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SEISMIC DESIGN OF RETAINING STRUCTURES WITH EXPANDED POLYSTYRENE (EPS)

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ABSTRACT

The design of retaining structures is an important issue of civil and geotechnical engineering. As the static earth pressures acting on the retaining structures depend mainly on the capability of the retaining structure to move and / or deform, the design of any retaining structure is a complex problem of soil-structure interaction. This problem becomes more complicated under seismic conditions since inertial forces are acting on the wall mass and additional dynamic earth pressures are caused, in addition to static earth pressures. In parallel, expanded polystyrene (EPS) is an industrial composite material that is used in a variety of technical projects because of its particular mechanical properties, and more specifically its relatively high strength combined with low weight and controlled compressibility. One of its modern applications is its use as a compressible inclusion between a retaining structure and the retained soil materials. Recent numerical analyses and experimental simulations have demonstrated the efficiency of EPS in terms of earth pressures under static and seismic conditions. On the basis of the aforementioned, the aim of this paper is to present the variation of dynamic earth pressures that develop on rigid or flexible retaining systems depending on the circumstances, and to investigate the possibility to decrease the seismic distress of retaining structures using EPS as inclusion. Parametric analyses with two-dimensional finite elements are performed, which are calibrated on the basis of experimental results from the literature, with the aim of developing design diagrams that could potentially be incorporated into seismic norms (e.g. EC8).

Keywords: retaining structures, expanded polystyrene (EPS), dynamic earth pressures, seismic design, isolation

1. INTRODUCTION

The design of retaining structures, such as retaining walls, basement walls, bridge abutments and harbor quay walls, is an important issue of civil and geotechnical engineering. As the static earth pressures acting on the retaining structures depend mainly on the capability of the retaining structure to move and / or deform, the design of any retaining structure is a complex problem of soil-structure interaction. As it is described in Psarropoulos et al. (2005) and Psarropoulos (2015), this problem becomes more complicated and demanding under seismic conditions since (a) inertial forces are acting on the wall mass, and (b) additional dynamic earth pressures are caused, in addition to the static earth pressures. A particular category of retaining structures are harbour quay walls, which in a number of seismic incidents in the past (e.g. Japan 1995, Taiwan 1999) have shown particular sensitivity to the phenomenon of soil liquefaction of the foundation materials of the quay wall and the retained soil materials.

In parallel, expanded polystyrene (EPS) geofoam is an industrial composite material that is used in a variety of technical projects because of its particular mechanical properties, and more specifically its relatively high strength combined with low weight and controlled compressibility. One of its modern applications is its use as a compressible inclusion between a retaining structure and the retained soil materials.

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Recent numerical analyses and experimental simulations have demonstrated the efficiency of EPS in terms of earth pressures under static and seismic conditions. The efficiency of EPS under seismic conditions has been confirmed in the studies of Zarnani & Bathurst (2009) and Athanasopoulos-Zekkos et al. (2012). In the first study, a comparison is made between numerical finite difference analysis and simulation results on a shaking table, while the second study presents the simulation results in a centrifuge, which are compared with previous finite element numerical analyses. Both works confirm the effectiveness of the use of EPS geofoam as a compressible inclusion between a rigid retaining structure and the backfill.

On the basis of the aforementioned, the aim of this paper is (a) to present the variation of dynamic earth pressures that develop on rigid or flexible retaining systems depending on the circumstances (wall flexibility and/or foundation compliance) and (b) to investigate the possibility of retaining structures using EPS to limit their dynamic distress due to seismic loading. Parametric analyses with two-dimensional finite elements are carried out, which are calibrated on the basis of experimental results from the literature, with the aim of developing design diagrams that could potentially be incorporated into seismic norms (e.g. EC8).

