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PARTIAL REPLACEMENT OF SOFT CLAY IN "TINA" PLAIN, SINAI, EGYPT BY GEOFOAM UNDER FOOTINGS*

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ABSTRACT

The soil of Tina Plain in Sinai is classified as very soft to soft clay. Buildings on this type of soil experience excessive settlements. Thus, deep foundations are considered as the most suitable type to support building loads. Another option is to use a light-weight material as a partial replacement under footings to decrease the stress on soil and consequently reduce the expected settlements. Expanded polystyrene (EPS) Geofoam blocks have been used as a light-weight-fill material under lightly loaded footings on soft clay soil to reduce settlements. An experimental study has been performed to assess the behavior of footings resting on soft clay, improved with EPS geofoam partial replacement. The experimental study of this research is divided into two parts; the first part is a laboratory program to investigate the mechanical properties of Geofoam. The second part is a field load testing program on small-scale model isolated footings founded on soft clay partially replaced by Geofoam blocks. Square and rectangular footings of dimensions 20 x 20 cm, and 20 x 30 cm respectively are loaded with an equivalent pressure of 50 kPa. The loading is performed stepwise with each step forming one fifth of the total applied load. The Geofoam thickness is varied from 50 mm to 300 mm and the width is varied from 200 mm to 500 mm. The software ABAQUS is used to model and verify the experimental results. Results showed that the geotechnical properties of Geofoam are similar to that of stiff or very stiff soil. Results also showed that replacement of Tina Plain soft clay by Geofoam could be used efficiently to limit foundation settlements of lightly loaded footings within tolerable values.

KEY WORDS*:* EPS Geofoam, Footings, Settlements, Experimental, Soft Clay, Tina plain.

REMPLACEMENT PARTIEL DE ARGILE MOLLE «TINA» DANS LA PLAINE, SINAÏ, EN ÉGYPTE SOUS PAR SEMELLES GEOFOAM

RÉSUMÉ

Le sol de la plaine de Tina dans le Sinaï est classée comme très doux à l'argile molle. S'appuyant sur ce type de colonies expérience excessive du sol. Ainsi, les fondations profondes sont considérées comme le type le plus apte à supporter les charges du bâtiment. Une autre option consiste à utiliser un matériau léger comme un remplacement partiel sous les semelles pour diminuer le stress sur le sol et de réduire les attendus conséquent colonies. Polystyrène expansé (EPS) des blocs Geofoam ont été utilisés comme un matériau léger de remplissage sous les semelles légèrement chargés sur le sol d'argile molle pour réduire les colonies. Une étude expérimentale a été réalisée pour évaluer le comportement des semelles reposant sur l'argile molle, l'amélioration des EPS Geofoam avec remplacement partiel. L'étude expérimentale de cette recherche est divisée en deux parties, la première partie est un programme de laboratoire pour étudier les propriétés mécaniques de Geofoam. La deuxième partie est un programme test sur le terrain de charge sur des semelles de modèle à petite échelle isolés fondés sur argile molle partiellement remplacés par des blocs Geofoam. Semelles carrées et rectangulaires de dimensions 20 x 20 cm et 20 x 30 cm, respectivement, sont chargés de pression équivalente de 50 kPa à. Le chargement est effectué par étapes à chaque étape de formation d'un cinquième de la charge totale appliquée. L'épaisseur Geofoam est varié de 50 mm à 300 mm et la largeur varie de 200 mm à 500 mm. Le logiciel ABAQUS est utilisé pour modéliser et de vérifier les résultats expérimentaux. Les résultats ont montré que les propriétés géotechniques de Geofoam sont similaires à celles du sol raide ou très raide. Les résultats ont également montré que le remplacement de Tina argile molle plaine pourrait être utilisée efficacement par Geofoam de limiter tassements des fondations de semelles légèrement chargés dans les valeurs tolérables.

MOTS-CLES: EPS plaine Geofoam, semelles, règlements, expérimentales, argile molle, Tina.

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1. INTRODUCTION

Tina Plain (Sahl El-Tina) is situated in the extreme North Eastern part of the historic path of the river Nile, with boundaries to the north formed by the Mediterranean Sea and to the west by the Suez Canal. The elevation of the Tina Plain is at or slightly above the sea level. The soil of Tina plain is classified according to their undrained shear strength as soft clay. The approximate unconfined compressive strength values of Tina plain clay by pocket pentrometer range between 20 ka to 45 kPa. In such low unconfined compressive strength, these clays are considered to be problematic for foundation purposes.

