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Research Article

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Behavior of Soft Clay Soil Reinforced by Floating Granular Piles with Different Materials

Abdel-Fattah A. Youssef[1], Ahmed M. Abdel-Galil[1], Enas A. Emam[2]*

[1]Civil Engineering Department, Faculty of Engineering, Menoufia University, Egypt
[2]Ph.D. Candidate, Civil Engineer

Abstract Because of significant reduction inadequate construction sites, a great awareness is devoted to improving geotechnical characteristics of them. One of the classic and most important improving techniques is granular piles. Granular piles have been extensively used to decrease settlement and to increase the load of soft clay deposits. Due to the scarcity of natural aggregates resources and environmental concerns, efforts have been made to explore the feasibility of using recycled aggregates as granular pile as an alternative to natural aggregate. In this research, laboratory model tests were performed on soft clay to study the efficiency of using floating granular piles compared to end-bearing piles using the unit cell concept. Also, the feasibility of using natural aggregate in addition to different recycled aggregates as a pile material was evaluated. The results were compared to clay without reinforcement. It can conclude that using floating granular piles of L/H = 0.75(where L is the length of pile and H is the depth of soft clay bed) is enough efficient compared to end bearing piles from the economic point of view. Also, using recycled aggregates as a material in granular piles in soft clay soils is efficient as well as natural aggregates.

Keywords Granular pile; soft clay; recycled aggregates; bearing capacity; floating; end bearing.

Introduction

Granular piles (*i.e.*, sand compaction piles and stone columns) have been used extensively in soft clay deposits to decrease settlement and to increase the load of structural foundations [1]. Also, it accelerates consolidation settlements due to reduction in flow path lengths. Granular piles have been used extensively over the last three decades in numerous ground improvement and foundation projects [1-9]

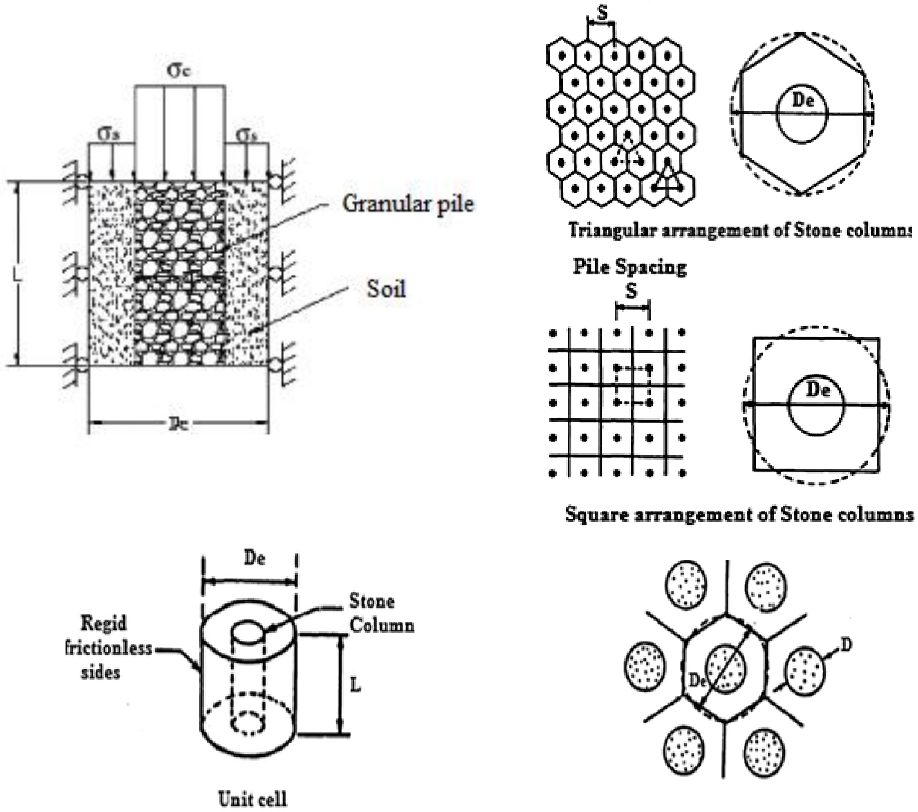
Granular piles may be fully penetrated and resting on a strong soil layer (*i.e.*, end bearing granular piles) or partially penetrated (*i.e.*, floating granular piles). The floating granular piles are considered an economic alternative system to fully penetrate granular piles in case of deep weak soil layer or in case of lightly loaded structures. Many parameters largely influence the effectiveness and behavior of floating granular piles such as granular pile length and diameter, strengths of granular pile material and surrounding soil, method of construction, flexibility of the footing and the number of granular piles beneath the footing. The behavior of floating granular piles with a length twice the width of the footing (L/B>2.0) is nearly similar to the behavior of end bearing piles [10].

