PERFORMANCE OF RIGID RAFT FOUNDATION RESTING ON SOFT CLAY IMPROVED BY GRANULAR PILES

Ahmed M. Abdel Galil, Tarik Abdelfattah Youssef, Mohamed I. Elsalhy

ABSTRACT- Foundations on soft cohesive soils suffer from excessive settlement and low bearing capacity. The granular piles technique is widely used to improve the bearing capacity and settlement performance of soft cohesive soils. In this paper, a three dimensional finite element analysis is performed using PLAXIS 3D to investigate the performance of a uniformly loaded rigid raft resting on soft clay soil improved by granular piles. The analysis is carried out to investigate the influence of some key parameters on the bearing capacity, the settlement and bending moment of the raft. The parameters include the area replacement ratio, length of the granular piles and thickness of the sand pad. The analysis also studies the efficiency of using recycled aggregates as an alternative granular pile material. The results indicate that the use of granular piles to reinforce soft soil under rigid raft improves the bearing capacity, settlement and bending moment of the raft. More improvement occurs due to the increase of area replacement ratio, granular piles length and thickness of the sand pad. Additionally, the results show that recycled aggregates may be effectively utilized as granular pile materials in the place of conventional natural aggregates for the improvement of soft clay.

Index Terms - End bearing; Floating; Granular pile; PLAXIS 3D; Recycled aggregates; Rigid raft; Soft clay.

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1 INTRODUCTION

The construction on soft clay soil which extends in Egypt and many regions around the world is considered a big challenge due to the low shear strength and high compressibility of the soft clay. Raft foundations are usually used for medium heavy structures constructed on soft clay. Due to the characteristics of soft clay, the structures built on it suffer from excessive settlement and low bearing capacity problems. These serious problems can cause damage in structure and reduction in the durability. Therefore, the soft soil under the raft foundation should be improved [1, 2].

Many soil improvement techniques have been developed and used in engineering practices to minimize the settlement and increase soil foundation bearing capacity. Stone columns or granular piles are one of the most effective ground improvement techniques. Granular piles are mainly used to reduce settlement, increase bearing capacity, and accelerate the consolidation process of the soft soil beneath the raft [3, 4].

Granular piles beneath the raft may be fully penetrating through the soft soil layer and resting on good bearing soil layer (i.e., end bearing granular piles) or partially penetrating the soft soil layer and not resting on strong soil layer (i.e., floating granular piles). For deep deposits of soft soil, Floating granular piles are considered as an economic alternative system to end bearing granular piles [5-8]. The optimum length for granular piles in-group depends on the foundation size, rigidity and soft soil thickness [9]. In practice, a layer of compacted coarse grain soil is usually placed below the raft and over the top of the soil improved by granular piles to facilitate drainage and distribution of the stresses coming from the raft [10].

For many years, natural aggregates have been used as granular pile materials. In recent years, the use of alternative aggregates has been encouraged in geotechnical engineering as the construction industry consumes a large amount of natural aggregates and also produces a huge mass of construction waste. Many studies have been made to investigate the use of recycled aggregate (RA), which is reproduced from construction wastes, as granular pile material in the place of natural aggregate for the improvement of soft clay [11-14]. Recycled aggregates may be utilized as granular pile materials replacing its traditional natural aggregate materials.

Many research works have been conducted to understand the behavior of raft resting on soft clay soil improved by granular piles but most of the previous studies have focused on the settlement behavior of the improved ground. In the design of the raft foundation, not only the settlement is a significant design factor, but also bending moment is very important design factor.

The main objective of this research is to investigate the behavior of raft foundation resting on soft soil improved by granular piles under long-term loading conditions. A three dimensional finite element analysis has been performed using PLAXIS 3D to study the performance of a uniformly loaded rigid raft resting on soft clay soil improved by granular piles. The analysis investigates the influence of some key parameters on the bearing capacity, the settlement and bending moment of the raft.

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The parameters include the area replacement ratio, length of the granular piles and thickness of the sand pad. The analysis also studies the efficiency of using recycled aggregates as an alternative granular pile material.

2 NUMERICAL MODELING

The foundation system under consideration consists of a rigid raft resting on a granular layer over soft soil, with thickness H, improved by granular piles as shown in Fig. 1. The raft foundation is square with a side dimension of B and subjected to a uniformly distributed load, q. The thickness of the granular layer is T. Diameter of granular piles is D. The length of the granular piles is considered equal to the thickness of the soft clay layer (i.e., case of end bearing granular piles) or less than the thickness of the soft clay layer (i.e., case of floating granular piles). The granular piles have been distributed uniformly under the raft.

Numerical modeling for the studied foundation system is performed using PLAXIS 3D program [15]. The 3D model and finite element mesh are shown in Fig. 2. The soil profile consists of soft clay layer with a thickness of 15 m, followed by a dense sand layer with a thickness of 20 m. The compacted sand pad with different thicknesses is utilized as a mat layer. The groundwater level is considered at the bottom of the sand pad layer. The raft foundation has the dimension of 10 m x 10 m and thickness of 1.0 m. Quarter of the problem is idealized due to the symmetry. The model is also square with a side dimension of 10 B to avoid the effect of the boundary conditions on the results.

