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Research Article

Effect of EPS Geofoam on the Dynamic Response in Clay soil

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Abstract

Unconnected piled raft foundation (UNCP) is considered a new type of foundation, which treat the piles in case as reinforcement to the soil instead of as structural elements. The piles are disjointed from the raft by a structural fill cushion used to redistribute the stress to subsoil. Herein, EPS, expanded poly-styrene geofoam, was used as fill cushion in order to reduce the soil deformation of rectangular raft under dynamic loads. In this study, PLAXIS two-dimensional finite element software was adopted after examination the validity through experimental study for square footing resting on Port-Said over consolidated clay. The effects of EPS thickness, density, dimension and cushion type on soil deformation were investigated. The parametric study was extended to consider the connected piled raft foundation (CP) and raft foundation to present a comparison between different cases. The study showed that unconnected piled raft foundation with EPS as cushion (EPS-UCPR) provides much better alternative for a connected piled raft foundation, especially under dynamic load effect.

Keywords: Unconnected Piled Raft; EPS, Expanded Polystyrene Geofoam; Dynamic Analysis

Introduction

The piled raft is a foundation system that includes three elements: piles, raft and soil. Its design procedure differs from the traditional methods for the design of foundation systems. Usually, the loads are assumed to be carried either by the raft or by the piles. More exactly, the design of piled raft should take into consideration the actual load share between the piles and the raft. The reduction in uniform and differential deformations, increase in stability of foundation, reduction in number of piles compared to pile foundation and reduction in bending stress for the raft are considered the major advantages of using a piled raft foundation.

Tom and Sindhu, [1] conducted experimental and numerical models to compare the load-settlement response of raft and piled raft. At the same settlement value, the load causing this settlement in piled raft case is higher than in the case of raft. They investigated the best piled raft configuration and the settlement ratio showing that the settlement ratio decreases with increasing the number of piles.

Due to the high shear force and bending moment, which generated in traditional piled raft system, Wong., *et al*. [2] suggested unconnected piled raft system. In this case, the piles disconnected from the raft and considered it as soil reinforcement to increase the soil bearing capacity. The gap between the raft and pile can be filled with a cushion of structural material. Liang., *et al*. [3] developed the concept of piled raft to new system called composite piled raft system as shown in figure 1, using a) Short pile to strength the shallow soft soil, b) Long pile to reduce the settlement and c) Cushion to redistribute the stress to subsoil. Sharma., *et al*. [4] studied the effect of cushion on composite piled raft, showing that the cushion can regulate the load-sharing ratios between piles and help to benefit of the bearing capacity of short piles.

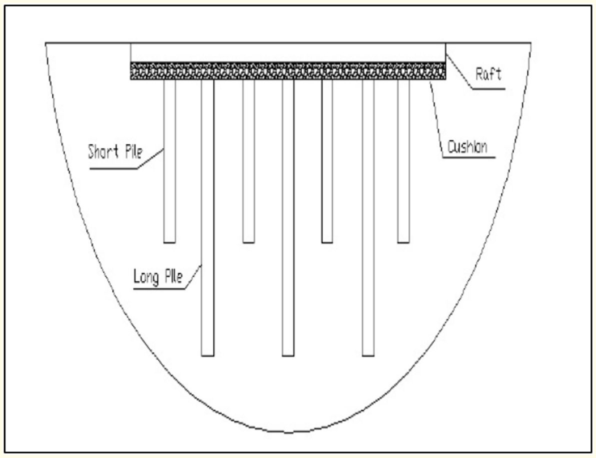

Figure 1: Sketch of composite piled raft foundation.

Solanki and Sorti [5] overviewed the connected and unconnected piled raft foundations. They observed that settlement of UNCP is greater than CP and the percentage of load taken by piles for UNCP decreased by 50% than that of the CP. The maximum lateral load in the connected system occurs at pile head and then decreases along the length of the pile, however, when unconnected system is provided, the location of maximum axial load is shifted downwards to a certain length below the pile head.

Ata [6] studied the effects of compacted structural cushion, piles diameter, length, and number in addition to raft thickness in reducing settlements. The study showed that UNCP provides an economical alternative for a CP foundation subject to vertical loads referring to the possibility of using only plain concrete. In the said system, plain concrete piles are adequate, without the need of reinforcement, where their basic function is to reinforce the top and reduce the maximum settlements. Moreover, the axial load at the pile head decreases with cushion thickness increasing and increases as the cushion modulus increase. Furthermore, increasing the pile diameter resulted in a decrease in the overall settlement.

In the other side, Expanded Polystyrene (EPS) geofoam is a lightweight material, which used in geotechnical engineering applications. It is characterized by very low density (about 100 times lower than soil) with relatively high compressibility, good flexural strength and high rupture strength in shear. Padade and Mandal [7] studied the behavior of shear strength parameters of EPS geofoam through direct shear tests with shaped the relationship between cohesion and density. Abdelrahman and El Kamash [8] used EPS to replace the soft to decrease settlement under raft foundation.

El-Gendy., *et al*. [9] introduced EPS as an efficient dynamic damper through experimental study for square footing resting on Port-Said clay. Athanasopoulos., *et al*. [10] presents the results of an experimental analysis of the dynamic properties of EPS through torsional resonant column tests and cyclic uniaxial tests which were conducted on block-molded EPS with different densities. In the present study, an attempt is made to use EPS as a cushion between the piles and raft strip footing subjected to dynamic loading in order to reduce the deformation of soil under the footing. The research aims to study the dynamic behavior of unconnected piled raft with EPS. Parametric study extended to consider EPS Thickness, density, dimension and cushion type in addition to comparison between these cases with connected piled raft foundation (CP) case.