Priebe [11] proposed a method to estimate the settlement of foundations resting on an infinite grid of stone columns based on the unit cell concept. In this concept, for an infinitely large group of columns subjected to a uniform vertical loading applied over the area, the behavior of each interior column may be simplified to a single column installed at the center of a cylinder of soil representing the column's influence zone. Due to the symmetry of the load and geometry, lateral deformation cannot occur across the boundaries of the unit cell, and the shear stresses on the outside boundaries of the unit cell must be zero [1] as shown in Fig. (1). Many researchers have used the unit cell concept [3, 12-14].

In practice, usually, a sand pad with a thickness of 30cm or more is used on the top of the soil improved by granular piles for drainage purpose, as well as distribution of the stresses coming from super structures [15]. Due to high-stress concentration near the top of the granular pile, bulging and subsequent failure of granular pile occurs in this region. This stress concentration is significantly influenced by the presence of sand pad [14].

Nowadays, the problems of natural aggregate reduction, as well as increasing of waste materials from construction and demolition activities, are becoming serious problems. Using alternative materials to the natural aggregates for granular columns is considered. Recycled aggregate "RA" is one of those alternatives. An extensive suite of Geotechnical and environmental aspects has been undertaken by many researchers to study the potential of using recycled and waste materials [16-19]. The RA may be used as granular pile material to improve the soft clay [20]. Kumar [8] studied the improvement of sand soil reinforced by recycled concrete aggregate "RCA" pile. The results showed that RCA may be utilized as pile material.

In this research, the behavior of soft clay reinforced by floating granular piles using different pile materials is studied.



(a) Unit cell concept.

(b) Unit cell diameter for triangular and square grids of column *installation*

Figure 1: Unit cell (Barksdale and Bachus, 1983) [1]

Experimental Program

A laboratory model tests were conducted on soft clay soil reinforced with floating and end bearing granular piles. Tests were performed after reinforcing the soft clay soil by introducing the granular piles with recycled materials (crushed concrete, crushed ceramics, and crushed red brick) as well as natural aggregate (basalt). The dimensions of molds were designed using the unit cell concept. The main variables in this study are; granular pile material, pile type (floating and end bearing), *L/d* ratio (as 6 and 9), and the area ratio (as Ar=15 and 33%). The details of the tests performed are presented in Table (1).

Table 1: The summary of tests

Test No.	**Test Description**	**Pile properties**							**Mold Dim.**	
		d_p *(cm)*	**Ar *(%)***	**L *(cm)***	**H *(cm)***	**L/H**	**L/d**	**Pile material**	***D_M* *(cm)***	**h_M *(cm)***
1	Soft clay	--	--	--	30	--	--	Without	15	35
2	Soft clay + sand pad	--	--	--		--	--			35
3	Soft clay + sand pad +end bearing pile	5	15	30	30	1.00	6	Basalt		35
4	Soft clay + sand pad + floating pile				60	0.5				65
5					45	0.67				50
6					40	0.75				45
7	Soft clay + sand pad end bearing pile	7.5	33		30	1.00	4			35
8	Soft clay + sand pad + floating pile				60	0.50				65
9					45	0.67				50
10					40	0.75				45
11	Soft clay + sand pad + end bearing pile pile	5	15	30	40	1.00	6	Cr. concrete	15	45
12								Cr. red brick		
13								Cr. ceramic		
14	Soft clay + sand pad floating pile			30	30	0.75		Cr. concrete		35
15								Cr. red brick		
16								Cr. ceramic		
17	Soft clay + sand pad + end bearing pile	7.5	33	30	40	1.00	4	Cr. concrete		45
18								Cr. red brick		
19								Cr. ceramic		
20	Soft clay + sand pad floating pile			30	40	0.75		Cr. concrete		35
21								Cr. red brick		
22								Cr. ceramic		
23	Soft clay + sand pad + floating pile	5	15	30	60	0.75	9	basalt	15	65
24								Cr. concrete		
25								Cr. red brick		
26								Cr. ceramic		