Geofoam is an industrial material, characterized by a very low unit weight compared to soil (average of 20 kg/m^3). According to Horvath (1996, 1997), Zekkos (2011) EPS Geofoam blocks are used in a wide range of geotechnical applications as a light weight fill, a compressible inclusion, and also as a lateral and seismic buffer behind earth retaining structures. The increased use and applications of EPS as a Geofoam material has evolved due to its very low density and relatively high strength-to-density ratio. Typical recent applications of EPS Geofoam include filling around and above underground structures such as basements (Aiassa, 2011), culverts and pipes, embankment roads on soft ground (Vaslestad, 2011), replacement of very soft soil under roads and pipes (Negussey, 2011), widening existing fills and roads and in filling and support of bridge abutments and slope stabilization (Horvath, 2005), (David, 2011).

Having a density ranging from 1.0% to 2.5% of that of typical soils, EPS possesses a compressive strength ranging between 70 kPa and 140 kPa and an elastic modulus ranging between 5 MPa and 12 MPa. Table (1) illustrates the relation between EPS density and the compressive strength at 10% Strain according to ASTM C 578-04. Riad et al. (2003) have indicated that EPS is a true solid and not a particulate material like soil, and is therefore self-stable with vertical side slopes. Neugussey and Johanandish (1993) concluded from laboratory tests that EPS having a density of 21 kg/m^3 is equivalent to medium stiff clay, whereas at a density of 30.4 kg/cm^3 the EPS is equivalent to very stiff clay. Horvath (1996) and Abd El-Rahman (2006) indicated that Poisson's ratio, in the initial linear range of the compressive stress-strain curve, is close to zero (less than 0.1). Negussey and Jahanandish (1993) showed that Poisson's ratio has a negative value in the post-elastic range.

Table (1): ASTM C 578-4 EPS Compressive Strength Values.

Density (kg/m^3)	12	15	18	22	29	35	48
Compressive Strength at 10% Strain, (kPa)	35	69	90	104	173	414	690

2. EXPERIMENTAL PROGRAM

2.1. Laboratory Investigation

The soft clay soil is one of the problematic soils covering wide areas in Northern Egypt, which causes excessive settlements under moderate loads. For such areas, partial replacement by EPS Geofoam may be considered as a promising alternative under embankments or under lightly loaded foundations. The properties of soft clay and EPS Geofoam used in the experimental work are presented in this section. Laboratory tests were performed on samples of soft clay from the site at the Tina plain to evaluate its natural, index, and mechanical properties. The expanded polystyrene material (Geofoam material) used in these tests is manufactured in Egypt and characterized by a unit weight of 20 kg/m^3. Other properties such as; compressive strength, shear strength, flexural strength, flammability, water absorption, resistance to chemicals, consolidation parameters are also presented.

2.1.1. Properties of soft clay

Samples of soft clay soil taken from Tina plain, Sinai (Egypt) are tested to investigate their natural, index, and mechanical properties. These tests were performed according to Egyptian code of practice, and include liquid limit, plastic limit, natural water content, specific gravity, void ratio, and unit weight. All the test results were average value of three tested specimens. The used soft clay soil characteristics are listed in Table (2). Approximate values of unconfined compressive strength were obtained using pocket pentrometer in the field before starting the experimental work in any tested pit. Plasticity chart classification showed that the clay is classified as clay of medium plasticity (CI). However, the high salt content rendered the soil less plasticity than it should be.

Table (2): Properties of Tina Plain Clay

Soft clay properties	Value
Average liquid limit,%	46.0
Average plastic limit, %	22.0
Plasticity index, %	24.0
Soft clay type (A-line chart)	CI
Average water content, %	36.0
Average specific gravity	2.59
Average void ratio (prism)	0.946
Average unit weight, kN/m^3	15.5
Pocket pentrometer, kPa	20 - 47
Cohesion (pocket), kPa	10 - 23.5

2.1.2. Properties of geofoam blocks

EPS Geofoam mechanical properties such compressive strength, elastic modulus, possion's ratio, shear strength, flexural strength, stiffness, creep behavior and other mechanical properties depend on the EPS Geofoam unit weight. It should be noted that the manufacturing cost of the EPS Geofoam increases with the increase of the density. For practical civil applications, EPS densities range between 11 and 30 kg/m^3 (Van Dorp, 1988). EPS Geofoam densities are categorized by ASTM C 578-04 to 5 types, 12, 15, 18, 22, 29 kg/m^3. The EPS density used in the experimental study of this research is 20 kg/m^3. Higher values of EPS densities are not used to minimize the actual project cost. The properties of geofoam having a unit weight of 20 kg/m^3 manufactured in Egypt listed in Table (3). Table (4) shows the effect of chemicals material on EPS Geofoam as tested in the Laboratory.

