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Reduction of Earth Pressure for Non-Yielding Retaining Walls using EPS Geofoam

Sayed M. Sayed, Tamer M. Sorour, Mohamed S. Belal

Abstract— Due to backfilling and surcharge pressures from the foundations of adjacent buildings, retaining walls are built to withstand the ground pressure and lateral thrust. Expanded low stiffness polystyrene (EPS geofoam) panels mounted vertically against the rigid non-yielding retaining structures to minimize lateral earth pressure due to their compressible nature. Numerical models are being developed in the present study to validate the recorded physical test results for a rigid non-yielding wall (Ertugrul and Trandafir 2011). The results illustrate the effectiveness of EPS geofoam in controlling the lateral earth pressure as a material of inclusion behind retaining structures. A series of numerical analyses were performed using finite element program Plaxis 2D V8.5. Parametric analyses were adopted to demonstrate the effectiveness of the geofoam density and the thickness of the geofoam buffer in reducing the lateral earth pressure produced behind the retaining structures.

Index Terms— Retaining wall, EPS geofoam, Reducing earth pressure, Analysis of finite elements.
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1 Introduction

LATERAL earth pressure is the main important parameter to be considered by designing all types of retaining structures. Retaining structures (cantilevered gravity, reinforced concrete retaining walls, bridge abutments or basement walls ......) design is mainly based on two considerations: Firstly, safe resistance to lateral earth strains. Secondly, safe resistance to surcharge from adjacent structures and earthquake loads. The most acting parameter in the design of the retaining walls is the lateral earth pressure resulting from backfill mass. Expanded Polystyrene (EPS geofoam) is one of the most effective solutions for reducing lateral earth pressure resulting from assisted backfill. Polystyrene extended (EPS geofoam) is a super-lightweight, closed structure, rigid, flexible foam. The unit weight positions it in a separate category as compared with other types of lightweight materials in engineering. EPS geofoam density can be considered the main index in most of its properties where compression strength, shear strength, tension strength, flexural strength, stiffness, creep behavior and other mechanical properties depend mainly on the density of EPS geofoam. EPS geofoam is a multifunctional material that makes it successful for many construction applications to be used. EPS geofoam can be used as a barrier between the retaining wall and the backfill material behind the retaining framework (Horvath, 1995). EPS provides a reduction in lateral earth pressure and flexural deflection of non-yielding retaining structures resulting from EPS lateral compression due to the soil arching effect (Horvath 1995). The use of EPS geofoam as a back-fill material (Horvath 2010) can cause excessive settlement to surface ground adjacent to the retaining structure. The EPS geofoam can be utilized as a shield behind the retaining system.

- *Sayed M. Sayed is currently Associate Professor, Structural Engineering Department, Ain Shams University, Egypt. E-mail: sayed_mohamed@eng.asu.edu.eg*
- *Tamer M. Sorour is currently Assistant Professor, Structural Engineering Department, Ain Shams University, Egypt. E-mail: tamer.sorour@eng.asu.edu.eg*
- *Mohamed S. Belal is currently Graduate M.Sc. student, Structural Engineering Department, Ain Shams University, Egypt. E-mail: msaadbelal@gmail.com*

(Trandafir, Moyles and Erickson 2010) presented the results of a finite element modelling analysis on the reduction of lateral earth retaining wall pressure at different heights (3.0 m, 6.0 m, 9.0 m and 12.0 m) using EPS geofoam as a wall buffer. The study outcomes indicated the expected load isolation efficiency for various EPS thicknesses and densities, where the results are based on the retained soil mass. In a more recent study, (Ertugrul and Trandafir 2011) used UWLC (form8 2006) to perform a physical model check with a finite element numerical model. The action of the soil mass retained and the EPS geofoam was fairly well predicted using an elastoplastic soil model. Control yield by EPS geofoam in backfill material helps to save on project design as it decreases structural demand to minimize the forces produced (Horvath 1995). EPS geofoam is manufactured worldwide with varying densities and sizes. After validation, a parametric analysis was performed to illustrate the effectiveness of changing EPS geofoam properties and thickness on the developed lateral earth pressure. Furthermore, whilst using EPS geofoam, the soil relative density affects the generated earth pressure that acts on the retention wall.

2 Methodology

This paper comprises numerical modelling to illustrate the effectiveness of using EPS geofoam in the reduction of lateral earth pressure on the non-yielding retaining walls. The study involves validation of a numerical model with the results of a physical test provided by (Ertugrul and Trandafir 2011).
During physical tests; (Ertugrul and Trandafir 2011) used a sandbox measuring (2.0x1.0x1.0) meters. The model consists of a steel wall (700.0x980.0x8.0) mm (height* length*thickness) which is rigidly welded to a steel foundation (980.0x500.0x8.0) mm (length*width*thickness). Four earth pressure cells with a capacity of 40.0 kPa were vertically fixed at 200.0 mm spacing along with the wall height. Fig. 1 demonstrates a sectional di-

agram of the test setup. The laboratory research was carried out for validation with numerical analysis using EPS geofoam using three different thicknesses t/h equivalent to (0.07, 0.14 and 0.28). Where "t" refers to the thickness of the EPS and "h" refers to the height of the wall.

