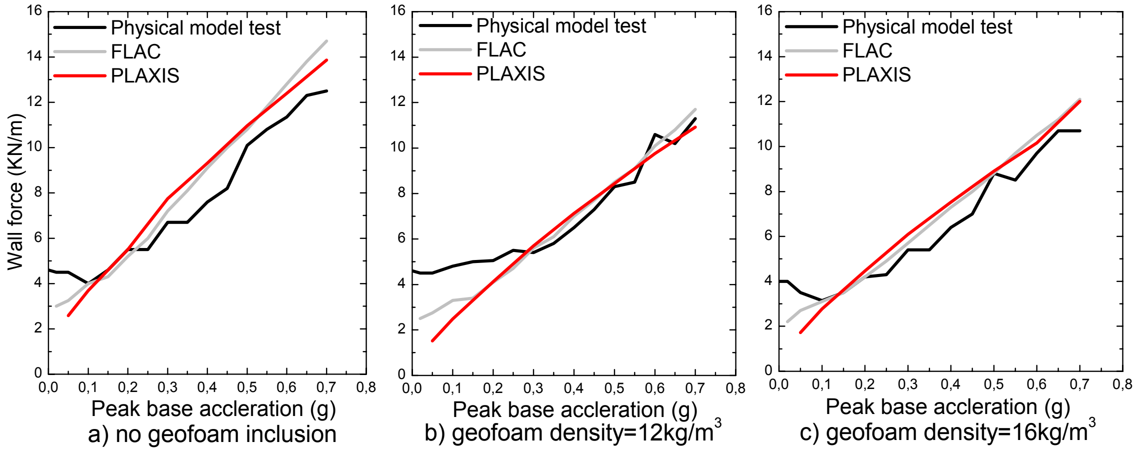

Figure 9. Measured vs. calculated response of a retaining wall physical model in shaking table test

b. Shape of Compressible Inclusion

A number of seismic response analyses were conducted for walls having a height of 4.0m and four different shapes of EPS buffer: orthogonal, (i.e. constant thickness with depth) and triangular (with maximum thickness at top, bottom and mid-height of wall), Figure 10. In all cases the area of the cross-section of the compressible inclusion (and therefore its mean thickness) was the same. The results of analyses indicated that the maximum values of isolation efficiency, A_r were obtained for shapes (a) and (b) with the shape (b) being slightly superior to shape (a). By considering the convenience of installing a constant thickness inclusion behind the wall it was decided to favor the orthogonal shape of inclusion, which was used in all subsequent analyses and it is recommended for practical applications (Stathopoulou, 2005). In subsequent sections the thickness of the compressible inclusion is normalized with respect to the wall height and denoted by t_r (%).

c. Flexibility of Wall

The results of many parametric analyses showed that the isolation efficiency of EPS compressible inclusion increases with increasing wall flexibility. It was found, however, that the differentiation of response between perfectly rigid walls and walls of common flexibility was less than 16 %. For this reason most of the results presented herein were obtained for rigid walls and are considered to be applicable to most common reinforced concrete walls.

d. Density and Thickness of Compressible Inclusion

Most of the analyses were conducted for walls with a height of 4.0m, with EPS buffers having density 15, 20 and 25kg/m^3 and normalized thickness, t_r, ranging from 5% to 40%. Typical results are presented in the diagrams of Figure 11, indicating that isolation efficiencies as great as 90% can be realized for shaking intensities ranging from 0.1g to 0.5g. Careful observation of the above diagrams, however, reveals that the realization of A_r values greater than 50% requires a significant increase of the thickness of the EPS inclusion (up to 40% of the wall height). Based on the above observation it was decided to consider the isolation efficiency of 50% as the preferable value for the estimation of the required thickness of inclusion. Further observation of Figure 11, also reveals that the isolation efficiency increases with decreasing EPS density; this effect is not significant, however, and in practical applications a balance between the desired higher isolation efficiency and the undesired backfill deformations, may be established by using an EPS density equal to ρ=20kg/m^3.