2.2. Field Model Tests

The field model tests are performed at a location in Tina plain selected at longitude and latitude of 30^o 58' 27.91" and 32^o 23' 53.03", respectively. Model load tests are performed on small-scale isolated footings over partially replaced soft clay. Figs. (1-a) and (1-b) show a photograph and a schematic of the different components of the experimental loading frame.

The footing is modeled by a steel plate stiffened by steel angles welded at the plate circumference and is placed at surface of the soft clay (or the EPS Geofoam). A vertical steel pipe is vertically placed over the footing (steel plate). This pipe is affixed using four inclined struts into the surrounding soil. The experimental loading frame used in this study consisted of a vertical steel pipe fitted inside another larger pipe. The larger pipe is affixed on top of soil with four inclined struts. A square steel platform is attached over the vertical pipe, to allow incremental loading by sand bags. The load increment is chosen to be one fifth of the total applied pressure of 50 kPa. Settlements are measured by two digital dial gauges affixed by two separates steel frames on the opposite sides of the horizontal steel plate. It should be noted that the total net pressure included the own weight of the testing plate, the vertical pipes, and the steel platform.

Table (3): Geofoam Block Properties.

Geofoam properties	Value
Unconfined compressive strength at 10% strain, (kPa)	94.5
Initial elastic modules, (kPa)	3549
Poisson's ratio	0.01
Angle of friction, (^{o})	15.87
Cohesion, (kPa)	27.07
Flexural Strength, (kPa)	245.4
Flexural Strain, (%)	6.3
The coefficient of compressibility, (MPa^{-1})	0.479
Compression Index	56.5
Recompression Index	2.51
Water absorption after 28 days, (%)	2.45%

Table (4): Effect of Chemical Material on EPS Geofoam.

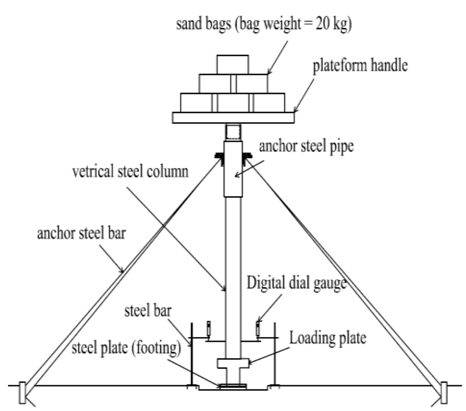
No.	Source of Chemical attack	Resistance
1	Sea water	Resistant
2	Benzene	Dissolved
3	Kerosene	Soft floating remains after 24 hrs.
4	Thinner	Soft floating remains
5	HCL	Remains as block but edge disintegration after 24 hrs.
6	Sulphuric acid	Remains as block but edge disintegration after 24 hrs.
7	Mobile oil	Resistant
8	Soapy water	Resistant
9	Alcohol	Remains as block but edge disintegration after 24 hrs.

The experimental study is mainly focusing in the EPS geofoam replacement width and thickness under the footing, in addition to the footing shape. The geofoam thickness is varied from 50 mm to 300 mm with 50 mm increment, and in such case the geofoam width was kept constant at 300 mm. However, in the case of studying the geofoam width, it was varied from 200 mm to 500 mm with 50 mm increment, while the geofoam thickness was kept constant and equal to 200 mm in this case.

3. NUMERICAL STUDY

A series of three-dimensional finite element analyses (FEA) on a prototype of partial replacement of soft clay by geofoam blocks were performed to evaluate the effect of geofoam thickness and width and to verify that the numerical model is capable of reproducing the experimental testing results. The analysis was performed using the finite element program ABAQUS software package (version 6.8.1). ABAQUS software is capable of handling a wide range of geotechnical problems such as deep excavations, tunnels, and earth structures such as retaining walls and slopes.