Cr. *= Crushed,* $\boldsymbol{d_p}$ *= Pile diameter, Area ratio* ***Ar*** *=A_P (area pile)/A_T (area total) ,*
L *=Pile length,* ***H*** *=clay Depth,* $\boldsymbol{D_M}$ *=Mold diameter,* $\boldsymbol{h_M}$ *= Mold height*

Properties of Materials

Materials used for this study are clay, aggregates, and sand having the following properties:

Soft clay

Obtaining undisturbed soft clay samples from the site is too difficult. Therefore, the soft clay has been excavated from a construction site, then, prepared in the laboratory. The procedures of preparing soft clay in the laboratory are described in the following section. The soft clay classification is CH according to The United Soil Classification System (USCS).The main properties of the soft clay are shown in Table (2).

Table 2: Main properties of soft clay

Property	**Value**
Water content	45% (±0.5%)
Bulk density	1.79 gm/cm^3
Liquid limit (LL)	62%
Plastic limit (PL)	28%
Plasticity index (Ip)	34%
Cohesion (c)	0.25 Kg/cm^2
Angle of internal friction (ϕ)	$\Phi = 0.5^o$

Aggregates

Three types of recycled aggregates (crushed concrete, crushed ceramics, and crushed red brick), as well as one type of natural aggregate (basalt), were used in this study. The size distribution of the aggregate is ranges between 0.1mm to 1mm (as about one-sixth of the pile diameter) as shown in Fig. (2). The three types of recycled aggregates and the natural aggregate used are well graded as shown in Fig. (2). The angle of internal friction of each type of aggregates has been determined using a direct shear test. The main properties of aggregates which used for granular pile are illustrated in Table (3).

Table 3: Main properties of aggregates

Aggregate	Basalt	Crushed ceramic	Crushed concrete	Crushed Red brick
Angle of internal friction (ϕ)	42.5^{o}	43^{o}	41.5^{o}	39.5^{o}
Specific gravity	2.79	2.3	2.4	2.1
Dry density $_{max}$	1.68	1.37	1.54	1.31
Cu	13.2	11.7	10.16	10
Cc	1.38	2.49	1.35	1.06

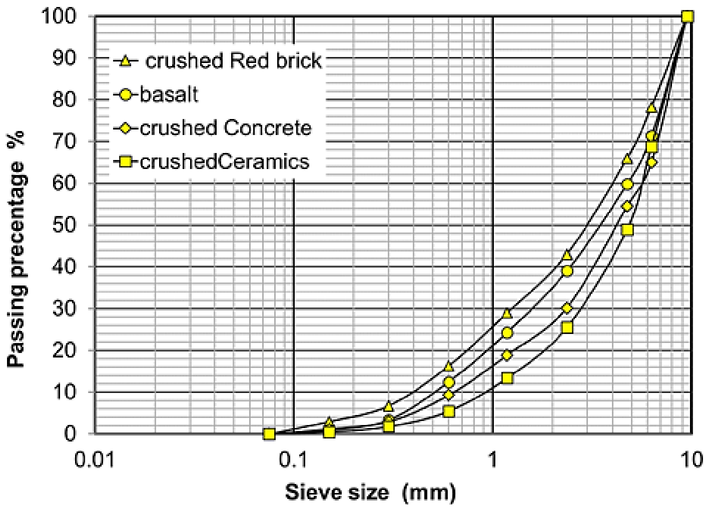


Figure 2: Grain size distribution curve of aggregates and sand

Sand

The sand used is poorly graded sand. The angle of internal friction $=36^{o}$ has been determined using a direct shear test.

Preparation of Laboratory Specimens

An identical technique was used to prepare all the specimens. The clay bed was prepared then, the granular pile was installed as follows.