Appropriate choices of material properties are necessary in order to have an accurate simulation of reinforcement system in the numerical modeling. The properties of soft clay, granular pile materials, sand pad and dense sand bearing layer have been idealized by Hardening Soil Model (HS). The properties of these soils are adopted from the study of Emam EA et.al [16]. The parameters of the used soils are shown in Table 1. The raft foundation is elasticity idealized by Plate Model. The modulus of elasticity of the raft is 2.1 E7 kPa

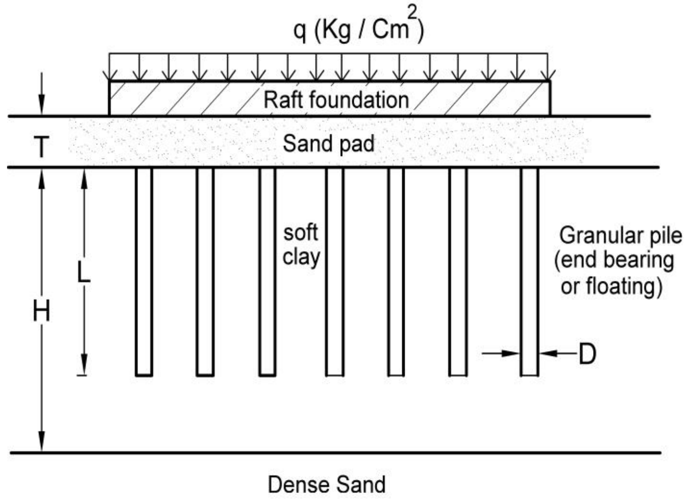

Fig. 1. The problem under consideration.

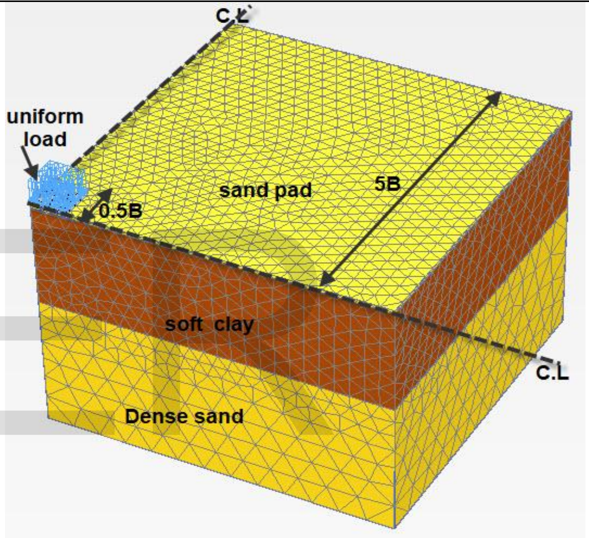

Fig. 2. Model geometry and finite element mesh.

TABLE 1
MATERIALS PROPERTIES USED IN NUMERICAL ANALYSIS

Parameter	symbol	Soil materials		Sand pad	Granular piles			
		Soft clay	Dense sand		Basalt	Crushed Ceramic	Crushed concrete	Crushed red bricks
Material model	type	HS	HS	HS	HS	HS	HS	HS
Loading	condition	drained	drained	drained	drained	drained	drained	drained
Saturated bulk density	γ_{sat} (kN/m^3)	17.9	20	20.64	20.6	17.54	18..79	16.68
Dry bulk density	γ_{dry} (kN/m^3)	12.5	17	17.7	16.8	13.7	15.4	13.1
Poisson's ratio	v	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Effective cohesion	C` (kN/m^2)	25	0	0	0	0	0	0
Effective Friction angle	$\grave{\varphi}$ °	0	40	36	42.5	43.73	41.5	39.5
Dilatancy angle	ψ °	0	10	6	12.5	13.73	11.5	9.5
Secant stiffness	E_{50}^{ref} (kN/m^2)	2800	50000	18000	65740	73000	60000	49380
Tangent stiffness	E_{oed}^{ref} (kN/m^2)	2800	50000	18000	65740	73000	60000	49380
Unloading reloading stiffness	E_{ur}^{ref} (kN/m^2)	8400	150000	54000	197220	219000	180000	148140
Power	m	1	1	1	1	1	1	1

3 PARAMETRIC STUDY

In this research work, a series of numerical models have been performed to investigate the performance of a uniformly loaded rigid raft resting on soft clay soil improved by granular piles. The effect of area replacement ratio, granular pile length, granular pile materials and thickness of sand pad on the bearing capacity, settlement and bending moment of the raft has been studied. The effect of each parameter is studied by varying only the parameter within a suitable range while all the other parameters are held constant at the basic values as presented in Table 2.