2. SEISMIC EARTH PRESSURES ON RETAINING STRUCTURES

The seismic analysis and design of retaining structures was based for many decades on the simple Mononobe–Okabe (M-O) method (Okabe 1926, Mononobe & Matsuo 1929), which actually comprises an extension of the static Coulomb theory (Figure 1). According to the M-O method, the seismic earth pressures are taken into account as pseudo-static pressures that depend on a fraction of the expected peak ground acceleration. However, the pseudo-static concept has limitations that stem from the limitations of the Coulomb theory: only one soil layer can be present, seismic excitation is taken into account as a single constant parameter, pore pressure built-up can be considered in a simplistic way, and of course, soil deformations or displacements are ignored. Nevertheless, being the main representative of the limit-equilibrium methods, M-O method prevailed mainly due to its simplicity and the familiarity of the engineers with Coulomb theory. However, experiments were proving that the M-O method was accurate only when the wall movements (sliding, tilting, bending deformations, or any possible combination of them) were large enough to cause non reversible plastic deformations in the soil. As the kinematic constraints imposed on some retaining systems (like basement walls, bridge abutments, anchors) deter the limit-equilibrium conditions, increased dynamic earth pressures were observed, that could not be predicted by the limit-equilibrium methods.

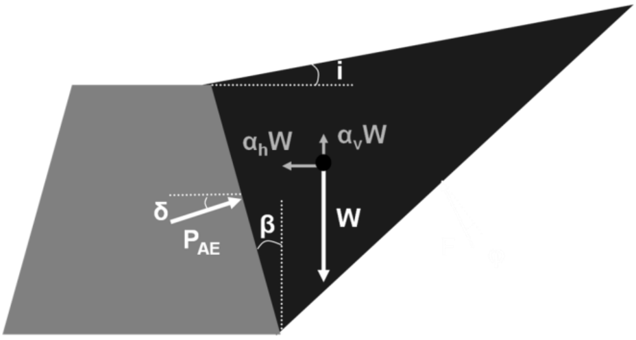

Figure 1: The static and pseudo-static forces acting on the soil mass according to Mononobe-Okabe method

In the early ΄70s, the first analytical elasticity-based methods were developed (e.g. Wood 1975). The predicted dynamic pressures were almost three times more than the corresponding ones predicted by the limit-equilibrium methods. This fact, in combination to the absence of spectacular failures of retaining structures, led to the impression that elasticity-based methods are over-conservative and rather improper for practical use. For that reason these methods were passed over for a long period, and on the other hand the limit-equilibrium methods prevailed, being incorporated in the most seismic norms. More recently (in 1994 and 1997) Veletsos & Younan proved that the relatively high dynamic

earth pressures of the elasticity-based methods up-to-date could be attributed to their main simplistic assumption that the wall is rigid and fixed at its base. They have drawn to that conclusion after having developed an analytical solution that takes into consideration both the wall flexibility and the potential compliance of the wall foundation. It was discovered that, for realistic values of wall flexibility and rotational compliance at the wall base, the dynamic earth pressures are substantially lower than the corresponding pressures predicted for rigid fixed-base wall. It is evident however that the elasticity-based methods have certain limitations. Their main disadvantage is the assumption of homogeneous soil material that behaves linearly. Although the hysteretic behaviour of the soil may be taken into account, a realistic simulation of a potential nonlinear behaviour is rather impossible. As described hereafter, the efforts to take into account the nonlinear soil behaviour (before reaching the limit-equilibrium conditions) are very few.
As mentioned before, the M-O method is the prevailing method for the seismic design of retaining walls. The method is based on the limit-equilibrium of a soil wedge retained by the wall. The inertia forces developed on the wedge due to the seismic excitation are also included in the force equilibrium. These forces are easily calculated from the horizontal (a_h) and the vertical (a_v) seismic coefficients. The seismic coefficients comprise portions of the peak ground acceleration $A_{\max}$(= $a_{\max}$g, where g is the acceleration of gravity), and, though they are usually calculated empirically, a value of a_h close to 65% of $a_{\max}$ is considered to be realistic. Note that the vertical acceleration A_v (= a_vg) is regarded trivial, and it is usually ignored in the design.
However, almost 50 years later than M-O method was developed, it was further simplified by Seed & Whitman (1970). As M-O method calculates the total force P_{AE}, and as the static force P_A is already known by Rankine or Coulomb theory, a dynamic coefficient of active earth pressures ΔK_{AE} can be easily calculated by the following equations:

$$\left.\begin{aligned} &P_{AE} = P_A + \Delta P_{AE} \Rightarrow \Delta P_{AE} = P_{AE} - P_A \\ &\Delta P_{AE} = \frac{1}{2}\Delta K_{AE}\gamma H^2 \end{aligned}\right\} \Rightarrow \Delta K_{AE} = \frac{2(P_{AE} - P_A)}{\gamma H^2} \tag{1}$$