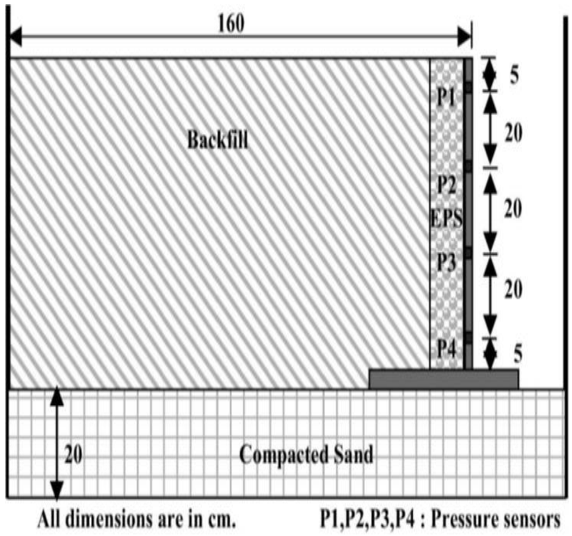

Fig. 1. Cross-section of the test set up. (Ertugrul and Trandafir 2011).

3 Material properties of EPS geofoam

In this study, the physical model setup used a vertical EPS panel of density 15.0 kg/m3, where it was simulated as Mohr-Coulomb material (Zarnani and Bathurst 2009). The stress-strain behavior of the EPS geofoam was specified through uniaxial compression tests. As shown in Fig. 2, (σa _ σr) represents the deviator stress (Where σa and σr represent the axial and radial stress). Based on the uniaxial compression test results, yield strength of the EPS geofoam was found as 38.0kPa, with a maximum strain of 2.0%.

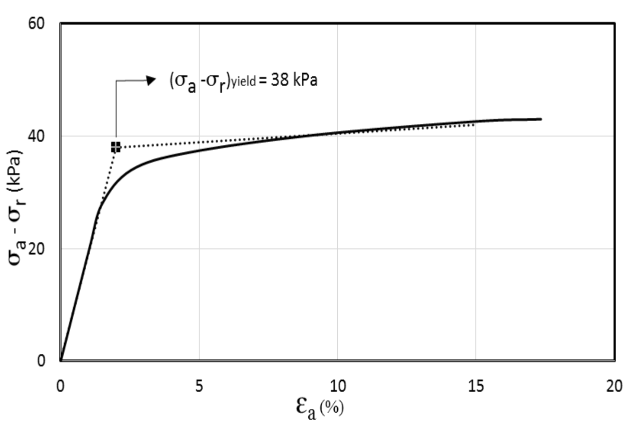

Fig. 2. Results of uniaxial compression test (σr = 0) on geofoam (Ertugrul and Trandafir 2011).

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nal friction angle of EPS geofoam; analyses were carried out by (Padade and Mandal 2012) using different densities of EPS Geofoam in triaxial loading tests. Referring to these tests result; the correlation of cohesion values concerning the corresponding density of EPS Geofoam best fitted to a curve was expressed in Equation (1).

$$C = 894.7\,\gamma\,2 - 214.3\,\gamma + 45 \quad (1)$$

Where "C" is the cohesion in kPa and "γ" is the density of EPS Geofoam in kN/m3.

From the previous equation and the results reported by (Padade and Mandal 2012) as presented in Table 1. The shear strength parameters of EPS Geofoam with density 15.0kg/m3 may be considered as; Cohesion (C) =33.75 kPa and angle of internal friction (ϕ) = 1.5° in the validation analyses.

According to Equation (2) reported by (Horvath 1995) For EPS geofoam with a density of 15.0 kg/m3 Poisson ratio is estimated at 9.0%.

TABLE 1
Properties of Expanded polystyrene (EPS) Geofoam. (Padade and Mandal 2012).

Density of EPS Geofoam (kN/m3)	Cohesion C (kPa)	Angle of internal friction angle (°)
0.15	33.75	1.50
0.20	38.75	2.00
0.22	41.88	2.00
0.30	62.00	2.50

$$\mu f = 0.0056{*}\rho f + 0.0024 \quad (2)$$

Where "ρf" is the density of geofoam in kg/m3 and "μf" is its Poisson ratio.

Table 2 summarizes the simulation parameters for EPS geofoam with a density of 15.0 kg/m3 for validation in numerical modelling, regarding the previous figures and equation.