In the numerical model, the soft clay soil mass is described by an 8-node brick, trilinear-displacement trilinear-pore pressure element. The soft clay soil was modeled as an elasto-plastic material with a non-associated flow rule and using the modified cam clay plasticity model. Soft clay soil is partially replaced by Geofoam blocks with different thicknesses and



(b) **(a)**

Fig. (1): a): Parts of Loading Frame.
b): Photo of Experimental Loading Frame.

widths under different footings shapes. The Geofoam unit weight is kept constant and equal to 20 kg/m^3. Geofoam and footing were modeled as an elastic material by an 8-node linear brick element with reduced integration and hourglass control. The material parameters used in this study are listed in Table (2). The soft clay domain, boundary conditions and finite element mesh are shown in Figs. (2-a) and (2-b).

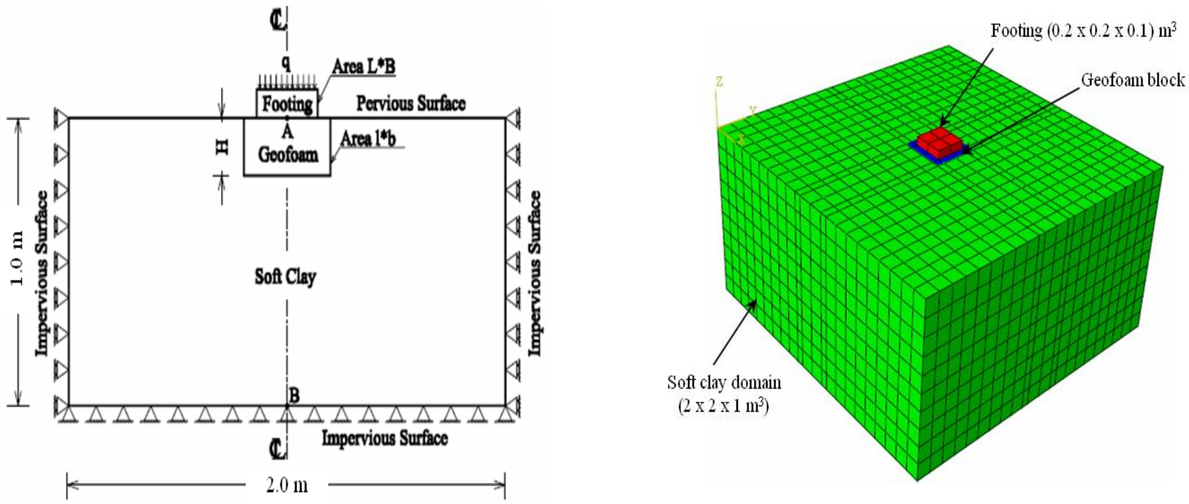


Fig. (2): right) Soft clay, Geofoam and Footing Model.
left) F.E.M. Mesh of Numerical Model.

Table (5): Material Parameters.

No.	1	2	3
Material	Soft clay	Geofoam	R.C. Footing
Model	Modified cam-clay plasticity	Elastic	Elastic
λ-factor	0.174	--	--
κ–factor	0.028	--	--
Void ratio	0.95	--	--
Poisson's ratio	0.45	0.10	0.15
γ_{sat}, (kN/m^3)	16	0.20	25.0
E, (kN/m^2)	600	3000	2.1E^{-7}
K, (m/sec.)	1E^{-8}	--	--
K_o	1.00	--	--
M	1.00	--	--

λ = Modified compression index,
κ = Modified swelling index,
γ_{sat} = Saturated unit weight,
E = elastic modulus (young modulus),
K = Coefficient of permeability,
K_0 = Coefficient of lateral pressure at rest,
M = Slope of the critical-state line

4. RESULTS AND DISCUSSIONS

A total of 28 field model tests were carried out to investigate the effect of geofoam thickness and width used in partial replacement over softy clay. The effect of geofoam parameters on the settlement were obtained and discussed.