Based on the previous expression, that coefficient is a function of the applied horizontal acceleration. For $\alpha_h < 0.4$, Seed & Whitman proposed a linear relationship between ΔK_{AE} and α_h. Specifically:

$$\Delta K_{AE} \approx \frac{3}{4}\alpha_h \tag{2}$$

Therefore, the normalized active force $\Delta P'_{AE}$ is given by:

$$\Delta P'_{AE}\left(= \frac{\Delta P_{AE}}{\alpha_h \gamma H^2}\right) \approx \frac{3}{8} \approx 0.4 \tag{3}$$

Note that the above equations are valid for dry soil conditions. In the case that the retained soil is below water table the equations are modified depending on the soil permeability. In the special case of very high permeability (e.g. > 10^{-3} cm/s) the soil particles move independently of the water, so hydrodynamic forces should be taken into account as well.
The advanced elasticity-based method of Veletsos & Younan (1994 and 1997), as well as its numerical evaluation by Psarropoulos et al. (2005), aims to the estimation of the amplitude and the distribution of the dynamic earth pressures applied on flexible walls capable to rotate at their base due to a seismic excitation. The effect of the involved parameters was surveyed. Soil was considered to act as a homogeneous visco-elastic layer characterized by constant density and infinite extend at the horizontal direction. The base of the wall and the soil layer are excited by the same horizontal seismic motion. The parameters examined are the characteristics of the excitation and of the soil layer, in addition to the stiffness of the wall itself and of its rotational spring at its base. Harmonic as well as seismic excitations were considered. Emphasis was put on the long-period, quasi-static excitations. The response of the dynamically excited system was expressed as the product of the corresponding quasi-static response with an appropriate amplification factor. Figure 2 shows the earth-pressure distribution of a quasi-statically excited retaining system with varying relative flexibility, d_θ, of the base rotational spring for different values of relative wall flexibility, d_w.

According to Psarropoulos et al. (2005), in the case of a rigid fixed-base wall the normalized active force $\Delta P'_{AE} \approx 1$. That value is in accord with the corresponding value proposed by Wood's solution (1975), but it is 2.5 times higher than the corresponding value proposed by Seed & Whitman (i.e. $\Delta P'_{AE} \approx 0.4$). On the contrary, in the case of a wall very flexible and almost free to rotate at its base, Psarropoulos et al. (2005) calculated $\Delta P'_{AE} \approx 0.4$, a value that is in agreement with Seed & Whitman, but it is in contrast to Wood's solution (i.e. $\Delta P'_{AE} \approx 1$) (see Figure 3).