Preparation of Soft Clay Bed

The soft clay bed was prepared by using a quantity of clay taken from a site under construction. It was drying in oven for 24 hours (at 105-110 °C) and pulverized. The clay was sieved through sieve No. 200 (0.074mm). Then; it is stored in plastic barrels' court closures. After that, the clay was mixed with a measured quantity of water to achieve a required water content of 45% to provide shear strength of 0.25 kg/cm^2. A mechanical mixer was used for well kneaded of clay sample. Four polypropylene molds of 150 mm diameter and various heights were used. The inner surface of each mold wall was covered with a very thin polyethylene sheet over a thin coat of grease that was applied to reduce the friction between the clay and the tank wall. Soft clay soil was filled in the tank with layers of 50 mm thick with a measured quantity by weight, then, compacted to achieve 1.79 t/m^3 density. Molds kept covered for 24 hours to achieve uniform consistency. After 24 hours of hydration, the soil is checked for water content. The proposed height of soft clay in the mold is lower than the mold heights by about 5 cm to put a 3cm sand pad after pile installation.

Granular Pile Installation

Before installation of the piles, shear strength of the prepared bed was checked by vane shear test. Granular piles were installed by the replacement technique. An open-ended seamless PVC pipe of required outer diameter having a 2.0mm wall thickness was pushed into the clay at the required place to a depth of 1/5th of the total required length of the pile then, soft soil was taken from inside of the pipe. After taking out the soil, the pipe was pushed further to the same depth as before and soil was again taken out in the same way. The process was repeated till the required depth of the pile was achieved. The aggregate particles were then poured into the hole in 50 mm thick layers, then compacted as the pipe was withdrawn in stages of 50 mm. Compaction was given with a 2kg circular steel temper with 10 blows of 100 mm drop to each layer. The molds covered with plastic sheet, then, left for 24 hours to ensure the homogeneity between clay and the pile. Steps of pile installation are illustrated in Fig. (3).