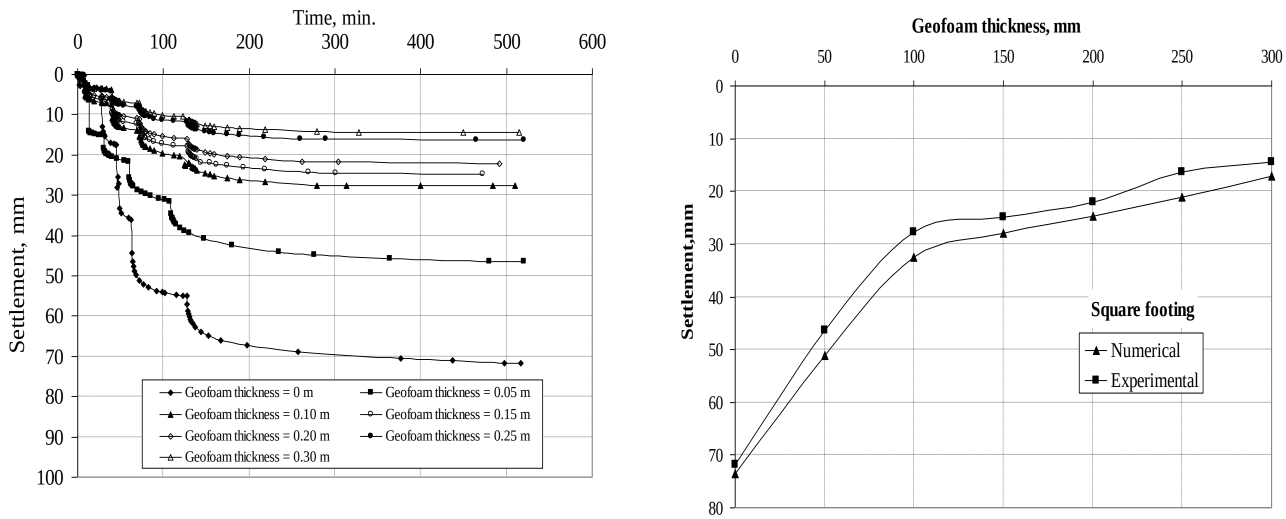
4.1. Square Footings

4.1.1. Effect of geofoam thickness

The geofoam thickness under the square footing, having dimensions of 200 x 200 x 10 mm, is increased from 50 mm up to 300 mm, with thickness increments of 50 mm each. The geofoam width in such case is kept constant at 300 mm. Fig. (3-a) shows the total settlement versus time at each load increment (1/5 of the total load), while Fig. (3-b) shows the total settlement versus geofoam thickness for both the cases of experimental and numerical study. The measured settlements in the experimental study for the case of square footing without EPS foam replacement was equal to 71.8 mm. However, modeling the same case numerically using ABAQUS software resulted in a calculated settlement of 73.6 mm. In such case the numerical model was capable of reproducing the experimental model accurately. Fig. (3-a) shows a relatively large immediate settlement just after load step application followed by relatively low settlements till reaching a rate of change equal to or less than 0.002 mm per minute, after which the next load step is applied. This may be attributed to the soft soil behavior in which large settlements took place just after load application with low settlements following the immediate settlement zone. The figure also shows that just adding a foam layer with minimum thickness has reduced the measured settlement to almost have its original value with no foam replacement. However, increasing the EPS foam thickness resulted in a relatively low decrease in the measured total settlements. The total settlement values from the experimental study are 46.5, 27.7, 24.8, 22.0, 16.2, 14.4 mm for geofoam thicknesses of 50, 100, 150, 200, 250, 300 mm respectively. In the meantime, the total settlement values from the numerical study are 51.1, 32.5, 28.0, 24.7, 21.0, 17.1 mm for the same geofoam thicknesses used in the experimental study. Results in Fig. (3-b) show that increasing the geofoam thickness results in a relatively sharp decrease in the measured settlements till reaching about half the footing width. Increasing the Geofoam thickness more than this value did not result in any noticeable decrease in the settlements. Comparison between the experimental and numerical results for the effect of geofoam thickness showed a good agreement, as presented in Fig. (3-b). Both the experimental and numerical results showed the same trend, assuring the numerical model capability of reproducing the experimental study results. The measured and computed total settlements showed that increasing the geofoam thickness more than 200 mm is not that effective in reducing the total settlement. Thus, an efficient and economic geofoam thickness equal to the width of footing is recommended in such case under low to moderate loads.