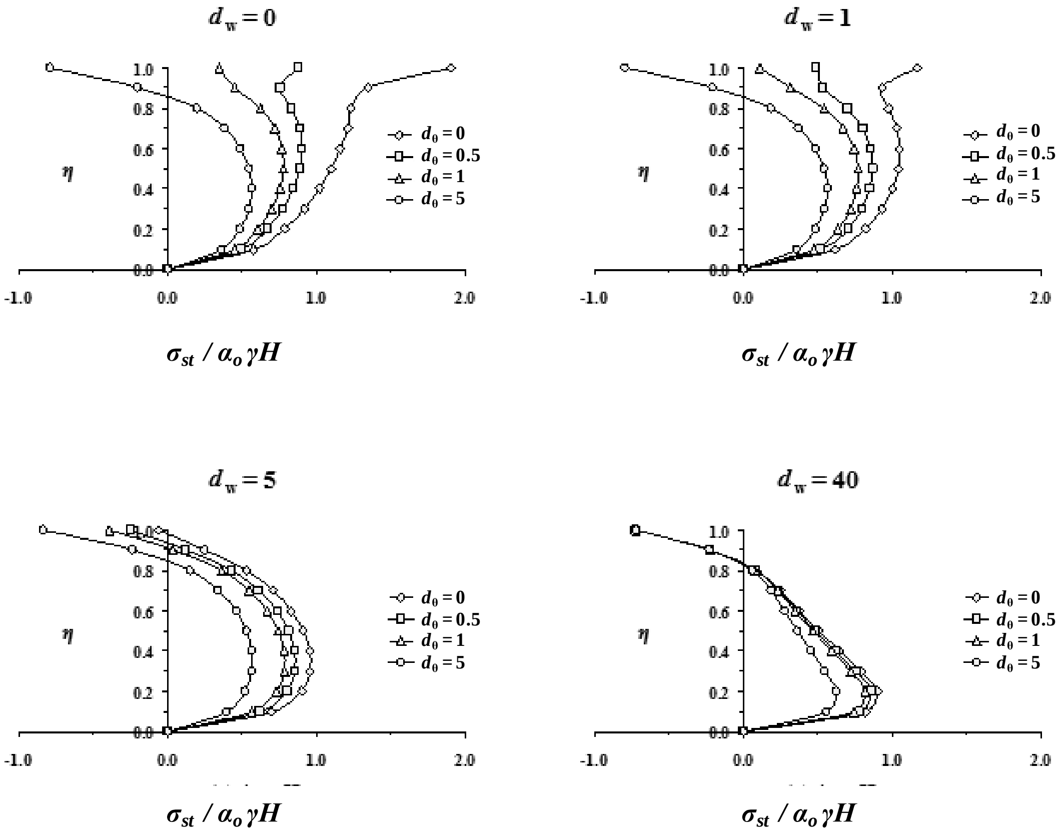

Figure 2: Earth-pressure distribution of a quasi-statically excited retaining system with varying relative flexibility, d_θ, of the base rotational spring for different values of relative wall flexibility, d_w. (after Psarropoulos et al. 2005).

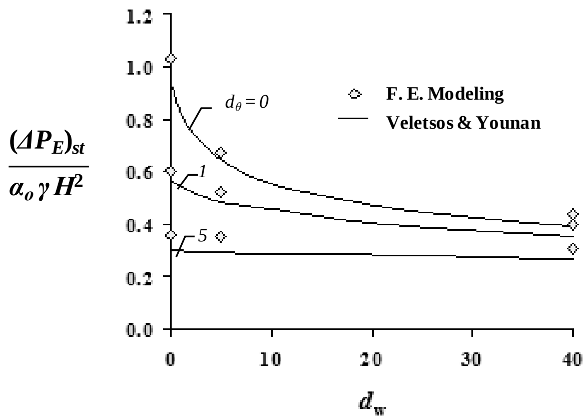

Figure 3: Comparison between the normalized values of base shear $(\Delta P_E)_{st}$ from the analytical formulation of Veletsos & Younan (1994) (continuous line) and those of the numerical simulation of the numerical study (dots). (after Psarropoulos et al. 2005).

3. IMPACT OF EPS ON THE SEISMIC EARTH PRESSURES

As shown in Figure 4, expanded polystyrene (EPS) can be used as backfill behind retaining structures to greatly reduce lateral pressures on the structure. Because the horizontal pressure acting on a retaining wall is proportional to the weight of the backfill, a less robust retaining structure is needed if the backfill soil in the active zone behind the retaining wall is replaced with EPS. It is evident that in retaining wall applications, adequate drains should be provided to prevent the development of hydrostatic pressure and uplift due to buoyancy for sites with shallow groundwater and loose soils.

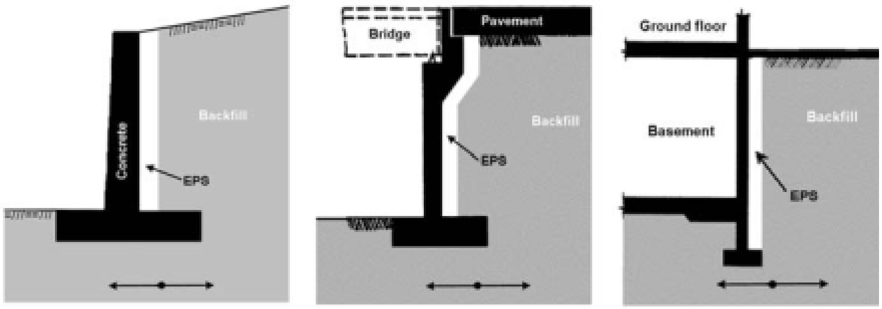

Figure 4: Sketch showing various retaining structures (i.e. retaining wall, bridge abutment and basement wall) with EPS being a compressible inclusion