TABLE 2
BASIC VALUES OF DIFFERENT PARAMETERS CONSIDERED FOR THE PARAMETRIC

parameter	value
Sand pad thickness	0.5 m
Granular pile length, L/H	1
Properties of granular pile material	Basalt pile, presented in Table 1
Area replacement ratio, Ar	19.6%

3.1 Effect of Area Replacement Ratio

The area replacement ratio, Ar, is a key parameter affecting the behavior of raft resting on soft soil improved by granular piles. The area replacement ratio is defined as the ratio of total area of the granular piles beneath the raft to the area of the raft. The effect of the area ratio on the behavior of the studied foundation system is investigated by varying the values of Ar ratio from 12.6% to 38.5%, the different values of Ar are obtained by changing the pile spacing to pile diameter ratio.

The raft settlement is expressed by a non-dimensional parameter known as the settlement ratio (S/B), which is defined as the ratio of the settlement of the raft (S) to raft width (B). Fig. 3 shows the load- settlement ratio curves for the different values of area ratios. For all the studied cases, it is clear that the load carrying capacity of the raft increases as the area ratio increases.

The improvement in bearing capacity due to the use of granular piles is evaluated through a non-dimensional factor, called the bearing capacity ratio (BCR), defined as the ratio of bearing capacity of soft clay with granular piles at a given settlement to that of soft clay without granular piles at the same settlement. Fig. 4 shows the influence of the area ratio (Ar) on the bearing capacity ratio (BCR) at settlement ratios of S/B = 3% and 10%, S/B = 3% which meets low settlement level and S/B = 10% which meets settlement level near failure. For the two studied settlement ratios, it is noticed that the BCR increases with increasing the area ratio. The rate of increase in BCR is high as the area ratio increases up to Ar of about 15% and after that the rate of increase in BCR is small (e.g., at a settlement ratio of 3%, the BCR increases by 44%, 4.2%, 3.3%, and 3.8% as the area ratio increases from 0% to 12.6%, from 12.6% to 19.6%, from 19.6% to 28.3%, and from 28.3% to 38.5%, respectively).

The reduction in settlement of the raft due to the use of granular piles is evaluated based on another parameter, called the settlement reduction factor (SRF), which is defined as the ratio of settlement of the raft with granular piles to that of the raft without granular piles at the same load level. Fig. 5 presents the effect of the area ratio (Ar) on the settlement reduction factor (SRF) at a load level of 100 kN/m². As shown in Fig. 5, the SRF decreases with increasing the area ratio. The rate of decrease in SRF is high as the area ratio increases up to Ar of about to 12.6%, after which the rate of decrease in SRF is decreased (e.g., at a load level of 100 kN/m², the SRF decreases by 68%, 22%, 20 %, and 25% as the area ratio increases from 0% to 12.6%, from 12.6% to 19.6%, from 19.6% to 28.3%, and from 28.3% to 38.5%, respectively).

Fig. 6 shows the effect of the area ratio on the bending moment of the raft along the x-axis. It is noticed that as the area ratio increases the maximum bending moment of the raft decreases (e.g., at a load level of 100 kN/m², the maximum moment at the center of the raft decreased by 29.4% due to the increase in the area ratio from 12.6% to 38.5%). It is also observed that for all the studied cases, the maximum value of the bending moment is located at the center of the raft and the bending moment decreases gradually till it reaches zero at the edge of the raft.

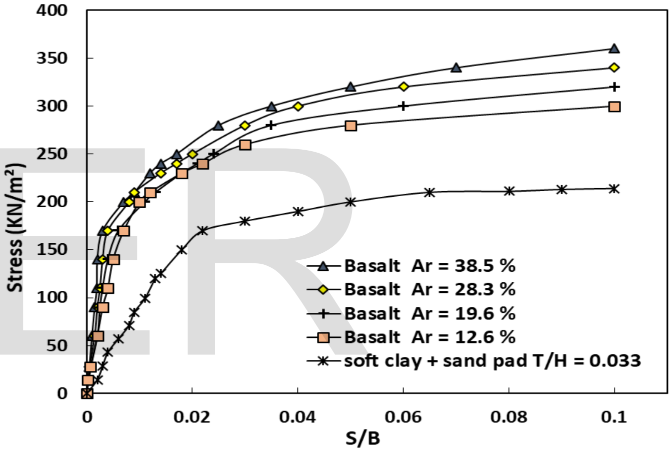

Fig. 3. Effect of area ratio, Ar, on the load-settlement curve of the raft for soft soil reinforced with end bearing basalt pile.