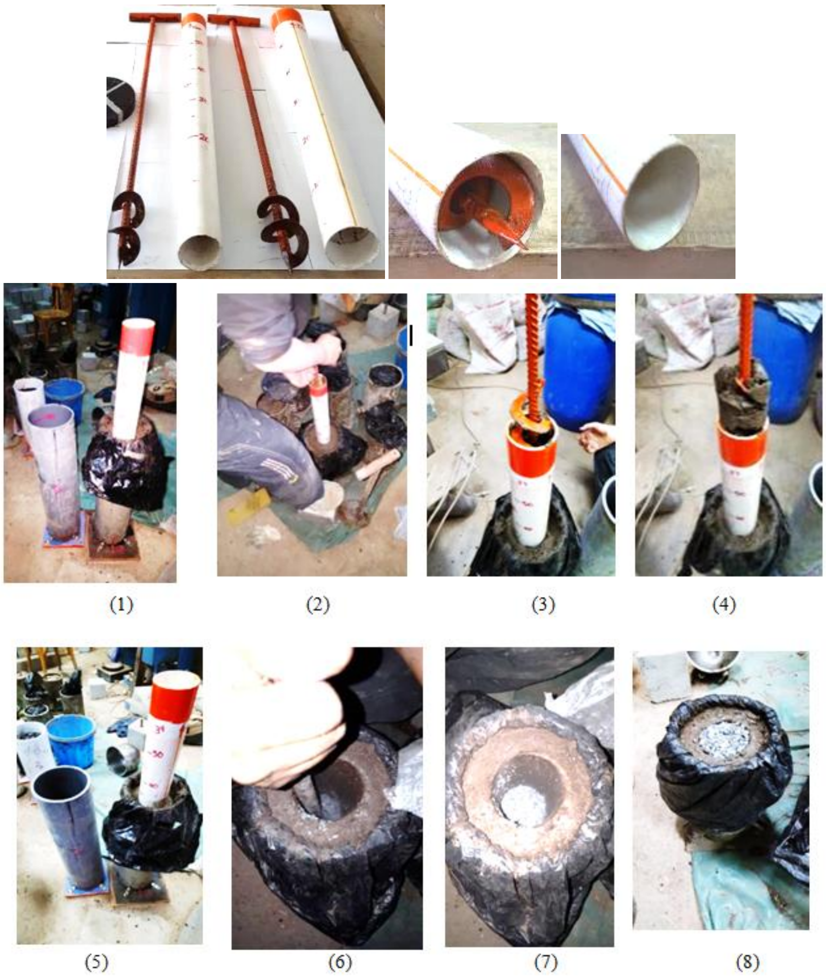


Figure 3: Steps of pile installation and the PVC pipes

Test Procedures

After installation of granular pile, A sand layer of 30 mm thickness was placed on the top of the sample as sand cushion. After that, the samples were loaded through a circular steel footing of 130 mm diameter and thickness equal 20 mm. The load applied through a proving ring of 7 KN capacity. The load increments are 10 kg for each interval. The settlement of the footing is recorded by means of two dial gauges set on the footing. The load increment is done after obtaining the steady condition of the reading of the dial gauge. The increment of load on the footing is continued until settlement equal 0.2B. A complete test set up an arrangement and schematic view of typical granular pile foundation for test has been shown in Fig. (4).

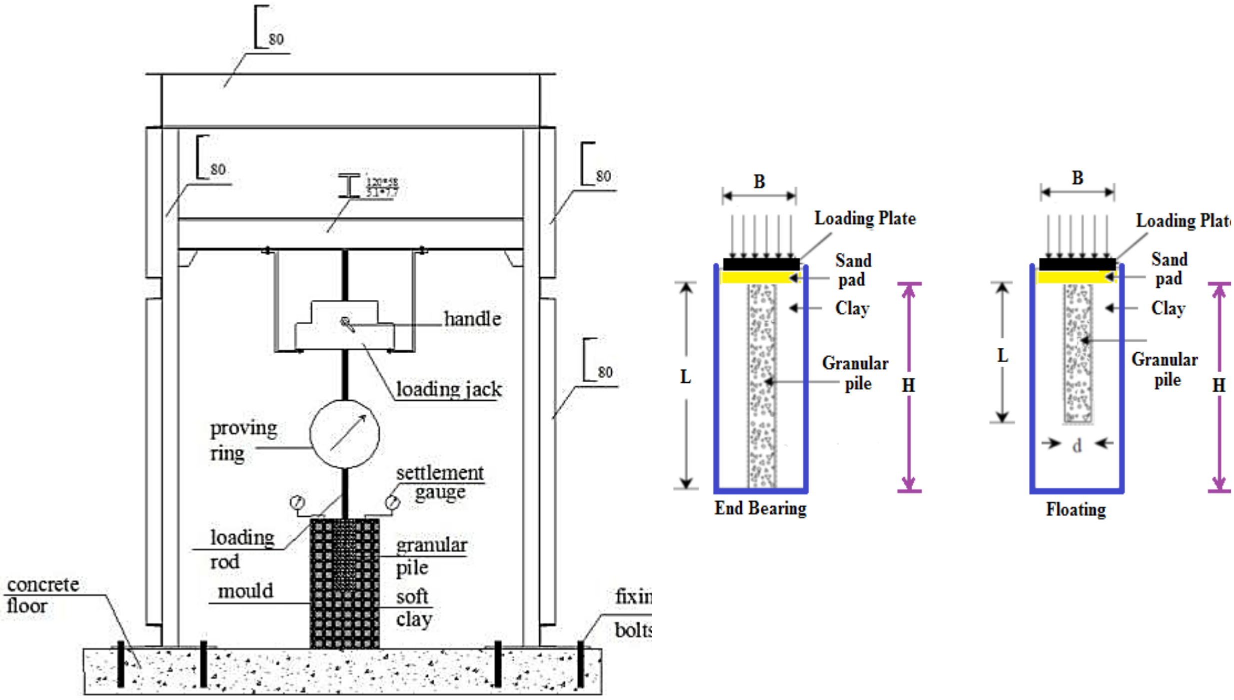


Figure 4: Loading system and Laboratory test setup

Results and Discussion

A laboratory model tests were conducted to investigate the effect of reinforcing soft clay soil by using floating granular piles. A typical load-settlement response of all tests is obtained. There is no observed failure load as identified that the soft soil follows the punching failure mode, which is characterized by no peak failure point or potential surface heave. As there is no observed failure, it is necessary to define the ultimate load value from the test data. So, the 0.1B method was used to determine the ultimate load.