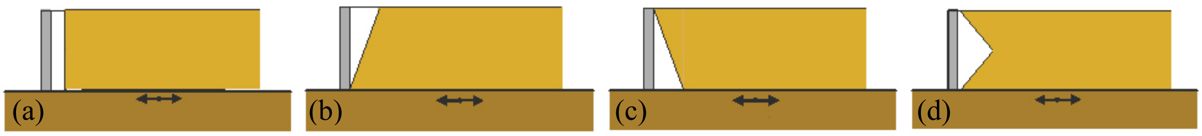

Figure 10. Different shapes of a compressible inclusion examined in the present study

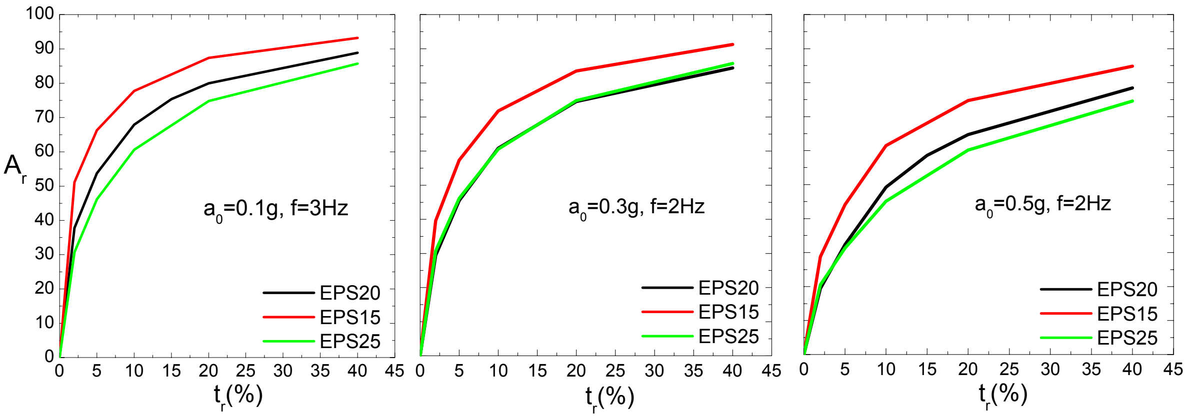

Figure 11. Seismic isolation efficiency of a compressible inclusion as a function of thickness, material density and intensity of motion

e. Wall Height and Intensity of Base Motion

A number of non-linear analyses were conducted for different wall heights and intensities of base motion varying from 0.1g to 0.5g. It was found that the isolation efficiency of the EPS buffer decreases for increasing wall height especially for strong ground motions. The diagrams of Figure 12 depict this type of behavior by comparing the responses of two walls with heights equal to 4.0m and 8.0m. Thus, when selecting the value of thickness t_r, corresponding to isolation efficiency of A_r=50%, the effects of base motion and wall height should be taken into account. The diagram of Figure13 (a), is based on the results of the present study and may be used for selecting the appropriate value of thickness, t_r, of an EPS 20 compressible inclusion for rigid walls of varying heights under different base motion intensities.

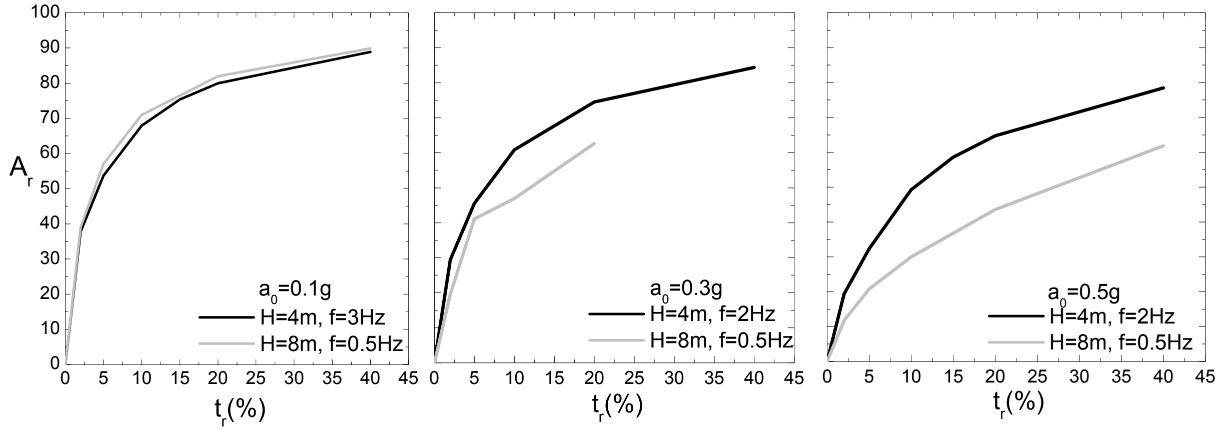

Figure 12. Effect of wall height and intensity of base motion on the seismic isolation efficiency of an EPS 20 compressible inclusion

f. Frequency of Base Excitation

The results of a number of analyses have shown that the isolation efficiency of an EPS compressible inclusion is dramatically reduced for excitation frequencies in the vicinity of the fundamental frequency, f_1, of the wall-backfill system, Figure 13 (b), especially in the case of rigid walls. An approximate value of f_1 may be obtained from the relationship $f_1= V_S/4H$, where H = the wall height and V_S = shear wave velocity of backfill material. Based on the available results it is concluded that the seismic isolation system remains fully effective only when the predominant frequency of base motion is less than $0.3f_1$ or greater than $2f_1$.