TABLE 2
EPS geofoam material properties

Parameters	EPS geofoam	Reference
Unit weight (kN/m3)	0.15	
Young's modulus (kPa)	1900.00	(Ertugrul and Trandafir 2011)
Fiction angle (ϕ)°	1.50	(Padade and Mandal 2012)
Cohesion (C) (kPa)	33.75	(Padade and Mandal 2012)
Poisson ratio %	9.00	(Horvath 1995)

4 Retaining Wall and Backfill Materials Properties

The 0.7 m high and 8.0 mm thick retaining wall facing is modelled using beam element in the numerical simulation using the finite element program "Plaxis" as an elastic material with the following properties; Young's modulus (E=1.61E8 kPa) and density (7800.0 kg/m3), respectively. (Ertugrul and Trandafir 2011) registered a unit weight of 16.5 kN/m3 of backfill materials with a relative density of 70.0%. A Hardening Soil Model (HSM) is used to model the granular backfill. The (HSM) is an advanced model that is used for soil properties simulation. Equation (3) is an analytical equation reported by (Bowles, n.d.) to estimate the soil parameters relation between ϕ′ values and soil relative density.

$$\phi' (°) = 28° + 15° Dr (\mp 2°) \quad (3)$$

Where φ′ is the angle of shearing resistance and Dr is the relative density of soil in decimal.

For the elasticity modulus of soil (*Es*) regarding assumed relative density, (Stroud 1989) gives the value of SPT-(N1)60 concerning backfill relative density as shown in Fig. 3. where SPT-(N1)60 is equal to 30.0 for a relative density of 70.0%. Stroud (1988) stated that the relation between SPT-*N* and *Es* depends on the load level (*q*net /*qu*lt) applied on the soil. By using a wide database, Stroud (1988) proposed a relation between SPT-*N* and *Es* with (*q*net /*qu*lt) for both cohesion and cohesionless soils as illustrated in Figure 4. Where; "*q*net" is the net foundation pressure while "*qu*lt" is the net ultimate bearing capacity. For a hardening soil model E50, (qnet /qult) = 0.5. As a result, the relation yields the value of Es = 21000.0 kN/m2, where Es/N60 (mN/m2) = 0.70 as shown in Figure 3.b.

Table (3) presents the backfill material physical properties used for the recorded tests (Ertugrul and Trandafir 2011), where the verification properties of the backfill Harding soil model are described in Table (4).

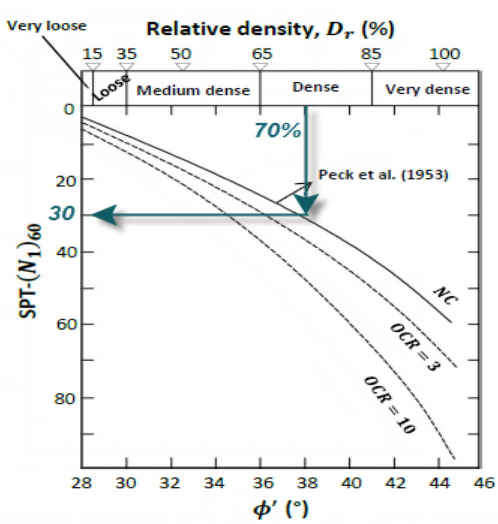

Fig. 3. Relation between SPT-(N1)60 – OCR after (Stroud 1989)

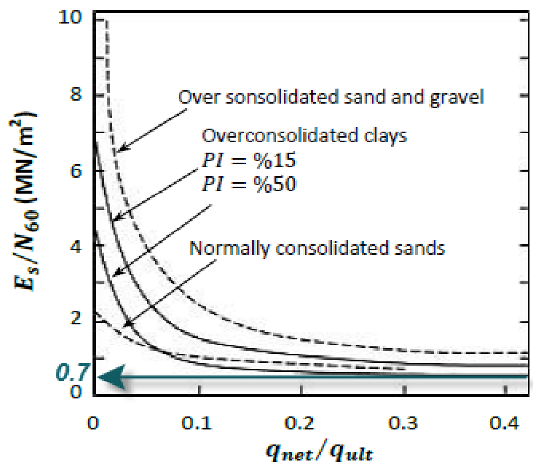

Fig. 4. Relation between Es and SPT-N and (qnet /qult) after (Stroud 1989)

TABLE 3
Constitutive model backfill properties after (Ertugrul and Trandafir 2011).

parameters	Backfill	Foundation
Unit Weight (kN/m3)	16.5	17.5
Young's modulus (kPa)	**5200.0**	**5500.0**
Poisson's Ratio (γ)	0.33	0.33
Friction Angle (degrees)	**43.5**	**45**
Dilatancy Angle (degrees)	22.5	22.5

TABLE 4
Hardening soil model (HSM) parameters for backfills material.

Parameters	Backfill
Unit weight (kN/m3)	16.5
E50ref (kN/m3)	**21000**
Eoedref (kN/m3)	20000
Power (m)	**0.5**
Friction angle ϕ (degrees)	38.5
Dilatancy angle Ψ (degrees)	**6.5**
Cref	0.01

5 Numerical Modelling

Finite element program Plaxis 2D was used, simulating the retaining wall using the numerical plane strain model with a 15-node element. To calibrate and verify the two-dimensional plane strain model; the findings of the instrumented retaining wall model tests were employed. The boundary conditions for the finite element study include restraining horizontal and vertical displacements along the horizontal bottom boundary and restraining horizontal displacement along both sides of the backfill side and the wall side.