Likewise, the use of EPS backfill behind retaining structures also limits the horizontal forces that can develop during earthquakes. Previous research on the effectiveness of EPS in providing isolation against the active earthquake lateral thrust, has focused on the case of non-yielding earth retaining walls. The concept was first proposed by Horvath in 1995 and evolved as an extension of the initial use of compressible inclusions for reducing the static lateral earth thrust against non-yielding walls (Horvath, 2004). The studies on the effectiveness of EPS compressible inclusions as a seismic isolator of non-yielding walls against earth thrust have followed two directions: (a) numerical analyses using limit static approach and finite element programs (e.g. Athanasopoulos et al. 2007) and (b) shaking table tests on small scale physical models (e.g. Zarnani & Bathurst, 2009). The soil behaviour in the numerical analyses was assumed to be either elasto-plastic or equivalent linear. The EPS, based on experimental data, was assumed to be either a purely cohesive material or an equivalent linear material. Based on the results of extensive parametric analyses, the isolation efficiency with respect to earth pressures (i.e. the ratio of the reduction of seismic thrust increment due to the isolation, to the value of seismic thrust increment without the isolation) of EPS compressible inclusions in the case of non-yielding walls was found to depend on the following parameters:

a) cross-section shape of compressible inclusion,

b) material density of EPS,

c) normalized thickness of compressible inclusion,

d) relative excitation frequency,

e) shaking intensity, and

f) wall height and flexibility.

The effectiveness of EPS compressible inclusions in reducing both the seismic earth pressure and displacement increment (i.e., horizontal translation and rotation) of yielding, gravity type, earth retaining walls, was investigated by parametric numerical analyses in Athanasopoulos-Zekkos et al. (2012). The isolation efficiency of the inclusions was studied as a function of the normalized – with respect to wall height – thickness of the inclusion and shaking intensity. The results of the analyses indicate that – as in the case of non-yielding walls – the isolation efficiency, in general, increases with increasing inclusion thickness and also depends on shaking intensity, wall height and excitation frequency. However, in contrast to the case of non-yielding walls, the isolation efficiency of yielding walls increases with inclusion thickness only up to a limiting value which cannot be exceeded with a further increase of inclusion thickness. It is concluded that EPS compressible inclusions can provide an effective means for reducing the permanent seismic displacement and lateral thrust increments for new or existing seismically retrofitted yielding earth retaining structures.

On the other hand, physical modelling can help verify the numerical analyses and validate their results. A common limitation with physical modelling for most geotechnical engineering applications is the large scale of most structures, including retaining walls that are of interest to this project. Centrifuge testing offers an invaluable opportunity to perform physical modelling on smaller scale model without boundary effect problems. In centrifuge testing the weight of natural material is artificially increased, thus making the behaviour of the small scale model to duplicate the behaviour of the prototype structure. It is emphasized that the centrifuge tests provide results representative of the actual field conditions, in contrast to the small scale (1g) shaking table tests in which the response depends on the scale of the model. Centrifuge testing has become an invaluable tool to understanding geotechnical earthquake engineering problems that would have been otherwise very hard to study.

A current physical modelling has been performed by Athanasopoulos-Zekkos et al. (2011). They performed two centrifuge tests on 4m tall retaining wall models founded and backfilled with dry, medium dense, Nevada sand. The models were shaken with a range of sinusoidal motions. These tests have given the first ever set of data for this type of project. Preliminary results and processing of the data from the centrifuge tests indicate that the EPS layer that was included in the second model acted as a buffer and helped reduce the seismic pressures that were applied on the retaining wall. The isolation efficiency of a t_r=10% inclusion of EPS was found to vary between 10% and 50% along the height of the wall for an input motion of 0.2g at a frequency of 2Hz. These results are in good agreement with previously performed numerical analyses for similar walls and soil conditions. These centrifuge tests will also provide us with high quality data that can be used towards a better understanding of the seismic response and performance of earth retaining structures in general.

Note that a particular category of retaining structures are the quay walls, since during a number of seismic incidents in the past (e.g. Japan 1995, Taiwan 1999) they have shown particular sensitivity to the phenomenon of liquefaction of (a) the underlying soil materials of the foundation of the quay wall and (b) the retained soil materials. Hazarika et al. (2001) and Hazarika (2005) have simulated the seismic behaviour of rigid retaining walls and quay walls, and have shown the need for an appropriate simulation of the backfill behaviour. They found that an economic solution to reduce seismic earth pressures was to replace the backfill (or part of the backfill) with low-density, but high-strength materials such as EPS. EPS could reduce the pressure on the wall by almost 50% to 60%, compared to the earth pressures of conventional backfill materials. It should be noted that in the case of a quay wall construction with EPS, an issue for which special care should be taken is the need to anchor the EPS to the quay and/or the underlying ground in order to prevent EPS from uplifting due to buoyancy.