Numerical modeling

In this research, the finite element analysis of a piled raft system is performed by PLAXIS 2D software. The behavior of a strip foundation is analyzed under dynamic loading of constant amplitude and varying frequency. Piles as well as the raft are modeled as elastic material. The clay and EPS are modeled with elastic ideally plastic constitutive model that obey the Mohr-Coulomb yield criteria. Due to consideration the soil is over consolidated clay, A perfectly-plastic constitutive model used with a fixed yield surface without account the stress -time effect.

Plane strain 15-noded triangular isoperimetric elements are used to represent the soil. The boundaries of the finite element model, both in horizontal and vertical directions, are set as far as 5-times the raft width, to minimize the boundary effect. To investigate the excess pore water pressure, build up under machine foundation due to harmonic excitation, saturated soil conditions with water table coinciding with the ground surface is presumed. All displacements are restricted at the base of finite element model, whereas horizontal fixities are applied at the extreme vertical side boundaries. Absorbent boundaries are applied along vertical and horizontal boundaries to avoid the reflection of stress waves back to the soil domain.

Verification of the numerical model

To ensure the validity of the proposed numerical model for dynamic analysis of piled raft, an experimental data set presented by El-Gendy., *et al.* [9] was selected for the verification. The experimental study was performed on clay soil obtained from ZOHR gas treatment plant located at Port-Said west. Regarding the soil technical report for this area tested by consolidated untrained triaxial test, it was considered the soil is silty clay with effective cohesion and angle of shearing resistance equal 7 kpa and 25°, respectively.

The experimental study included the effect of static and dynamic loading on the settlement behavior of a 15 x 15 cm square steel foundation with thickness 3 cm, in the presence as well as in the absence of EPS. Two motors with different velocities; 1000 and 450 rpm were used to generate the dynamic loading. From elementary dynamics and referring to Florjanic and Frei [11] a mass me connected to a motor shaft with an arm of y rotating at a circular frequency of ω produces a force at any instant in time of Fm.

$Fm = U.\omega^2$ (1)

where:

U is the unbalance force =me.y

ω is the circular operating frequency of the motor, ($\omega = 2\pi f$)

f is the operating frequency.

In the experimental study, the rotating mass was changed with the different motors velocity to get the same dynamic force. Thus, the only variable is the circular operating frequency of the motor. The rotating mass is equal to 0.65 and 3.2N for the motor frequency 1000 and 450 rpm; respectively, effect on the same distance in the two cases which equal 7 cm from the center of motor shaft. According to equation (1), the generated dynamic forces are 0.05 kN. The clay was consolidated by applying a uniform vertical pressure on a steel plate to get soil bearing capacities of 20, 40 and 60 kN/m^2. Each load step on the footing is keep up for around two days in all the case studies until the settlement stops relatively. An elastic material model is assumed for the plate in the analysis, whereas the mohr-coulomb constitutive model is adopted for clay and EPS. The underlying soil dimension are 1.40 X 1.40 m and 0.8 m deep, as shown in figure 2.

Results of the finite element analysis for the maximum cases of settlement obtained by PLAXIS 2D and compared to the experimental results for the following study cases:

a) Static loading without EPS,
b) Dynamic loading with ɯ = 450 rpm without EPS,
c) Dynamic loading with ɯ = 1000 rpm without EPS, and
d) Dynamic loading with ɯ = 1000 rpm with EPS.

A comparison of the finite element results for the settlement (in mm) to those of the experimental study is presented in table 1 and figures 2-6. The results of the computed values of the settlement are in a good agreement with the experimental results; except for Case (a) under applied stress of 60 kN/m^2, as the theoretical estimation of settlement was about 40% of the test result.

Loading Type		**Applied Stress (kN/m^2)**	**20**	**40**	**60**
Without EPS	a) Static Load	Experiment	4	9	29
		FEA	4.2	8.4	11.7
		Variation (%)	+5%	-7%	-60%
	b) Dynamic Load with ω = 1000 rpm	Experiment	4.6	8.6	16.6
		FEA	4.9	10.2	14.1
		Variation (%)	+7%	+19%	-15%
	c) Dynamic Load with ω = 450 rpm	Experiment	6	10	14.5
		FEA	5.2	10.5	14.3
		Variation (%)	-13%	+5%	-1%
Utilizing EPS	d) Dynamic Load with ω = 1000 rpm	Experiment	1.9	5.3	11.3
		FEA	2.3	6.3	9.4
		Variation (%)	+12%	+19%	-17%

Table 1: Finite element versus experimental results for the settlement [mm] of a square footing.

Figure 2: Finite element model of a square footing.

Figure 3: Results of experimental and numerical models for static load case without EPS.

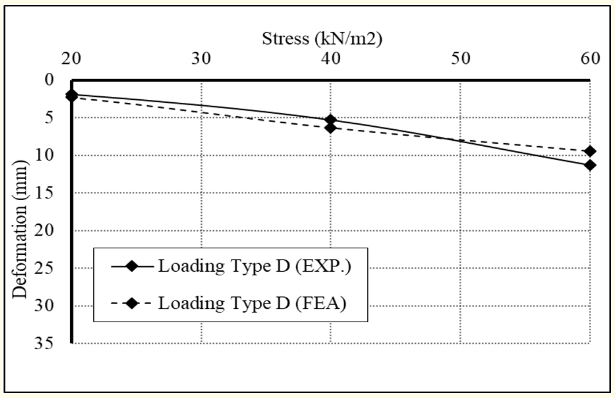

Figure 6: Results of experimental and numerical models for dynamic Load case with ω = 450 rpm with EPS.