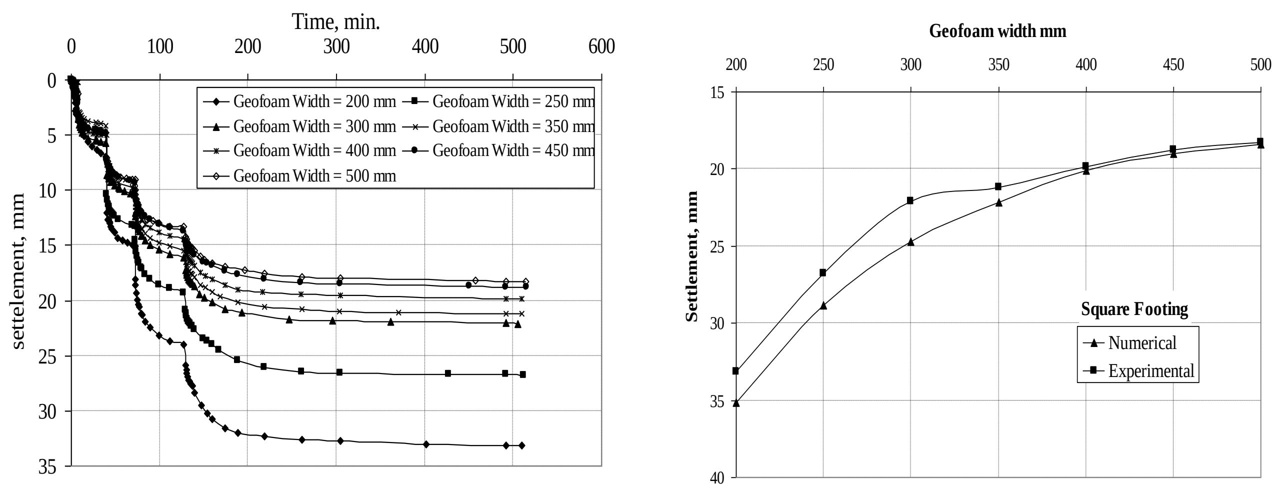
4.1.2. Effect of geofoam width

EPS geofoam is placed under steel footing, having dimensions 200 x 200 x 10 mm, with thickness of 200 mm and the EPS Geofoam width (B) varied between 200, 250, 300, 350, 400, 450, 500 mm. Fig. (4-a) shows the total settlement versus time at each load increment (1/5 of the total load), while Fig. (4-b) shows the total settlement versus geofoam width for both the case of experimental and numerical study. Fig. (4-a) shows a relatively large immediate settlement just after load step application followed by relatively low settlements till reaching a rate of change equal to or less than 0.002 mm per minute, after which the next load step is applied. This may be attributed to the soft soil behavior in which large settlements took place just after load application with low settlements following the immediate settlement. The Figure also shows that adding a geofoam layer with minimum width has reduced the measured settlement to almost half its original value without replacement. However, increasing the EPS geofoam width resulted in a relatively low decrease in the measured total settlements. The total settlement decreases with increasing the EPS geofoam width; total settlements from experimental study are 33.2, 26.8, 22.1, 21.2, 19.8, 18.8, 18.3 mm for geofoam widths of 200, 250, 300, 350, 400, 450, 500 mm respectively and total settlements from numerical study are 35.1, 28.9, 24.7, 22.2, 20.10, 19.0, 18.4 mm for geofoam widths of 200, 250, 300, 350, 400, 450, 500 mm respectively. Fig. (3-b) shows that increasing the geofoam width results in a relatively sharp decrease in the measured settlements till reaching about 1.5 times of footing width. Increasing the Geofoam thickness more than this value did not result in a noticeable decrease in the settlements. Comparison between the experimental and numerical results for the effect of geofoam width showed a good agreement, as presented in Fig. (3-b). Both experimental and numerical study results showed the same trend, assuring the numerical model capability of reproducing the experimental study results. The measured and computed total settlements for various geofoam widths showed that increasing the geofoam width more than 300 mm is not effective in reducing the total settlement. Thus, an efficient and economic geofoam width equal to 1.5 times of footing width is recommended in such case.



(a) Settlement Versus Time of experimental (b) Settlement Versus geofoam thickness

Fig. (3): Effect of EPS Block Thickness on The Total Settlement of Square Footing.