In the current study parametric analyses with 2D finite elements are carried out, which are calibrated on the basis of experimental results from the literature, with the aim of developing design diagrams that could potentially be incorporated into seismic norms. Figure 5 shows the basic numerical model developed in this study. It consists of a gravity wall of height H = 5m that retains a soft soil material. The wall is founded either on rock or on soil, while between the wall and the retained soil a thin layer of EPS may be incorporated. The properties of all materials are given in Table 1.

Figure 6(a) includes some indicative results of the numerical analyses. More specifically, the total (static and seismic) horizontal earth pressures acting on a rigid wall founded on rock are shown. The wall is examined under static and seismic (pseudo-static) conditions. In the case of seismic loading, two acceleration levels have been considered: a=0.15 and a=0.25. It is evident that using a thin layer of EPS between the wall and the retained soil may lead to a substantial reduction of the horizontal earth pressures, not only under seismic conditions, but under static conditions as well. Figure 6(b) shows the seismic horizontal earth pressures compared with the analytical values of Wood (1975).

Table1. Mechanical properties of all the materials used in the numerical simulations .

	retained soil	**underlying soil**	**underlying rock**	**wall (concrete)**	**EPS**
unit weight, γ (kN/m^3)	18	20	25	25	0.2
modulus of elasticity, E (kPa)	$6 \cdot 10^4$	$1 \cdot 10^5$	$2.9 \cdot 10^7$	$2.9 \cdot 10^7$	9694
Poisson's ratio, ν (-)	0.33	0.33	0.15	0.15	0.17
angle of friction, φ (^{o})	35	40	-	-	-

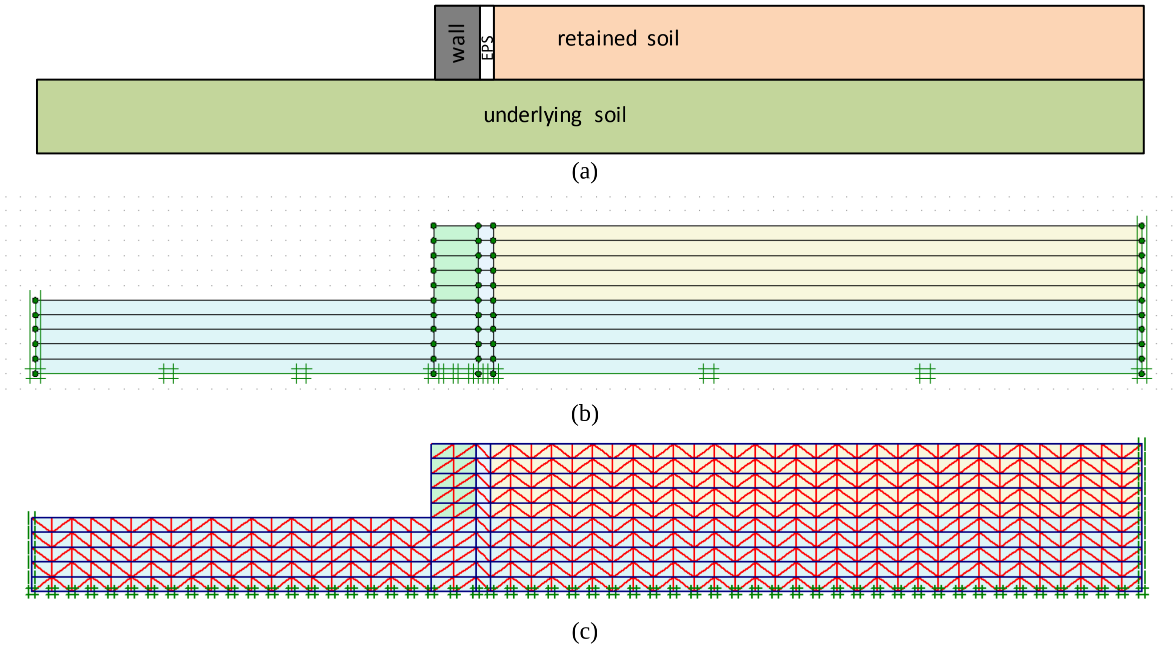

Figure 5. The numerical model developed in the current study: (a) sketch of the model, (b) model and boundary conditions, and (c) finite-element mesh. The model consists of a gravity wall retaining soft soil material, while between the wall and the retained soil a thin layer of EPS may be incorporated.