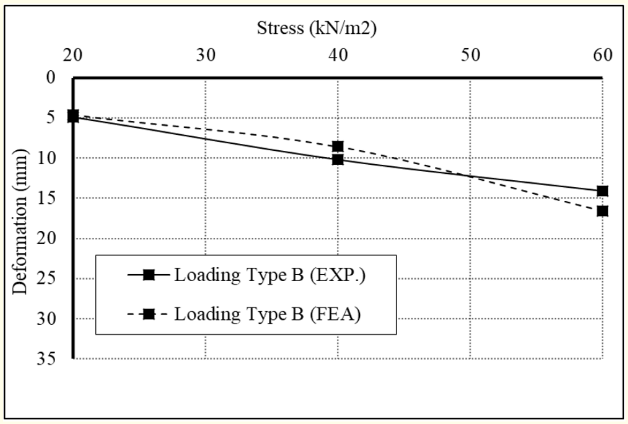

Figure 4: Results of experimental and numerical odels for dynamic Load case with ω = 1000 rpm without EPS.

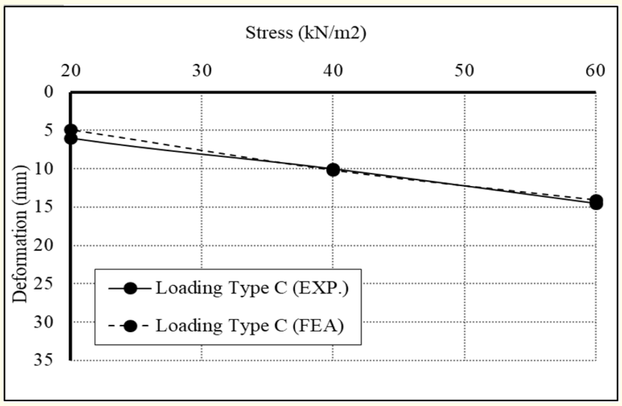

Figure 5: Results of experimental and numerical models for dynamic Load case with ω = 450 rpm without EPS.

Methodology and developed model

Consider the piled raft shown in figure 7. The raft is 2.0 [m] thick with 9 x 9 [m] side dimensions. A group consists of nine similar concrete piles (0.76 [m] diameter and 15 [m] length) supports the raft. The pile group is separated from the raft by EPS cushion as shown in the Figure.

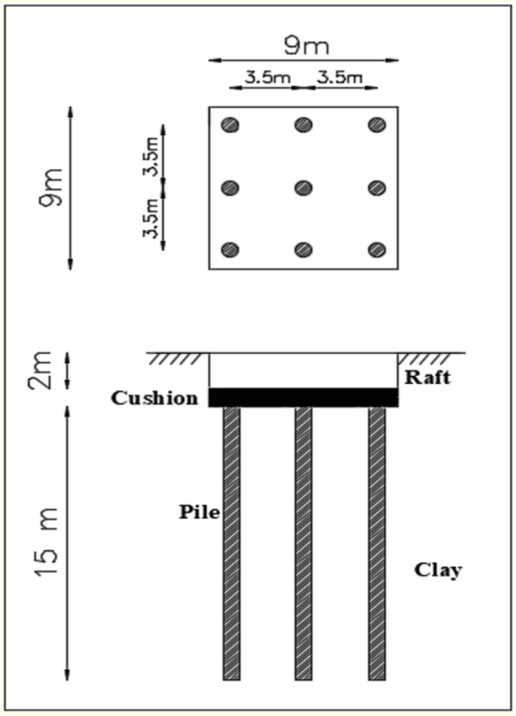

Figure 7: Unconnected piled raft model with cushion.

To represent the three-dimensional problem as a two-dimensional model in the finite element solution, the "out off"-plane rows of piles are represented as wall elements, called plane strain piles as illustrated in figure 8. The plane strain piles are modeled in PLAXIS 2D by using plate elements with corresponding interface elements, which describe the interaction between the piles and the soil.

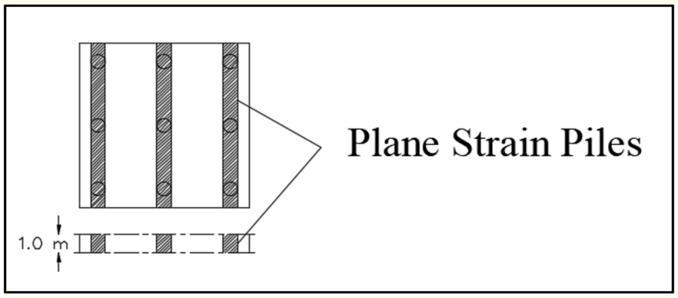

Figure 8: Plane strain model of piled raft.

Any theoretical model for analyzing piled raft should consider the complex interactions among piles, raft and soil. Therefore, plane strain and axi-symmetric finite element models can be used for this purpose. However, the plane strain model involves the fundamental simplification of condensing a finite size piled raft ratio into a strip piled raft. Desai., *et al.* [12] showed that this type of model can provide good results.

Ryltenius [13] simplified the piles into strips with equivalent pile young's modulus. In this study, the wall element is defined per meter; the normal stiffness, bending stiffness and weight for the piles in the "out off"-plane row of piles is therefore per meter as the following:

$$EA_{psp} = EA_p \frac{n_{p\text{-}row\text{-}i}}{L_r}$$

where L_r: Raft length in plane.

$N_{p\text{-}row\text{-}i}$: Number of piles in row i.

EA_p: Normal stiffness for one pile.

EA_{psp}: Normal stiffness for plain strain pile.

Analogously, the bending stiffness is inputted as

$$EI_{psp} = EI_p \frac{n_{p\text{-}row\text{-}i}}{L_r}$$

where; EIp: Bending stiffness for one pile.

EIpsp: Bending stiffness for plain strain pile.

and the weight as

$$W_{psp} = W_p \frac{n_{p\text{-}row\text{-}i}}{L_r}$$

where; wp: Bending stiffness for one pile.

wpsp: Bending stiffness for plain strain pile.