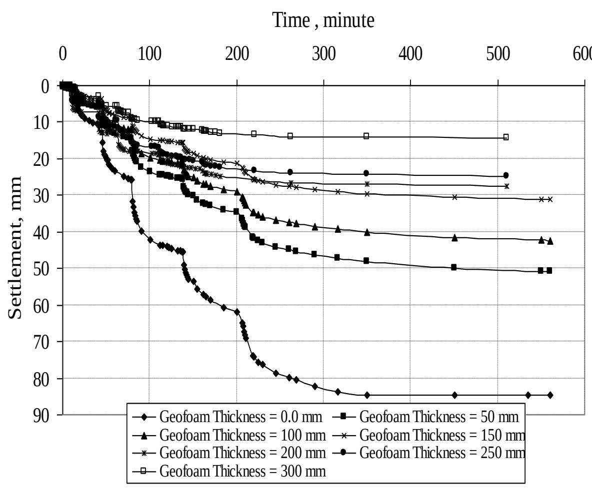
(a) Settlement Versus Time of experimental (b) Settlement Versus geofoam width

Fig. (4): Effect of EPS Block Width on The Total Settlement of Square Footing.

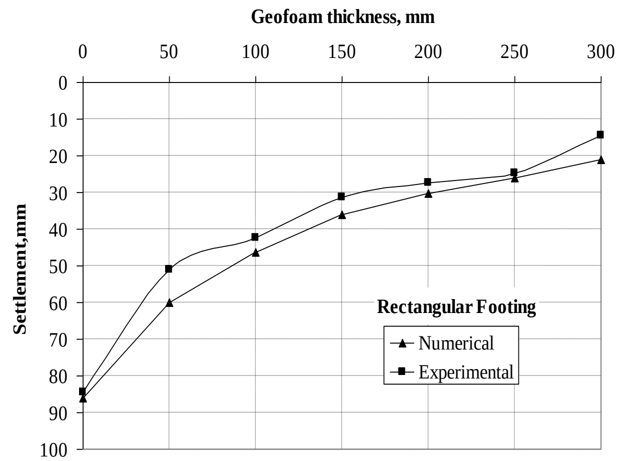
4.2. Rectangular Footings

4.2.1. Effect of geofoam thickness

The geofoam thickness under the rectangular footing, having dimensions of 300 x 200 x 10 mm, is increased from 50 mm up to 300 mm, with an increment in thickness of 50 mm. The geofoam width in such case is kept constant at 300 mm. Fig. (5-a) shows the total settlement versus time at each load increment (1/5 of total load), while Fig. (5-b) shows the total settlement versus geofoam thickness for the both the cases of experimental and numerical study. The measured and calculated total settlements in the case of no replacement by geofoam are 84.6 mm and 86.1 mm respectively. The measured total settlement decreases with increasing the EPS geofoam thickness; the total settlements values from experimental study are 50.9, 42.4, 31.2, 27.4, 24.7, 14.4 mm for geofoam thicknesses of 50, 100, 150, 200, 250, 300 mm respectively. In addition, the total settlement values from numerical study are 60.0, 46.4, 36.0, 30.3, 26.0, 21.2 mm for geofoam thicknesses of 50, 100, 150, 200, 250, 300 mm respectively. The results showed that the settlement-thickness curves of geofoam for both the experimental and numerical studies are having the same trend. The measured and computed total settlements for various geofoam thickness showed that increasing the geofoam thickness more than footing width is not that effective in reducing the total settlement. Thus, an efficient and economic geofoam thickness of equal to the footing width is recommended in such case.



(a) Settlement Versus Time of experimental



(b) Settlement Versus geofoam thickness

Fig. (5): Effect of EPS Block Width on The Total Settlement of Rectangular Footing.