Effect of Using Sand Pad

It can be observed that the load-settlement curves of the soft clay and the soft clay with sand pad are nearly the same up to a settlement nearly equal 3%B.Beyond this ratio, the sand pad starts to influence significantly as shown in Fig. (5). Using a sand pad increases the ultimate load by about 25%. This could be attributed to that the sand pad is stronger and stiffer than soft clay only. Using a sand pad helps in redistributing vertical pressures over a larger area, and minimizing settlements and stress concentration which satisfies previous researches [14-15].

Effect of L/H ratio

Based on Figs. (6) and (7), increasing the ratio of pile length to the thickness (L/H) of the clay deposit leads to improve the load carrying capacity of the soft clay soil. At any specific settlement, the load in case of reinforced soft clay with granular pile is higher than that of the corresponding load in case of clay with sand pad for all used area replacement ratios. Results indicated that the more (L/H) ratio, the more load carrying capacity for different area replacement ratios. This is attributed to adequate mobilization of skin resistance and end bearing capacity through the increase in peripheral area and overburden pressure.

The ultimate load increased by about 12%, 19%, 27%, and 49% for L/H = 0.5, 0.67, 0.75, and 1, respectively, for area ratio Ar =15% compared to clay with sand pad as shown in Figs. (6) and (7). At area ratio Ar=33%, the ultimate load increased by about 20%, 26%, 37%, and 51% for L/H = 0.5, 0.67, 0.75, and 1, respectively compared to clay with sand pad.

As the length of the pile increased, the ultimate load increases and the settlement decreases for end bearing piles than for floating piles with different L/H ratios for all area replacement ratios used. The behavior of floating granular pile with L/H = 0.75 nearly similar to that recorded for the end bearing pile. Any increase in the granular pile length causes an increase in the ultimate load with all area replacement ratios. When increasing the pile length from L/H = 0.75 (floating pile) to L/H = 1 (end bearing pile), the increase in the ultimate load is about 22% and 14% for Ar=15% and Ar=33%, respectively compared to unreinforced clay with sand pad.

From Figs. (8) to (15), it can be observed that the end bearing granular piles has the best performance in reducing the settlement values and by increasing the ultimate load carrying capacities. The settlement values of the floating pile with L/H = 0.75 closed to those of the end bearing pile for all granular pile materials used and for all area replacement ratios used.

The ultimate load of end bearing granular piles with basalt, crushed ceramic, crushed concrete, and crushed red brick increased by about 22%, 22%, 13%, and 12%, respectively, compared to the floating piles with the same granular pile materials (at Ar=15%). When using Ar=33%, the ultimate load of end bearing granular piles with basalt, crushed ceramic, crushed concrete, and crushed red brick increased by about 14%, 14%, 8%, and 9%, respectively compared to the floating piles with the same granular pile materials. The ratio of L/H = 0.75 is suggested as a better L/H ratio (in the range of this study). Results satisfy the previous studies conducted by Elsawy and El-Garhy, 2016 [**21**].

Effect of the Pile Material

Using granular piles with different materials, as soft clay reinforcement leads to a noticeable improvement in the ultimate load of the soft clay soil as shown in Figs. (16) to (20). At any specific settlement, the ultimate load of reinforced soft clay with granular pile is higher than that of the clay with sand pad for different replacement ratios whatever the pile is floating or end bearing *(in the range of this study)*.

When considering the effect of using each material as granular pile material, in the case of using basalt, the ultimate load increased for Ar=15% and 33% by about 49% and 53%, respectively, for end bearing pile and increased by about 27% and 37% for the floating piles (with L/H = 0.75), respectively compared to the clay with sand pad.For crushed ceramic piles, the ultimate load of end bearing piles increased by about 64% and 67% for Ar=15% and 33%, respectively, while the ultimate load of the floating pile increased by about 42% and 53% for Ar = 15% and Ar = 33%, respectively. For end bearing crushed concrete piles, the ultimate load increased by about 33% and 37%, corresponding to Ar=15% and 33%, respectively, while for the floating crushed concrete piles with L/H = 0.75, the ultimate load increased by about 20% and 29% for Ar=15% and 33%, respectively. The ultimate load of end bearing crushed red brick piles increased by about 18% and 20% for Ar=15% and 33%, respectively, while for the floating crushed red brick piles of L/H = 0.75, load increased by about 6% and 12% for Ar = 15% and Ar = 33%, respectively.