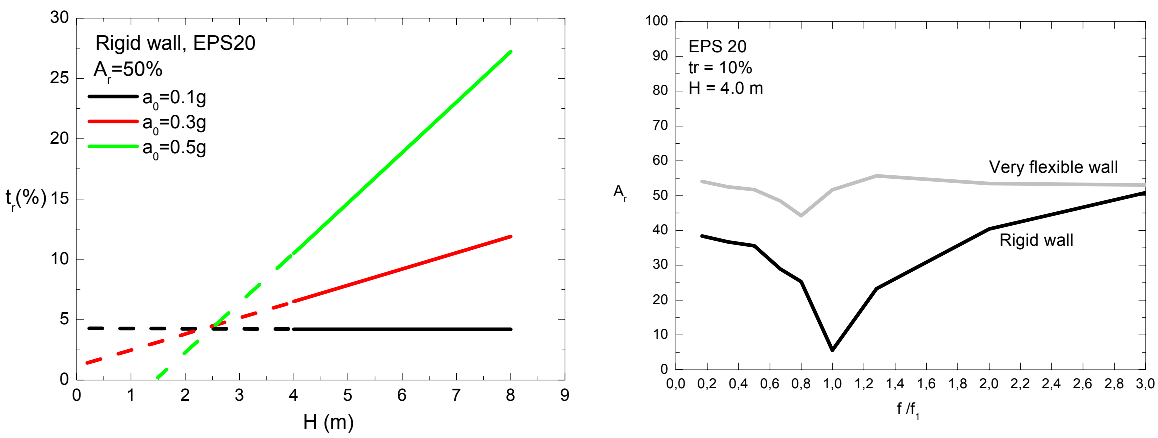

Figure 13. (a) Effect of wall height and base motion intensity on the thickness of an EPS 20 compressible inclusion for A_r=50%, (b) Effect of normalized excitation frequency on the seismic isolation efficiency of an EPS compressible inclusion, for rigid and very flexible walls

g. Height of Application of the Seismic Component of Thrust
According to the results of the analyses of the present study the height of application of the seismic component of the lateral thrust is not affected by the presence of an EPS compressible inclusion.

h. Compressible Material vs. Light-weight Material
An interesting question regarding the seismic isolation efficiency of the EPS geofoam is whether this efficiency is due to its very low unit weight or to its high compressibility, compared to the soil materials. To obtain an answer on this issue a number of analyses were conducted, for a wall having a height of 4.0m. In these analyses the wall is seismically isolated with an inclusion having a thickness of t_r=5%. The magnitude of the seismic component of the thrust was estimated for three cases: (a) for a non-isolated wall, (b) for an isolation inclusion having a density equal to actual EPS density and stiffness equal to the stiffness of the backfill material and (c) for an isolation inclusion having a density equal to the density of the backfill and a very low stiffness, compared to the stiffness of the soil. The results of the analyses indicate that for both weak and strong ground motion the isolation efficiency of EPS is derived almost entirely from its low stiffness rather than from its low unit weight (Nikolopoulou, 2006).

PROPOSED DESIGN METHODOLOGY

Based on the results of the tests and analyses presented in the previous sections the following two-step design methodology is proposed for reinforced concrete retaining structures seismically isolated by EPS geofoam compressible inclusions:

- Proportion the structure by considering a seismic component of thrust equal to 50% of the value that would be used for a non-isolated wall,
- Estimate the required thickness of the EPS 20 compressible inclusion as a function of wall height and intensity of base motion, based on the diagrams developed in the present study.

Preliminary comparative cost analyses have shown that by applying the above methodology, a cost reduction of 50% or more, can be achieved. Also, further analyses are underway to compare the required thickness of compressible inclusion for the cases of static and seismic isolation. The results of such a comparison will allow the development of a unified design methodology for both static and seismic isolation of earth retaining structures.

CONCLUSIONS

The static and dynamic properties of EPS geofoam (strength, moduli, damping and void ratio) depend mainly on density, mean confining pressure and amplitude of deformation. Empirical relations are proposed for estimating values of these properties. The relations are useful not only for the compressible inclusion application but for other applications as well.

The effectiveness of an EPS geofoam seismic buffer depends on material density and thickness, wall height and flexibility and intensity and frequency of base motion. The proposed tentative design methodology is based on the concept of 50% reduction of the seismic component of lateral thrust by using a material with density of 20kg/m^3 or compressive strength of 100kPa. An advantage of the above method of seismic isolation is its potential to be used in seismic retrofitting of existing structures.

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