As illustrated in table 2, four model groups were considered in the analysis depending on utilizing EPS and cushion or not. In Case A, a shallow foundation without EPS or cushion is considered. A raft with connected piles is examined Case B. An unconnected piled raft system with EPS cushion is investigated in Case C. Finally, and to study the effect of changing the cushion material on the settlement behavior, an unconnected pile raft system with compacted soil fill instead of the EPS cushion is studied in Case D.

Model groups			Symbol
A	Without EPS	Raft	Raft
B		Connected Pile	CP
C	Utilizing EPS	Unconnected Pile	EPS-UNCP
D	Utilizing Compacted Fill Material (Granular soil)		CFM-UNCP

Table 2: Classification of model groups.

The cushion is composed of coarse-grained compacted soil, which is modeled as an elastic material in the present analysis. figure 9 shows the finite element fine mesh for the unconnected piled raft system, including the cushion and soil mass. The properties of soil, EPS cushion, pile and raft are presented in table 3.

Figure 9: Finite elements mesh of unconnected piled raft.

Type	Density (kN/m^3)	Cohesion (kN/m^2)	Modulus of elasticity (kN/m^2)	Angle of riction	Poisson's ratio
Clay soil	18	7	2000	25	0.35
EPS	0.15	30.75	2480.76	3	0.1
	0.20	36	4070.55	4	0.1
	0.30	59.75	7550.28	6	0.1
Cushion with compacted fill (granular soil)	20	_	40000	_	0.25
Concrete raft and pile	25	_	3.5E+07	_	0.2

Table 3: Material properties used in the analysis.

In Plaxis-2D, soil initial condition should be determined prior to performing the main calculations phases. This initial condition includes calculating both the initial effective stress-state and the initial water pressures in the soil. Plaxis provides two manners to generate the initial water pressures, either directly from the phreatic level or by a steady state ground water calculation. Both methods require the definition of the phreatic levels. In this study, the phreatic level is assumed to be at the ground surface. Hydrostatic pore pressures are generated in the whole geometry according to this phreatic line.

The initial stress is defined by the vertical stress together with the horizontal stress. There are two sources for the vertical stress. The first one is the external load and the latter is the dead weight of the soil. The horizontal stress could further be calculated with knowledge of the coefficient K. Plaxis calculates these two stresses in every stress point in the model for an initial condition. The initial condition implies no external loads and the vertical stresses are therefore calculated using the soils unit weight.

Parametric study

The present parametric study covers a wide range of expanded poly-styrene geofoam variables; namely: EPS density (Ed), EPS thickness (Et), and EPS size (Es). Fifty study cases were analyzed to investigate the settlement response of unconnected piled raft resting on clay soil. The main features of the parametric study are shown in table 4.

In dynamic load, at low speeds the displacement can be high while at high speeds the displacement will be very small. This fact makes displacement more sensitive to the lower frequencies and is better for slow speed machines below 600 rpm. So that, in this study the foundation is subjected to dynamic load with constant amplitude and with a variable frequency ranging from one to ten Hz.

Parameters	Values and ranges
EPS density, E_d [kN/m^3]	0.15 - 0.20 - 0.30
EPS thickness, E_t [cm]	50 - 100 -150 - 200
EPS size, E_s [m]	9 x 9 - 11x11 – 13 x 13
Pile length [m]	15
Pile diameter [m]	0.76
Raft thickness [m]	2
Applied amplitude [kN/m^2]	80
Applied frequency, ƒ [Hz]	1 to 10

Table 4: Parametric study variables.

Results and Discussion

Effect of changing the cushion material

In this study, one of the following two types fills the gap between the raft and the piles:

a) Compacted structural fill material (granular soil)

b) Expanded Polystyrene Geofoam.

For piled raft foundation, the cushion is used beneath the raft to redistribute the vertical stresses between the piles and the soil. To study the effect of cushion on the central settlement under dynamic loading for shallow and deep foundations (for either connected and unconnected piles), a 9 x 9m square piled raft as shown in Figure 7 is considered. For the unconnected piled raft study cases, the cushion is taken exactly as large as the raft with thickness 200 cm and the density of EPS is 0.30 kN/m^3.

Figure 10 shows a comparison of the central settlement for the different systems. As it is expected, all types of piled raft reduce the deformations significantly for all load frequencies.

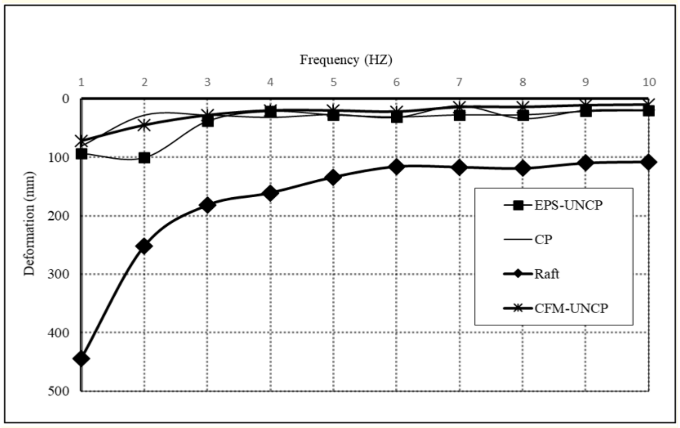

Figure 10: Sensitivity of dynamic response to foundation type.

The effect of pile uncoupling on the deformations is relatively small, for both types of cushion materials at the high frequencies.