The geofoam material is modelled as solely cohesive material as stated (Zarnani and Bathurst 2009), where the backfill soil was modelled as a Harding Soil (HSM) model.

At-rest maximum soil pressure (γHK0) acting at the base of the wall stem was measured as 3.5 kPa where the model's height is 0.70 m, the density of the backfill is considered 16.5 kN/m3 and the backfill friction angle was 43.5°. According to the equation proposed by (Jaky 1944), (i.e., K0 = 1 - sin φ, in which K0 is the coefficient of lateral earth pressure at-rest), thus the soil pressure is much smaller than the yield stress of the geofoam (σyield = 38 kPa). For the physical model without using EPS geofoam, maximum soil pressure acting on the wall stem from (Ertugrul and Trandafir 2011) was determined for the at-rest condition. As shown in Fig. 5, a value for K0 = 0.48 could be considered for modelling the backfill material.

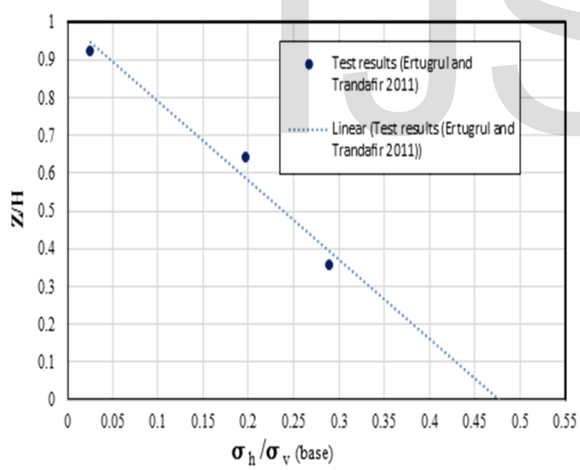

Fig. 5. Test results for retaining wall without using EPS geofoam after (Ertugrul and Trandafir 2011).

At the contact for the following cases: wall stem/geofoam inclusion, geofoam/backfill, and base/foundation wall; elastoplastic Mohr-Coulomb interface elements were added. The interface properties were re-calculated by (Ertugrul and Trandafir 2011) using a numerical calibration method to match the measured stresses and test data. For stem/geofoam, geofoam/backfill; friction angle of the wall stem/backfill interfaces was 15°, 24°, and 32° respectively. The model test experimental method was calibrated with numerical model analysis using Plaxis 2D V (8.5). Fig. 6 illustrates the model discretization, where the height of the model's retaining wall was 0.70 m and its thickness was 8.0 mm. The retaining wall's backfill dimensions are 1.60 m in length. The rigid base dimension of the foundations is 2.00 m long and 0.20 m thick.

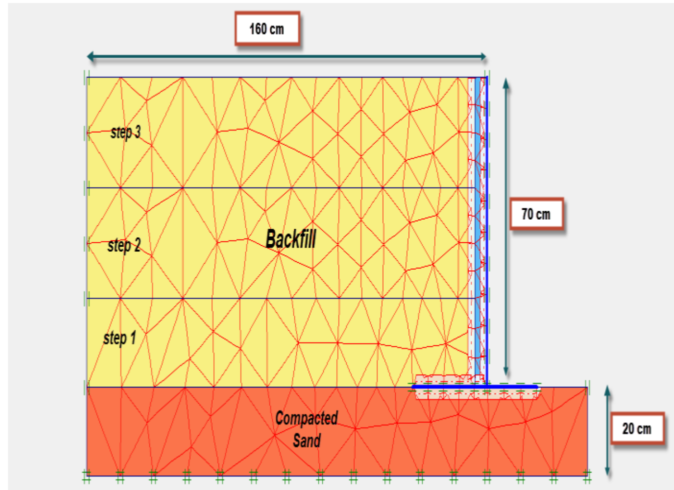

Fig. 6. Model discretization

6 Model Validation

The results of the instrumented retaining wall model tests served for the calibration and validation of the two-dimensional plane-strain FE model. According to (Ertugrul and Trandafir 2011), retaining wall models with EPS geofoam of relative thickness t/h = 0.07, 0.14 and 0.28 are considered. Where "t" is the geofoam thickness and "h" is the wall height. A comparison of physical model test results and numerical model results in terms of lateral earth pressure variation along the height of the wall using a 3-step model for backfilling are presented in Figs. 7,8 and 9. For the first model shown in figure 6; using geofoam with relative thickness 0.07, the results show a good agreement with experimental data from physical test results for the upper part of the wall with a small variance for the lower part. For the second model shown in figure 7, using geofoam with relative thickness 0.14, the results illustrate a good agreement with experimental data from physical test results for the upper and lower parts of the wall with a small variance for the middle measurement. for the third model, using geofoam with relative thickness 0.28, the results show good agreement for the upper part of the wall but a small deviation for the lower part close to the wall about 30% of the wall height. The figures demonstrate that numerical results are reasonably closer to physical test results, lateral earth pressures are decreased with increasing EPS geofoam thickness along with the wall height.