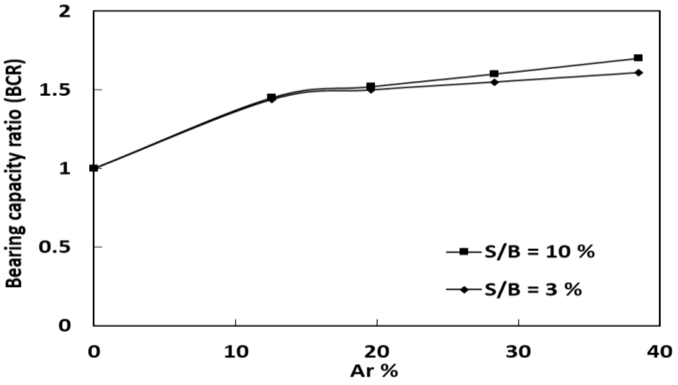

Fig. 4. Effect of area ratio, Ar, on the BCR –settlement ratio curve.

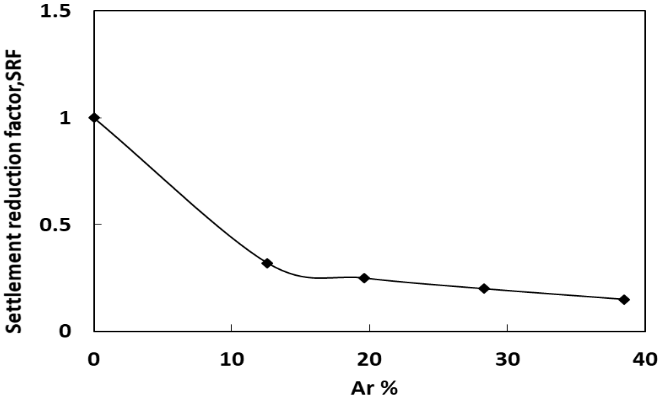

Fig. 5. Effect of area ratio, Ar, on the settlement reduction factor, SRF, at load level 100 KN/m^2.

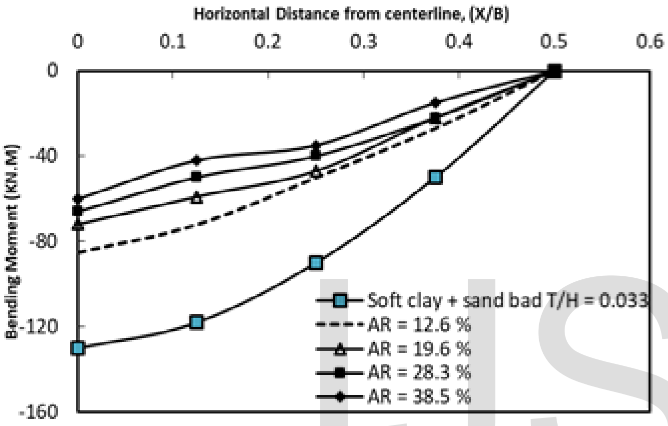

Fig. 6. Effect of area ratio, Ar, on the bending moment of the raft along x-axis at load level 100 KN/m^2.

3.2 Effect of Granular Pile Length

In order to study the effect of granular pile length on the performance of the raft resting on soft soil, different pile lengths have been used. The pile length (L) is expressed in a non-dimensional form in terms of the soft soil thickness (H), as the ratio L/H. The used L/H ratios are 0.5, 0.67, 0.75, and 1 to investigate the behavior of the floating and the end bearing granular piles.

Fig. 7 shows the influence of pile length on the load-settlement ratio curves at different values of L/H ratio. It is noticed that increasing the ratio of L/H leads to significant improvement in the load carrying capacity of the raft.

Fig. 8 shows the variations of BCR with L/H ratios at two S/B ratios, S/B = 3%, S/B = 10%. As shown in Fig. 8, it is clear that the BCR increases with increasing pile length and the case of the end bearing granular piles has the maximum improvement in the bearing capacity. It is also observed that the rate of increment in BCR as the length increases from L/H = 0.5 to L/H = 0.75 is higher than that of increasing length from L/H= 0.75 to L/H = 1 (e.g., for S/B = 3%, the BCR increased by 19%, and 8% as L/H increased from 0.5 to 0.75, and from 0.75 to 1, respectively). Hence, the BCR of the case of floating granular piles with length ratio L/H = 0.75 is slightly smaller than the case of end bearing granular piles.

Fig. 9 shows the effect of L/H ratios on the settlement reduction factor, SRF. It is clear that the SRF decreases with increasing pile length and the case of the end bearing granular piles has the best performance in reducing the amount of settlement. It is also noticed that, the rate of decrement in SRF as the length increases from L/H = 0.5 to L/H = 0.75 is higher than that of increasing length from L/H= 0.75 to L/H = 1. Hence, the SRF of the case of floating granular piles with length ratio L/H = 0.75 is slightly greater than the case of end bearing granular piles.

Fig. 10 presents the effect of L/H ratios on the bending moment of the raft along the x-axis. It is observed that, as the granular pile length increases the maximum bending moment of the raft decreases (e.g., at a load level of 100 kN/m^2, the maximum moment at the center of the raft decreased by about 11.5%, 6%, 7.4 %, and 28% as the L/H increases from 0 to 0.5, from 0.5 to 0.67, from 0.67 to 0.75, and from 0.75 to 1, respectively). It is also observed that for all the studied cases, the maximum value of the bending moment is located at the center of the raft and the bending moment decreases gradually till it reaches zero at the edge of the raft.