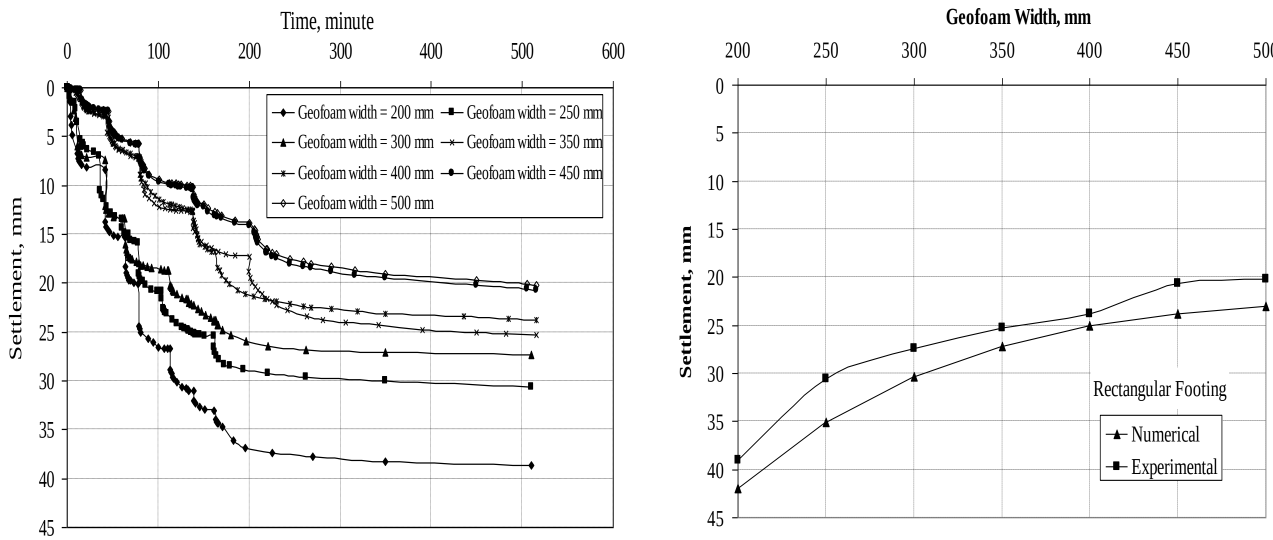
4.2.2. Effect of geofoam width

EPS geofoam is placed under rectangular steel footing, of dimensions of 300 mm x 200 x10 mm, with thickness of 200 mm, unit weight of 20.0 kg/m^3, the EPS geofoam width (B) varied between 200, 250, 300, 350, 400, 450, 500 mm, while EPS Geofoam length (L) varied between 300, 350, 400, 450, 500, 550, 600 mm. Fig. (6-a) shows the total settlement versus time at different load increments, while Fig. (6-b) shows the total settlement versus geofoam thickness for both the case of the experimental and numerical studies. The total settlement decreases with increasing the EPS geofoam width; total settlements from experimental study are 39.0, 30.6, 27.4, 25.3, 23.8, 20.7, 20.2 mm for geofoam widths of 200, 250, 300, 350, 400, 450, 500 mm and geofoam length of 300, 350, 400, 450, 500, 550, 600 respectively and total settlements from numerical study are 41.99, 35.1, 30.4, 27.2, 25.1, 23.8, 23.0 mm for geofoam widths of 200, 250, 300, 350, 400, 450, 500 mm and geofoam length of 300, 350, 400, 450, 500, 550, 600respectively. Fig. (6-b) shows that increasing the geofoam width more than 1.5 times of footing width is not that effective in reducing the total settlement. Therefore, a geofoam width of (1.5 x B) under a footing width (B) is considered efficient and economic.

5. CONCLUSIONS

This paper presents the results of an experimental study of partial replacement of soft clay by EPS geofoam under both square and rectangular footings. The study also included numerical modeling to verify the experimental work and provide the numerical model parameters that can be used in extending the experimental work study range.

Based on the results of the current research, the following conclusions are drawn:



(a) Settlement Versus Time of experimental (b) Settlement Versus geofoam width

Fig. (6): Effect of EPS Block Width on The Total Settlement of Rectangular Footing.

1- Partial replacement of soft clay by geofoam under footings is a successful and efficient solution for foundations over soft clay soils under low to moderate loads.
2- Experimental and numerical studies showed that using a geofoam thickness equal to the footing width is effective in reducing the total settlements by one fold. Thus, it is recommended to use geofoam thickness equal to the footing width.
3- Results indicated that increasing the geofoam width more than 1.5 times the footing width is not that effective in reducing the total settlement. Therefore, a geofoam width of 1.5 times the footing width is considered efficient and economic.
4- Experimental and numerical results showed that geofoam thickness have a noticeable effect on reducing the settlement values of partial replacement of soft clay by geofoam blocks more than the geofoam width.
5- A good agreement is noticed between the experimental and numerical results indicating the capability of used numerical model in simulating the experimental work.

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