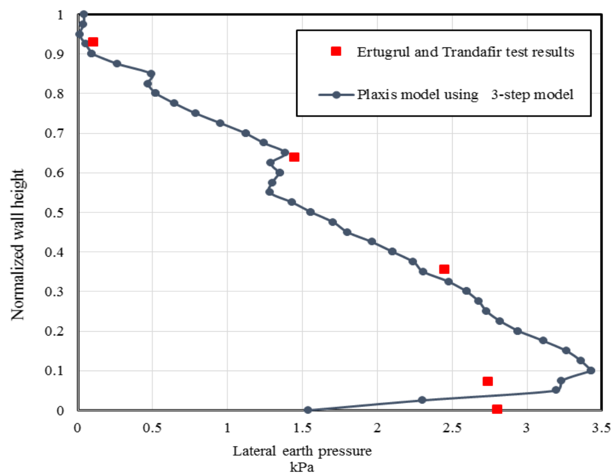

Fig. 7. Numerical results for 3-steps analysis with (t/h=0.07).

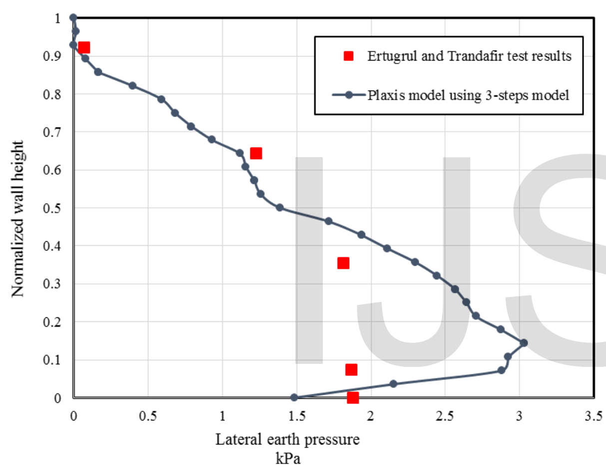

Fig. 8. Numerical results for 3-steps analysis with (t/h=0.14).

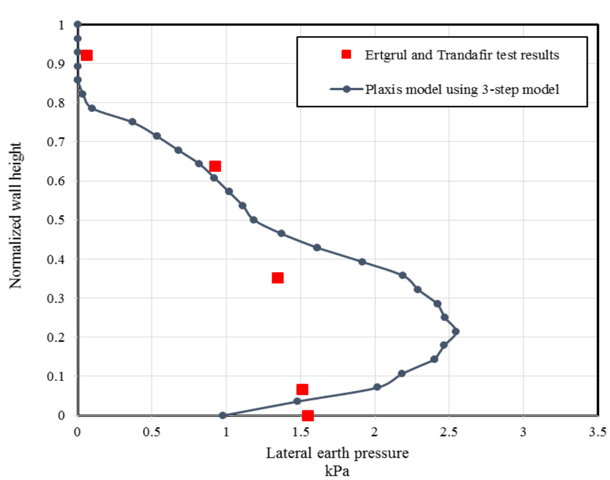

Fig. 9. Numerical results for 3-steps analysis with (t/h=0.28).

7 Parametric Study

A parametric study was conducted to show the effect of EPS geofoam buffer thickness, density and relative backfill compaction adjustment on the resulting lateral earth pressure acting on the non-yielding wall. The study is based on a non-yielding basement wall that has a depth of 12.0 m. The used EPS geofoam in these analyses are in line with the American ASTM D6817 requirements as shown in Table 5. EPS geofoam properties are obtained from ASTM D6187, from which the angle of internal friction and cohesion are obtained for modelling (Padade and Mandal 2012). Poisson's ratio value is calculated using the same correlation as a validation study reported by (Horvath, 1995). Fig. 10 demonstrates a cross-sectional sketch of the used model in the parametric study.

TABLE 5

Typical physical properties of EPS Geofoam according to (ASTM D6817).

	ASTM D6817		
Properties	**EPS 15**	**EPS 22**	**EPS 46**
Density (kg/m3)	14.4	21.6	45.7
Elastic modulus (kPa)	**2500**	**5000**	**12800**

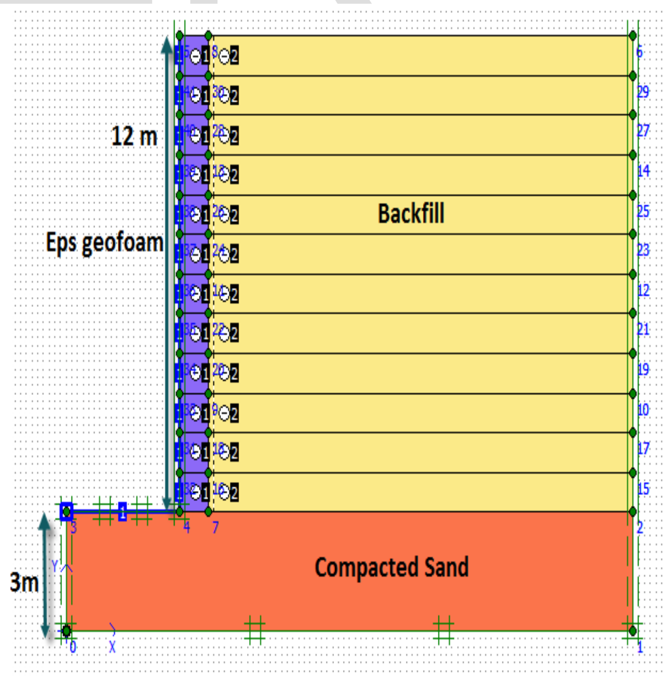

Fig. 10. Cross-sectional sketch of the used model in the parametric study.