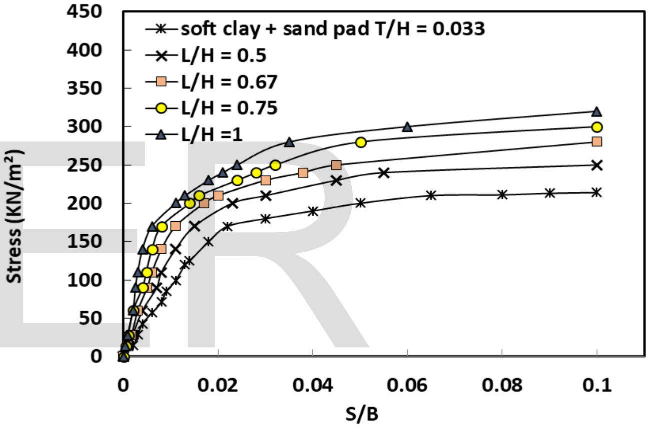

Fig. 7. Effect of pile length on the load-settlement curve of the raft for different L/H ratios, (Ar = 19.6%).

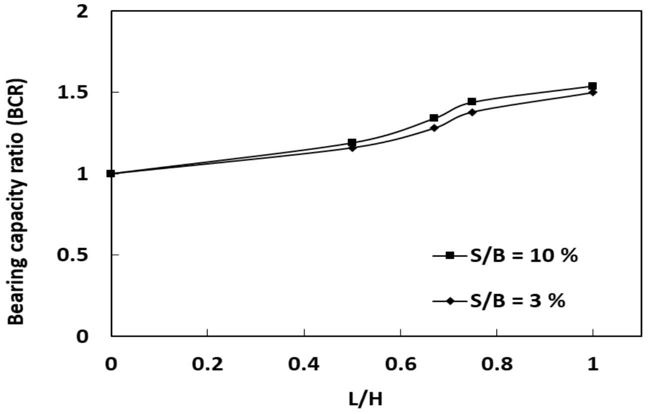

Fig. 8. Effect of (L/H) ratio on the BCR –settlement ratio curve.

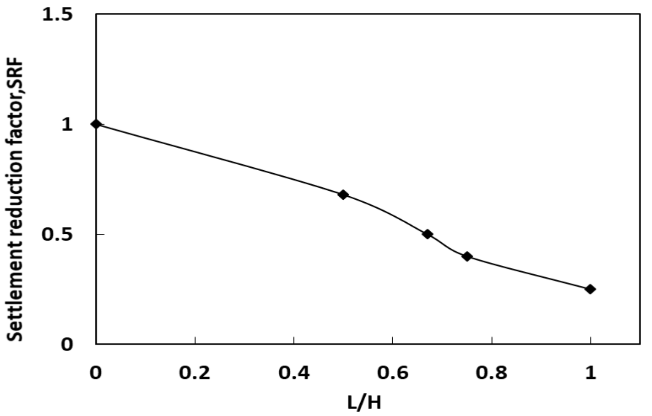

Fig. 9. Effect of (L/H) ratio on the settlement reduction factor, SRF, at load level 100 KN/m^2.

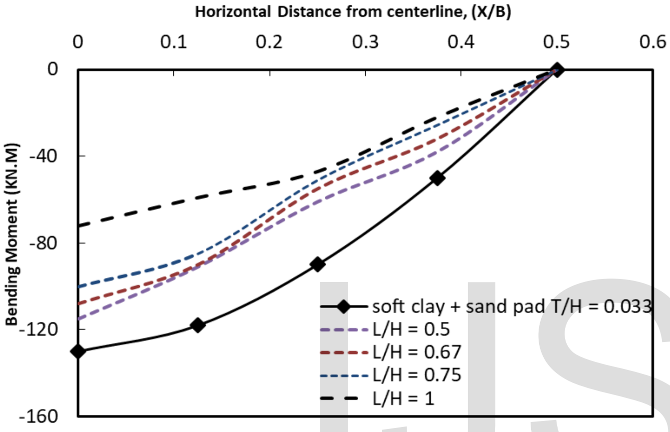

Fig. 10. Effect of pile length on the bending moment of the raft at load level 100 KN/m^2.

3.3 Effect of Granular Pile Materials

To study the efficiency of using recycled aggregates as an alternative granular pile material, three types of recycled aggregates (crushed concrete, crushed ceramic, and crushed red brick), as well as one type of natural aggregate (basalt), are used in this research.

Fig. 11 shows the load- settlement ratio curves for the different used granular pile materials. For all the studied cases, regardless of the type of the aggregates used, it is clear that using granular piles to reinforce soft soil improves the load carrying capacity of the raft. It is also noticed that, using crushed ceramic is the most efficient between the used granular pile materials.