Effect of EPS density and thickness

In the present study, three different values for the density of the expanded poly-styrene geofoam are considered (0.15-, 0.20- and 0.3-kN/m^3). Moreover, four different values for the cushion thickness are studied (EPS thickness 50-, 100-, 150- and 200- cm, respectively). The effect of EPS density variation on the settlement at 9 x 9 m raft center, for the different values of EPS thickness are presented in Figures 11 through 14. For all values of EPS density and thickness, the central settlement is hardly affected by the variations of density and thickness for all frequencies, except for ƒ = 2-Hz. For ƒ = 2-Hz, a denser and thinner EPS geofoam cushion gives relatively smaller values for the settlement. This value of frequency was determined before by Athanasopoulos., *et al.* [10]. They concluded that loading frequency affects the dynamic properties of EPS geofoam in a way that is opposite to the behavior of viscoelastic materials. Namely, the elastic moduli values were not significantly affected by the loading frequency, whereas the damping ratio increased significantly by decreasing the loading frequency from 2.00 to 0.01 Hz. Where the damping ratio is the lowest at the 2 Hz value, so the settlement value is high at this value of the frequency. Therefore, it may that result in this change in values at frequency 2 Hz in this study.

Almost similar results can be noticed for larger cushion dimensions, as can be seen in Figures 15 through 18, and Figures 19 through 22, for 11 x 11m and 13 x 13m square rafts, respectively. For the indicated larger sizes of EPS cushion, the settlement response at ƒ = 2-Hz, is also hardly affected by the variations of EPS density and thickness such as all other frequencies.

In these cases, improved deformation as a result of the EPS size overcome the improvement of deformation as a result of changing the EPS density and thickness.

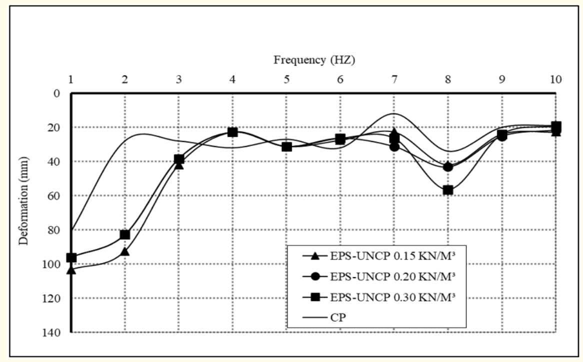

Figure 11: Sensitivity of dynamic response to EPS density (for a 9 x 9 m cushion 50-cm thick).

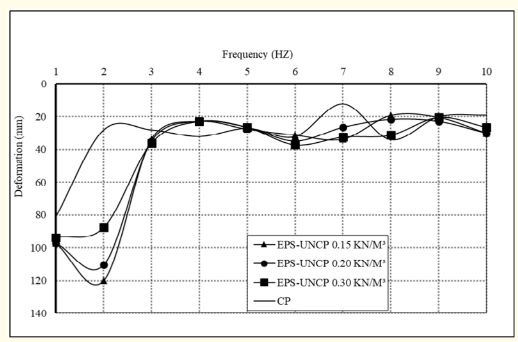

Figure 12: Sensitivity of dynamic response to EPS density (for a 9 x 9 m cushion 100-cm thick).

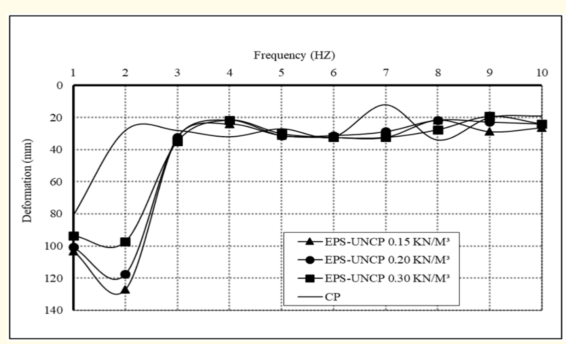

Figure 13: Sensitivity of dynamic response to EPS density (for a 9 x 9 m cushion 150-cm thick).

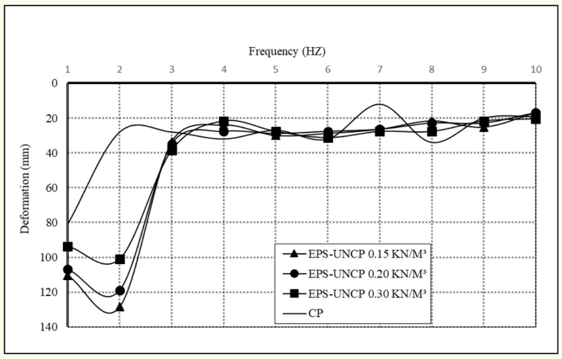

Figure 14: Sensitivity of dynamic response to EPS density (for a 9 x 9 m cushion 200-cm thick).

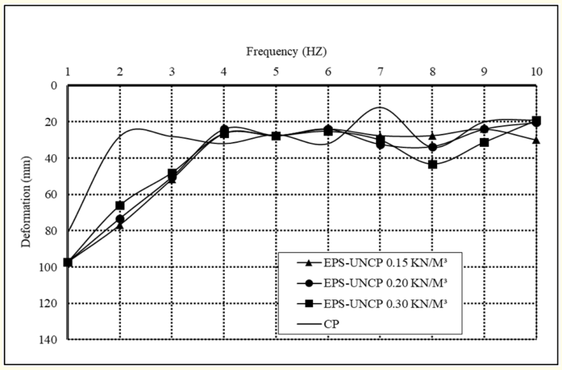

Figure 15: Sensitivity of dynamic response to EPS density (for a 11 x 11 m cushion 50-cm thick).

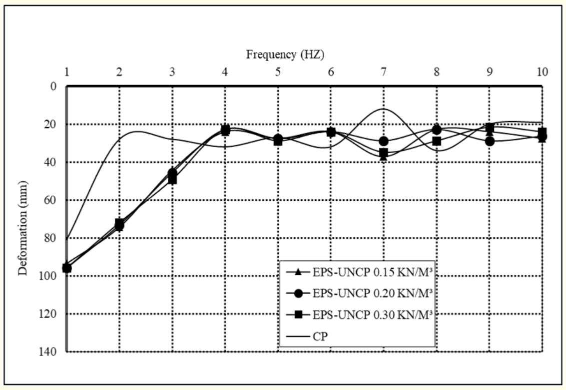

Figure 16: Sensitivity of dynamic response to EPS density (for a 11 x 11 m cushion 100-cm thick).