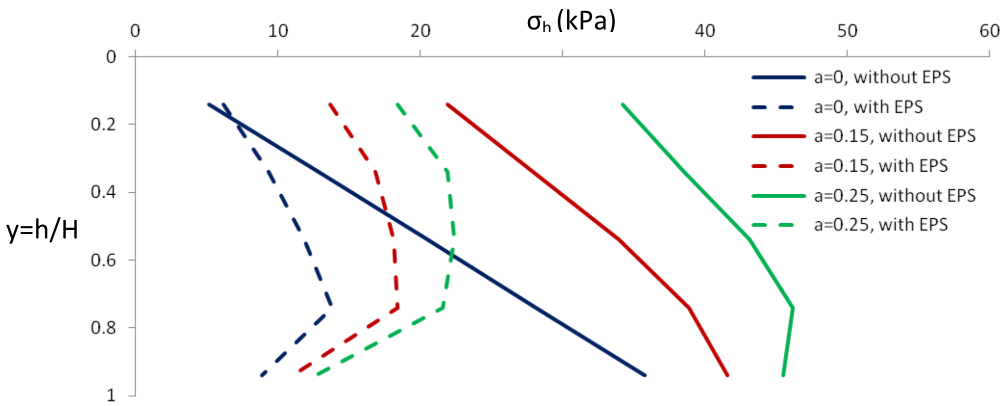

Figure 6(a). Typical numerical results of the total (static + seismic) horizontal earth pressures, σ_h, acting on a rigid wall founded on rock for the three cases of applied acceleration: (a) a=0 (static case), (b) a=0.15, (c) a=0.25

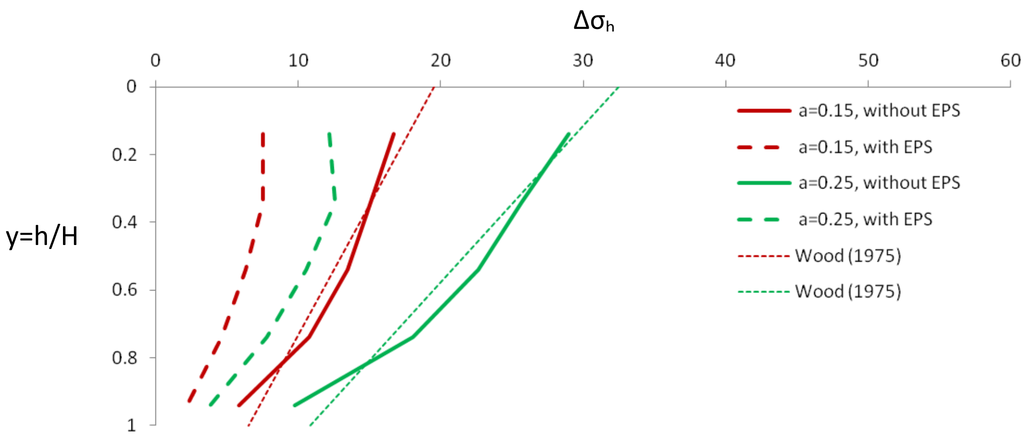

Figure 6(b). Typical numerical results of the seismic horizontal earth pressures, $\Delta\sigma_h$, acting on a rigid wall founded on rock for the three cases of applied acceleration: a=0.15 and a=0.25.

4. CONCLUSIONS

The current paper is involved with the seismic distress of retaining structures (i.e. retaining walls, bridge abutments, and basement walls), giving emphasis on the beneficial impact of expanded polystyrene (EPS) on the amplitude and the distribution of the seismic earth pressures acting on the retaining structure. The numerical results of the current study verify previous studies in the literature (based on numerical and/or experimental simulations) that have demonstrated the efficiency of EPS in terms of earth pressures under static and seismic conditions.

5. ACKNOWLEDGMENTS

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