Table (6) provides a list of analytical models performed by Plaxis 2D to study the effect of changing EPS geofoam density, thickness, and relative soil density on the resulting lateral earth pressure acting on the non-yielding wall.

8 Effect of EPS Geofoam density variation

The first group of parametric models are to demonstrate the effect of using different densities of EPS geofoam (14.4 Kg/m3, 21.6 Kg/m3 and 45.7 Kg/m3) to minimize lateral earth pressure on the basement wall while using thicknesses of EPS buffer (20.0 cm and 100.0 cm) and soil relative density of 75.0%. Fig. 11 presents the first set of models by using EPS geofoam with thickness of 20 cm; the results show that the resulting lateral earth pressure on the wall leads to maximum value while using high density of 45.7 Kg/m3 and elastic modulus of 12800.0 kPa, and decreases gradually with decreasing the density to 14.4 Kg/m3 and elastic modulus of 2500.0 kPa. Also, the results show that the earth pressure produced ranges from 90.0 percent to 97.0 percent of the at-rest pressure according to small EPS geofoam thicknesses. A larger geofoam buffer thickness equal to 100.0 cm is used, and the results are indicated in Fig. 12. The results showed again that using larger EPS geofoam density/elasticity yields more lateral earth pressure on the wall. In this case; the earth pressure produced ranges from 68.0 percent to 82.0 percent of the at-rest pressure. The use of a low-density EPS geofoam reduces lateral pressure on the basement wall effectively due to its relative high deformation which is close to produce active condition.

TABLE 6
Numerical models for EPS geofoam with different parameters

List of figures	Soil Relative Density (%)	EPS Thickness (cm)	EPS Density (kg/m3)
Figure 10	75.0	20.0	14.4, 21.6 and 45.7
Figure 11	75.0	100.0	14.4, 21.6 and 45.7
Figure 12	75.0	20.0, 50.0 and 100.0	14.4
Figure 13	75.0	20.0, 50.0 and 100.0	45.7

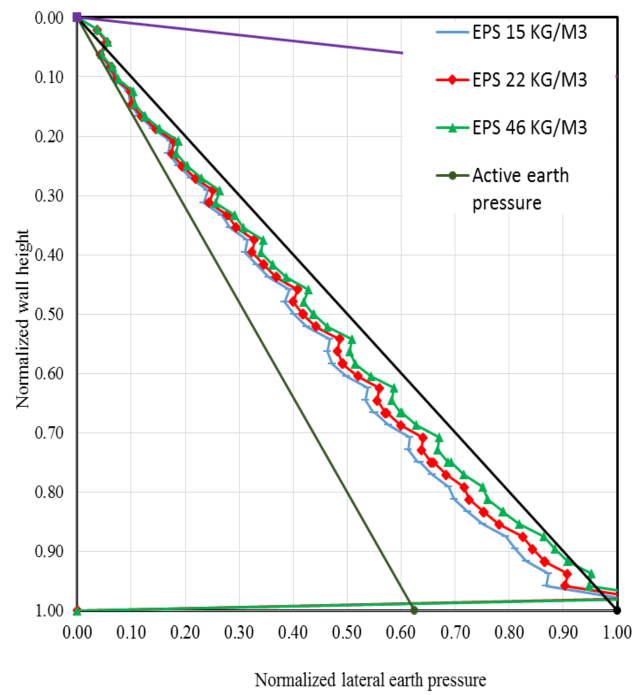

Fig. 11. Numerical findings for 12.0 m basement wall using 20.0 cm EPS geofoam thickness with different densities and backfill relative density of 75.0%

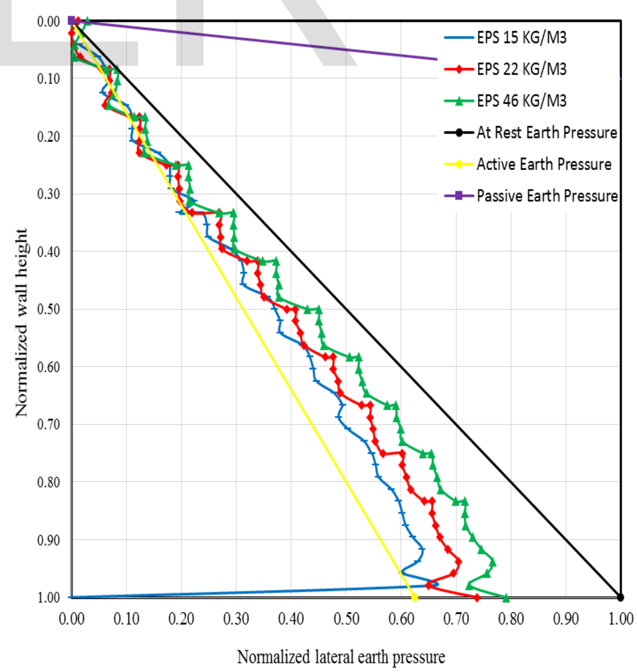

Fig. 12. Numerical findings for 12.0 m basement wall using 100.0 cm EPS geofoam thickness with different densities and backfill relative density of 75.0%