The modulus of elasticity of the granular pile material (Ep) plays an important role in the behavior of granular piles, as Ep increase the stiffness of the granular pile increase. It is more suitable to represent the effect of Ep in a dimensionless parameter called modular ratio, Ep/Es, (where Ep is the modulus of elasticity of granular pile and Es is the modulus of elasticity of soft clay).

Fig. 12 shows the effect of different values of modular ratio, Ep/Es, on the bearing capacity ratios, BCR, of the raft at two S/B ratios, S/B = 3 %, S/B = 10 %. It is observed that as the modular ratio increases, the BCR increases. (e.g., for S/B = 3%, the BCR increased by 12%, 8%, and 14% as Ep/Es increased from 17.6 to 21.4, from 21.4 to 23.5, and from 23.5 to 26.1, respectively). This is due to that as the modular ratio increases, more stress is transferred from soft soil to granular pile due to their stiffness difference, which causes reduction in the settlement and increases in the bearing capacity of the raft foundation.

Fig. 13 shows the effect of the modular ratio, Ep/Es, on the settlement reduction factor, SRF. It is noticed that, at a load level of 100 kN/m^2 the SRF decreases as the modular ratios increases (e.g., at a load level of 100 kN/m^2 ,the SRF decreases by about 36.4%, 40%, and 25% as the modular ratio increases from 17.6 to 21.4, from 21.4 to 23.5, and from 23.5 to 26.1, respectively).

Fig. 14 presents the effect of the granular pile materials on the bending moment of the raft along the x-axis. For all the studied cases, it is clear that as the stiffness of the pile materials increases the maximum bending moment of the raft decreases. e.g., at a load level of 100 kN/m^2, the maximum moment at the center of the raft decreased by about 53.1%, 44.6%, 43.8%, and 39.2% for crushed ceramic pile, basalt pile, crushed concrete pile, and crushed red brick pile, respectively, compared to the clay with sand pad.

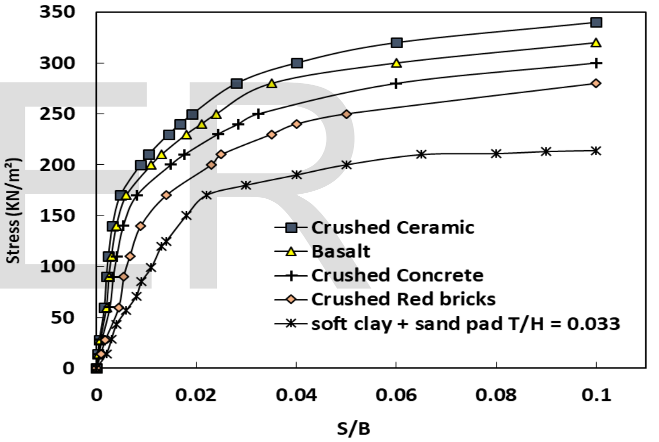

Fig. 11. Effect of pile materials on the load-settlement curve of the raft, (Ar = 19.6%).

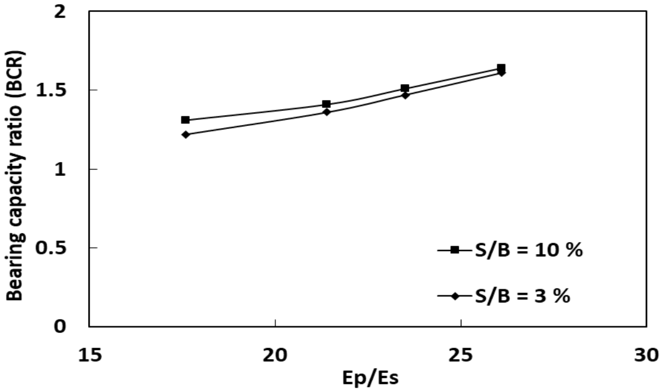

Fig. 12. Effect of modular ratio, Ep/Es, on the BCR –settlement ratio curve.

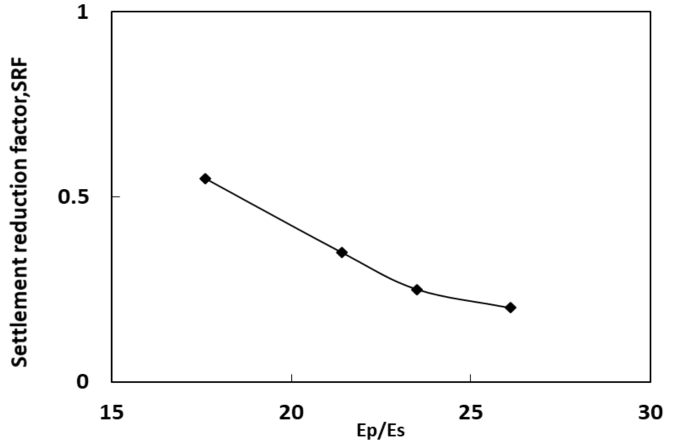

Fig. 13. Effect of modular ratio, Ep/Es, on the settlement reduction factor, SRF, at load level 100 KN/m^2.