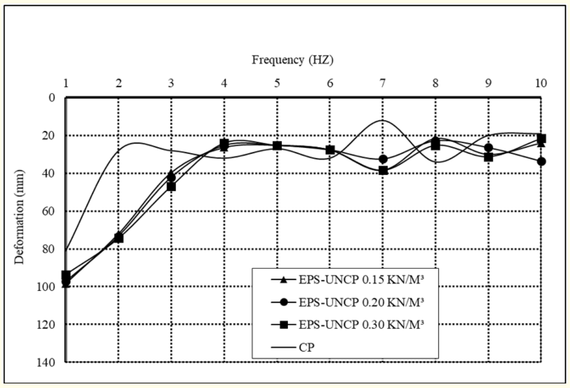

Figure 17: Sensitivity of dynamic response to EPS density (for a 11 x 11 m cushion 150-cm thick).

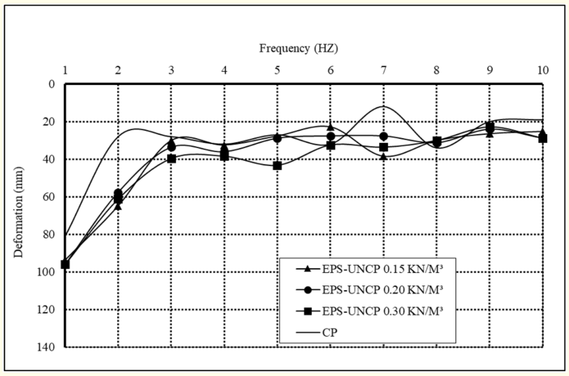

Figure 18: Sensitivity of dynamic response to EPS density (for a 11 x 11 m cushion 200-cm thick).

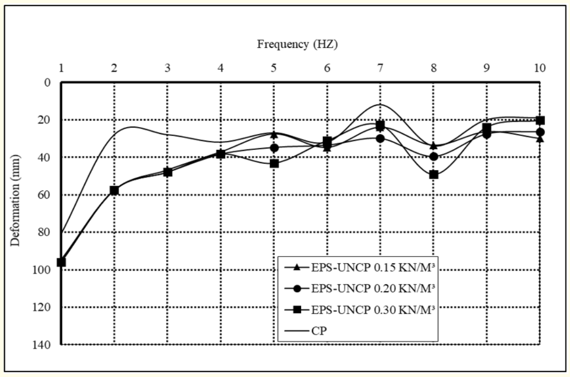

Figure 19: Sensitivity of dynamic response to EPS density (for a 13 x 13 m cushion 50-cm thick).

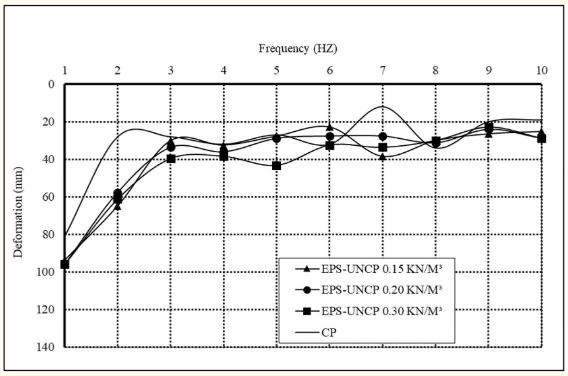

Figure 20: Sensitivity of dynamic response to EPS density (for a 13 x 13 m cushion 100-cm thick).

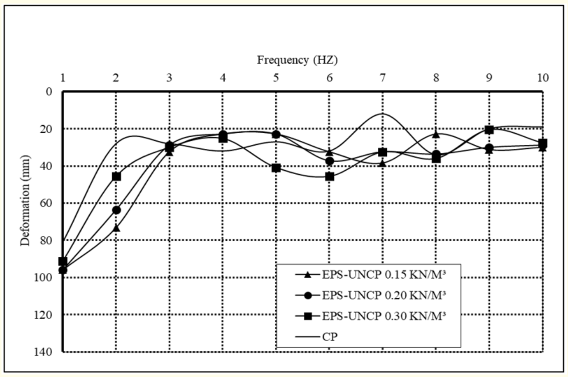

Figure 21: Sensitivity of dynamic response to EPS density (for a 13 x 13 m cushion 150-cm thick).

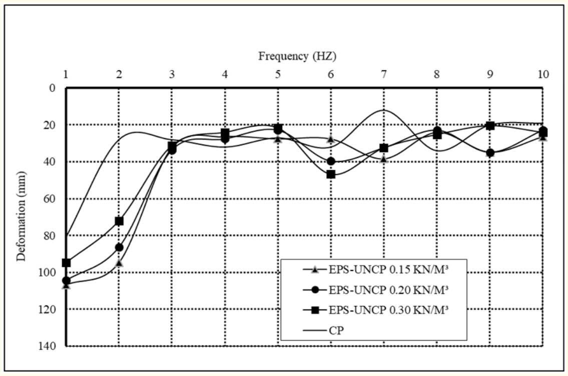

Figure 22: Sensitivity of dynamic response to EPS density (for a 13 x 13 m cushion 200-cm thick).

Effect of EPS Size

The size effect of EPS cushion on the settlement at 9 x 9 m raft center, for the different values of EPS thickness and density is presented in Figures 23 through 34. Except for ƒ = 2-Hz, the cushion size has a slight effect on the settlement disregard the EPS cushion density or thickness. For ƒ = 2-Hz, the use of EPS cushion coinciding with the raft dimensions mostly produces a maximum central settlement. For this loading frequency, the larger the EPS cushion, the smaller the central settlement.