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9 EPS thickness influence

Constant relative density (75 percent) and variable thickness for EPS geofoam (20.0, 50.0 and 100.0 cm) with densities of 14.4 and 45.7 kg/m3 and soil relative density of 75.0% are analyzed for the second group of models. Fig. 13 illustrates the acting lateral earth pressure on the wall using EPS geofoam of density 14.4 kg/m3 and different thicknesses. For a thickness of 20.0 cm (about 1.7 percent of the wall height); the lateral earth pressure produced is about 92.0 percent of the at-rest pressure. While for the geofoam thickness of 50.0 cm (about 4.2 percent of the wall height); the lateral earth pressure is about 79 percent of the at-rest earth pressure. For the thickness of 100.0 cm (about 6.7 percent of the wall height), the lateral earth pressure is nearly close to the active earth pressure. It is observed that the lateral earth pressure decreases with increasing geofoam thickness along with the wall height. Fig. 14 illustrates the same set of previous numerical models but with a geofoam density of 45.7 kg/m3. Where the geofoam of thickness 20.0 cm produces a lateral earth pressure of 94.0 percent of at-rest pressure. For a thickness of 50.0 cm, the produced lateral earth pressure is about 81.0% of the at-rest pressure. While the geofoam thickness 100.0 cm produces a lateral earth pressure about 71.0% of at the rest-pressure. The results show that increasing the thickness of the EPS Geofoam buffer has a positive influence on decreasing the lateral earth pressure on the wall height.

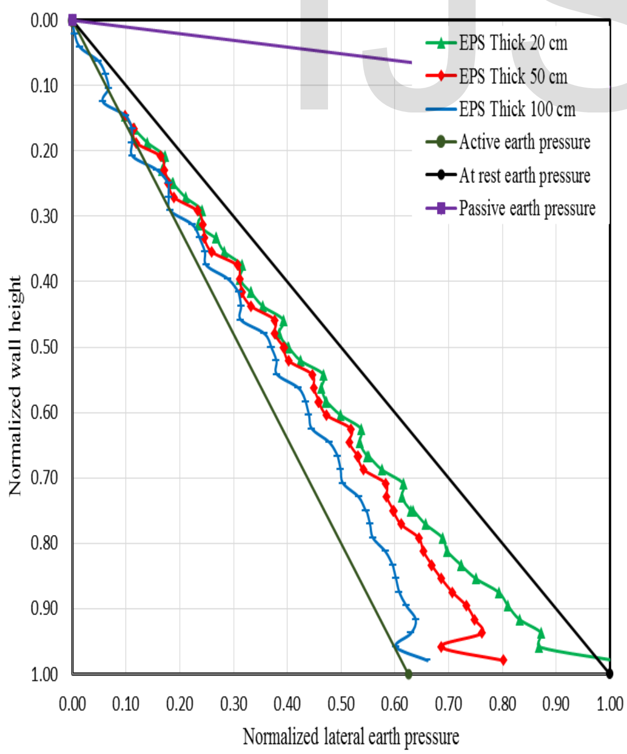

Fig. 13. Numerical findings for 12.0 m basement wall using 14.4 kg/m3 EPS geofoam density with different thicknesses and backfill relative density of 75.0%.

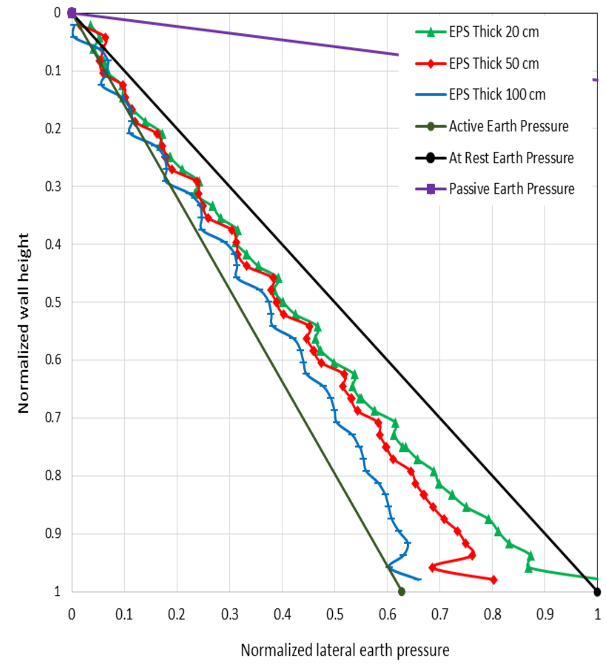

Fig. 14. Numerical findings for 12.0 m basement wall using 45.7 kg/m3 EPS geofoam density with different thicknesses and backfill relative density of 75.0%.