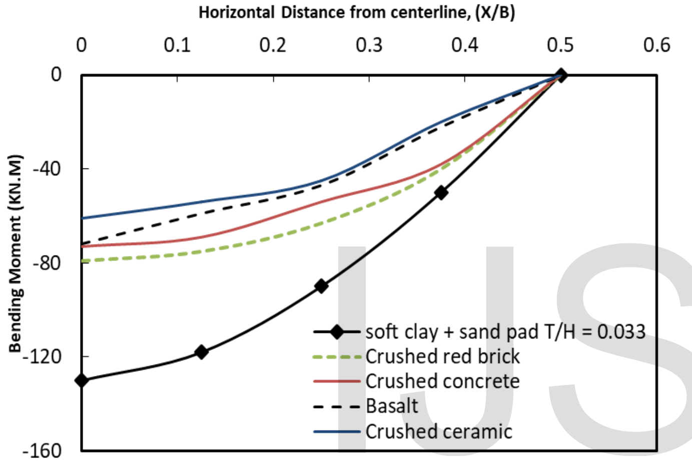

Fig. 14. Effect of different pile materials on the bending moment of the raft along x-axis at load level 100 KN/m^2.

3.4 Effect of Sand Pad Thickness

To investigate the effect of the thickness of the sand pad on the performance of the raft resting on improved soft soil with granular pile, a sand pad with different thicknesses (T) of 0.25m, 0.5m, 0.75m, and 1m has been used. The used sand pad thicknesses are corresponding to T/H ratio of 0.017, 0.033, 0.05, and 0.07 where (H) is the soft soil thickness.

Fig. 15 shows the load – settlement ratio curves for the different used T/H ratio. It is clear that, increasing the T/H ratio leads to improve the bearing capacity and reduce the settlement of the raft and further improvement is achieved with the increase of T/H ratio. This may be due to that the sand pad is stronger and stiffer than soft clay and the increase in sand pad thickness is proportional to its stiffness.

Fig. 16 shows the variations of BCR with T/H ratios at two S/B ratios, S/B = 3 %, S/B = 10 %. It is clear that the BCR ratio increases as the T/H ratio increases. For the two studied S/B ratios, the increase in BCR is approximately the same up to T/H = 0.02, beyond T/H of 0.02 the BCR has higher values for S/B = 10 %.

Fig. 17 shows the effect of the T/H ratios on the settlement reduction factor, SRF. It is observed that, at a load level of 100 kN/m^2 the SRF decreases as the T/H ratios increases (e.g., at a load level of 100 kN/m^2 the SRF decreases by about 37%, 19%, 19.6%, and 14.6% as T/H ratio increases from 0 to 0.017, from 0.017 to 0.033, from 0.033 to 0.05, and from 0.05 to 0.07, respectively).

Fig. 18 shows the effect of the T/H ratios on the bending moment of the raft along the x-axis. It is observed that as the T/H ratio increases the maximum bending moment of the raft decreases (e.g., at a load level of 100 kN/m2, the maximum moment at the center of the raft decreased by 10.5% due to the increase in T/H ratio from 0.017 to 0.07). It is also observed that for all the studied cases, the maximum value of the bending moment is located at the center of the raft and the bending moment decreases gradually till it reaches zero at the edge of the raft.