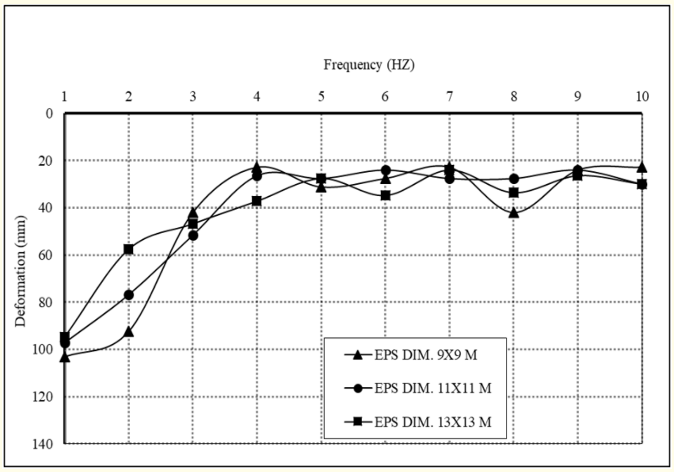

Figure 23: Sensitivity of dynamic response to EPS size (EPS thickness 50 cm and density 15 kN/m^3).

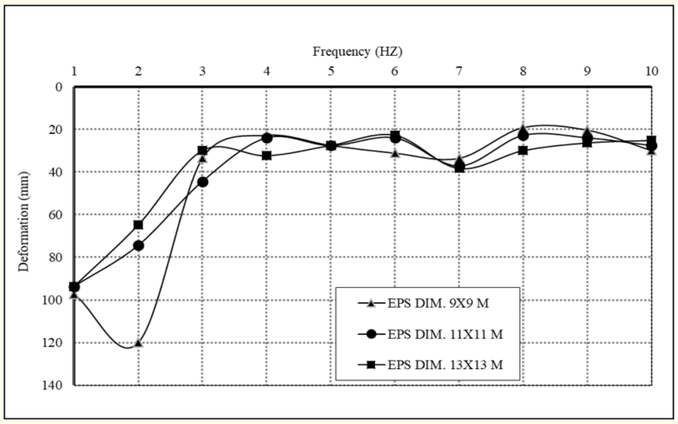

Figure 24: Sensitivity of dynamic response to EPS size (EPS thickness 100 cm and density 0.15 kN/m^3).

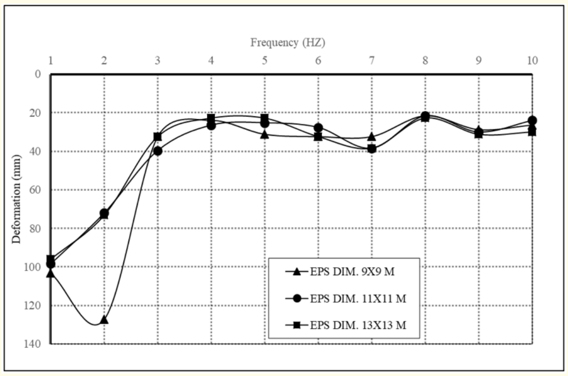

Figure 25: Sensitivity of dynamic response to EPS size (EPS thickness 150 cm and density 0.15 kN/m^3).

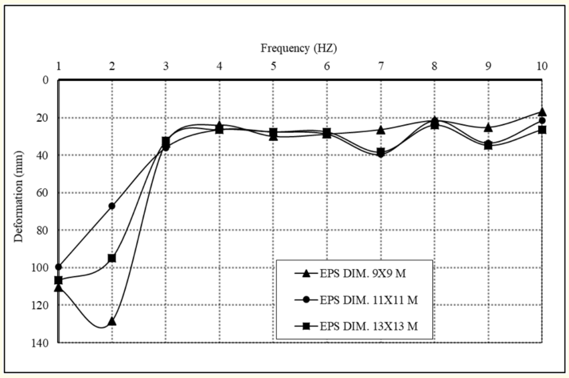

Figure 26: Sensitivity of dynamic response to EPS size (EPS thickness 200 cm and density 0.15 kN/m^3).

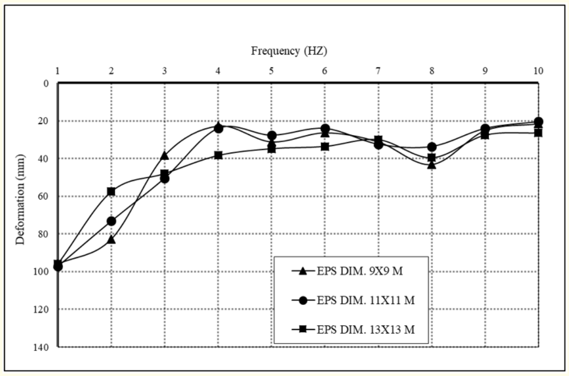

Figure 27: Sensitivity of dynamic response to EPS size (EPS thickness 50 cm and density 0.20 kN/m^3).

Figure 28: Sensitivity of dynamic response to EPS size (EPS thickness 100 cm and density 0.20 kN/m^3).

Figure 29: Sensitivity of dynamic response to EPS size (EPS thickness 150 cm and density 0.20 kN/m^3).