10 Thickness and Density Factors

From the previous results, we can conclude a relation between EPS geofoam stiffness factor (η) and normalized lateral earth pressure factor (F). To maintain this relation, the following values for η and F are assumed in Equations 4 and 5.

$$\eta = ((\text{EPS thick (m)}/1.0(\text{m})) \div (\text{EPS density (kg/m3)}/1000.0\ (\text{kg/m3})) \quad (4)$$

$$F = (\sigma h - \sigma ha) \div (\sigma ho - \sigma ha) \quad (5)$$

Where:
η: Stiffness factor of EPS geofoam.
F: Normalized lateral earth pressure.
σh: Maximum lateral earth pressure.
σha: Active lateral earth pressure.
σho: At-rest earth pressure.

Table 9 summaries the results of the previous numerical models as a function of the parameters "η" and "F". Fig. 15 shows the best-fit equation for the relationship between EPS geofoam stiffness and normalized lateral earth pressure factor in which the equation could be used to assume the deformed lateral earth pressure on the wall concerning the EPS geofoam stiffness factor (density and thickness).

TABLE 9

Stiffness factor of EPS geofoam "η" and normalized lateral earth pressure "F" values.

Figures	Thickness (cm)	Density (kg/m3)	η	F
Figure 10	20.0	14.4	13.33	72.0%
	20.	21.6	9.09	80.0%
	20.0	45.7	4.35	89.0%
Figure 11	100.0	14.4	66.67	7.0%
	100.0	21.6	45.45	21.0%
	100.0	45.7	21.74	31.0%
Figure 12	20.0	14.4	13.33	72.0%
	50.0	14.4	33.33	33.0%
	100.0	14.4	66.67	7.0%
Figure 13	20.0	45.7	4.35	89.0%
	50.0	45.7	10.87	40.0%
	100.0	45.7	21.74	31.0%

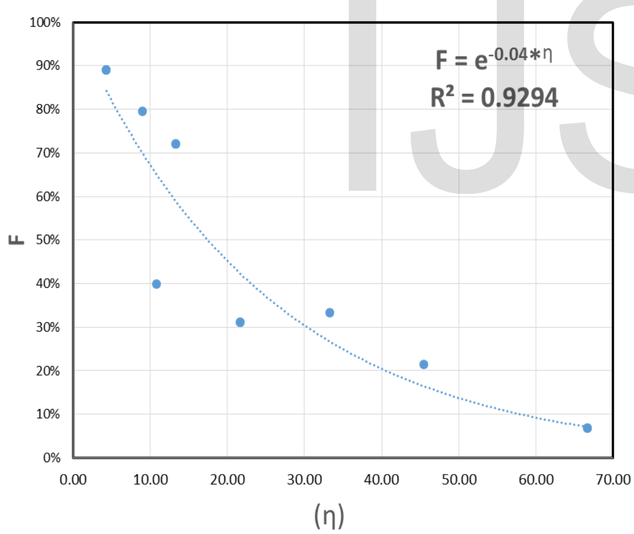

Fig. 15. Relation between the stiffness component of the EPS geofoam and the normalized lateral factor of earth strain.

11 Conclusion

The present study highlights the usefulness of using EPS geofoam as a compressible buffer material behind the retaining walls. Using Plaxis 2D V8.5; numerical models of retaining walls with geofoam inclusions were simulated. The numerical model was first validated by comparing the results recorded from the small-scale model test showing a good agreement between the lateral earth pressure measured and the model results. Also, a parametric study was carried out using numerical models to demonstrate the efficiency of EPS density and thickness in reducing lateral earth pressure on the basement wall with a depth of 12.0 m. The following conclusions are drawn:

1. EPS geofoam thickness and density are dominant factors that reduce lateral earth pressure.

2. Increasing geofoam thickness; decreases the earth pressure on the retaining wall. Moreover, it is more effective when using low-density geofoam.

3. By decreasing EPS geofoam density; more reduction in lateral Earth pressure on retaining wall is induced, while this reduction is more effective with increasing the thickness of geofoam buffer.

4. Retaining structures could withstand high earth pressure by controlling its yielding properties. For example, at-rest soil pressure can be reduced to reach the active condition by implementing a compressible inclusion between the wall and the backfill. Also, compressible inclusion can be implemented for existing retaining walls to improve its overall performance.

5. The most important factors affecting the reduction of lateral earth pressure are EPS geofoam thickness and its density (thereby its elasticity modulus and Poisson's ratio). Due to the reduction of lateral earth pressure acting on the wall, parameters of design demand such as the bending moment and shear forces are reduced. Geofoam thus works effectively to reduce the load and decrease the design requirements.

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