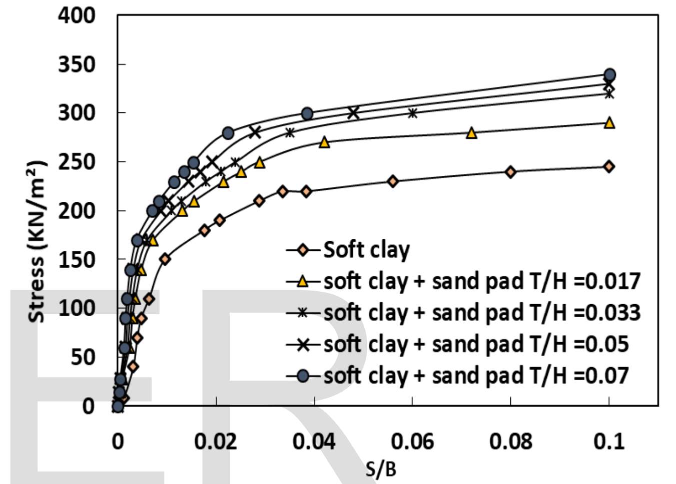

Fig. 15. Effect of sand pad thickness on the load - settlement curve of the raft

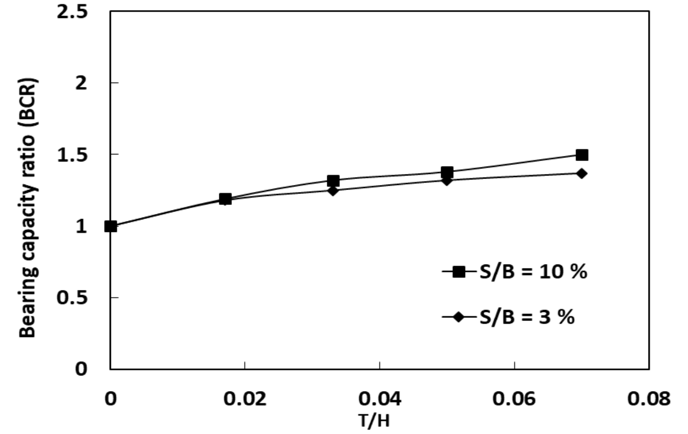

Fig. 16. Effect of (T/H) ratio on the BCR –settlement ratio curve.

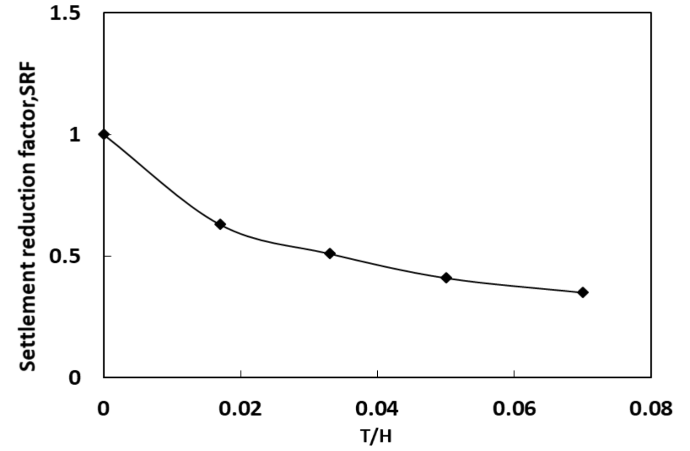

Fig. 17. Effect of (T/H) ratio on the settlement reduction factor, SRF, at load level 100 KN/m^2.

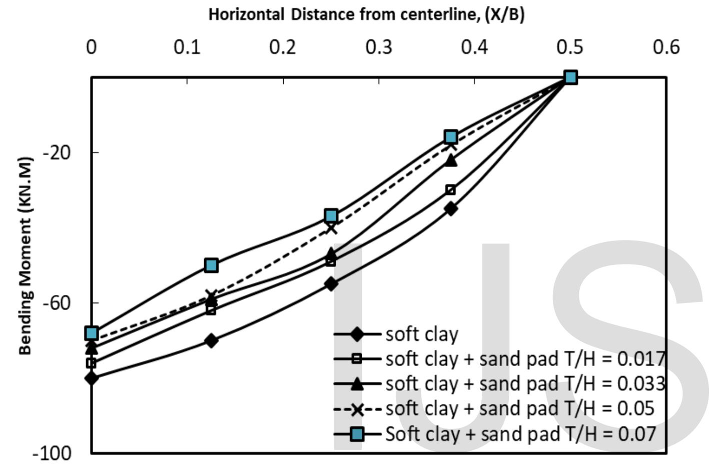

Fig. 18. Effect of sand pad thickness on the bending moment of the raft at load level 100 KN/m^2.

4 CONCLUSION

A three dimensional finite element analysis has been carried out to using PLAXIS 3D to investigate the performance of a uniformly loaded rigid raft resting on soft clay soil improved by granular piles. The analysis investigates the influence of some key parameters on the bearing capacity, the settlement and bending moment of the raft. The parameters include the area replacement ratio, length of the granular piles and thickness of the sand pad. The analysis also studies the efficiency of using recycled aggregates as an alternative granular pile material. Based on the results of the numerical analysis, the following conclusions can be drawn:

- The use of granular piles to reinforce soft soil under rigid raft improves the bearing capacity, settlement and bending moment of the raft. More improvement occurs due to the increase of area replacement ratio.
- Increasing lengths of the granular piles has significant effects on enhancing the bearing capacity, settlement and bending moment of the raft. The end bearing granular piles have the maximum improvement in the performance of the raft. Floating granular pile with L/H = 0.75 is nearly close to end bearing granular pile in improving soft soil under raft footing.
- For all the studied cases, the use of recycled aggregate (RA) as a material for granular piles in soft clay soils is efficient as well as natural aggregates. Using crushed ceramic is the most efficient then using crushed concrete and finally using crushed red brick. The modular ratio (Ep/Es) plays an important role in the behavior of granular piles, increasing the modular ratio leads to significant improvement on the performance of the raft.
- The presence of sand pad, below the raft and over the top of the soil improved by granular piles, enhances the behavior of raft foundation in terms of bearing capacity, settlement and bending moment. More improvement occurs due to the increase of the sand pad thickness.

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