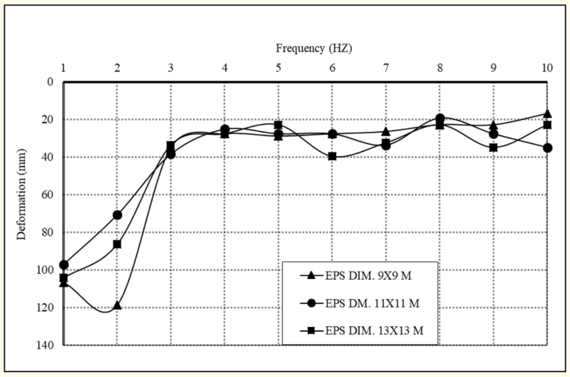

Figure 30: Sensitivity of dynamic response to EPS size (EPS thickness 200 cm and density 0.20 kN/m^3).

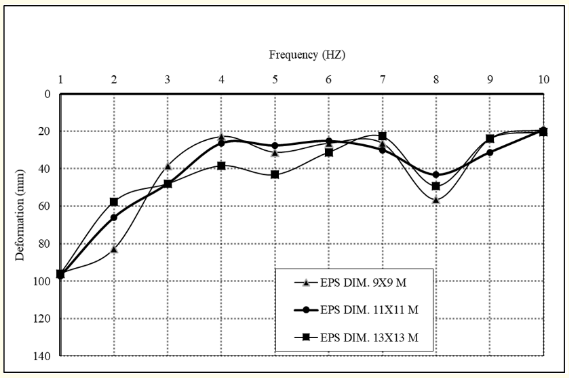

Figure 31: Sensitivity of dynamic response to EPS size (EPS thickness 50 cm and density 0.30 kN/m^3).

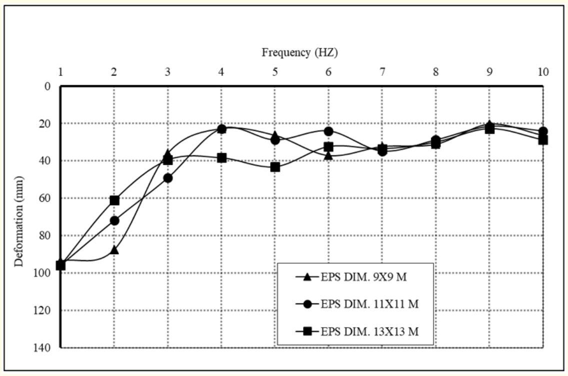

Figure 32: Sensitivity of dynamic response to EPS size (EPS thickness 100 cm and density 0.30 kN/m^3).

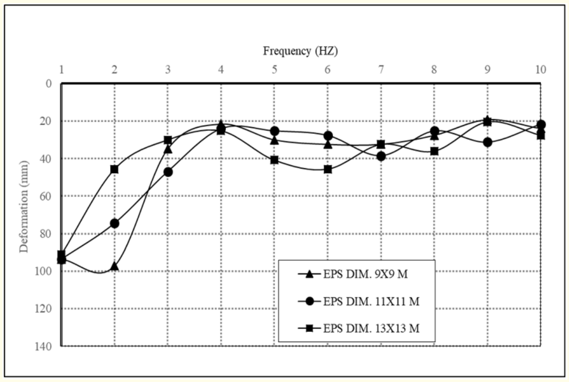

Figure 33: Sensitivity of dynamic response to EPS size (EPS thickness 150 cm and density 0.30 kN/m^3).

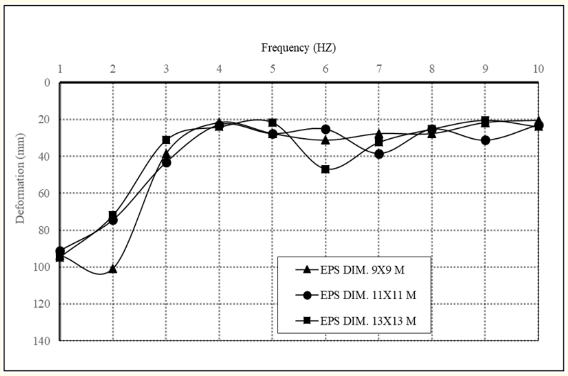

Figure 34: Sensitivity of dynamic response to EPS size (EPS thickness 200 cm and density 0.30 kN/m^3).

Conclusions

In this research, the use of expanded poly-styrene geofoam, EPS as a settlement reducer for unconnected piled raft on clay was investigated by the finite element method. The studied cases compared the behavior of EPS cushion to the compacted soil fill, in addition to the conventional case of connected pile raft foundation. Then, the analysis was extended to cover about 50 study cases of unconnected piled raft with EPS cushion. The influence of EPS density, thickness and size on the dynamic settlement behavior of the piled raft system was investigated. From the comparative studies carried out in this works, it could be concluded that:

1. Compared to the case of raft without piles, the maximum settlement of the connected piled raft has decreased by high percentages due to the weak soil, which required deep foundation to sustain the loads. By increasing the load frequency, the unconnected piled raft has a same effect in decreasing the settlement in case existence EPS or compacted soil as cushion.
2. Compared to the case of connected pile, damping harmonic motion resulting from dynamic loads shows clearly when utilizing EPS as cushion, due to the ability of EPS to absorb the energy.
3. The settlement is decreasing with increasing the density of EPS. This effect appears well in case of EPS existence with high thickness subjected to the early frequencies because the effect of these frequencies on the displacement is high compared to the high frequencies.
4. The effect of EPS thickness depending mainly on its dimension regarding the foundation size, due to the stress distribution beneath the base. For the same foundation size, increasing the EPS thickness results in an increase in the overall settlement. On the other hand, in case of increasing the EPS size to be with width almost equal the EPS depth, increasing the EPS thickness results in a decrease in the settlement.

5. The effect of EPS size shows clearly under the low frequencies with applying high densities of EPS. In this range, increasing the EPS size leads to decreased settlement.
6. In case increasing the cushion to 200 cm thickness, the best size for EPS to reduce the deformation is 11 x 11 m. It can be estimated about the value of thickness from both directions of the foundation, which is considered suitable in terms of the redistribution of stresses under the base.

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