All suggested granular pile materials performed efficiently with suitable behavior to be used as granular pile materials to reinforce the soft clay soil.

Effect of Area Replacement Ratio

Increasing the replacement ratio leads to improve the ultimate load of the soft clay soil as shown in Figs. (21) to (28). Increasing the area replacement ratio from Ar =15% to Ar =33% improves the ultimate load of end bearing basalt piles by about 2%. Also, it increases by about 10% for floating basalt piles (with L/H = 0.75).The ultimate load of crushed ceramic piles increased by about 3% and 11% for end bearing and floating crushed ceramic piles, respectively compared to Ar =15%. Also, the same were obtained for the end bearing crushed concrete piles which recorded an increment of about 4% compared to Ar = 15%. The ultimate load increased by about 9% for floating crushed concrete piles. The ultimate load of end bearing crushed red brick piles increases by about 2% for Ar = 33% compared to Ar = 15%. For floating crushed red brick piles (with L/H = 0.75), it increases by about 6% compared to Ar = 15%. This increase is due to increase the skin resistance and end bearing capacity through the increase in peripheral area and overburden pressure.

Effect of the Slenderness Ratio

It has been observed that for all granular piles with different slenderness ratios, the ultimate load of the soft soils improved. When L/d ratio is small (specimens containing short piles), the ultimate load is high. As this ratio increased, load of specimen decreases. When L/d ratio increased to 9, granular piles of basalt, crushed ceramic, crushed concrete, and crushed red brick improves the ultimate load by about 15%, 24%, 7%, and 4%, respectively compared to the clay with sand pad as shown in fig.(20), while the ultimate load of floating piles (with L/d = 9) with basalt, crushed ceramic, crushed concrete, and crushed red brick as granular pile materials decreases by about 12%, 18%, 13%, and 2%, respectively compared to results recorded for those with L/d = 6 at the same area ratio of Ar =15%.As shown in Figs. (29) to (32). When the L/d ratio increased to 9, the bulging failure takes place due to the increase in slenderness ratio and the granular pile offer little significant improvement. This is because the additional resistance due to the increase in length remains immobilized due to the excessive bulging of the top of the granular pile. Due to the excessive bulging, the granular pile materials lose their interlocking properties and continue to deform at their residual strength leading to no significant additional performance.

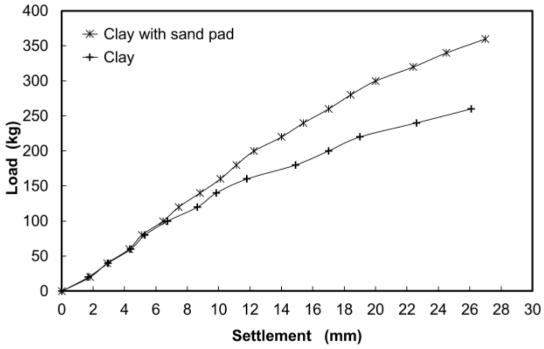


Figure 5: Effect of sand pad on the load - settlement relationship.

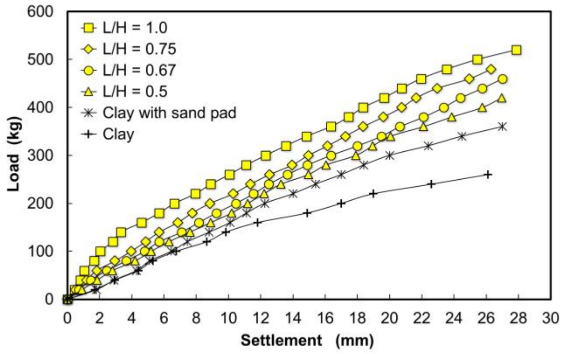


Figure 6: Effect of basalt pile length corresponding to soft clay depth on the load - settlement relationship. (Ar=15%).

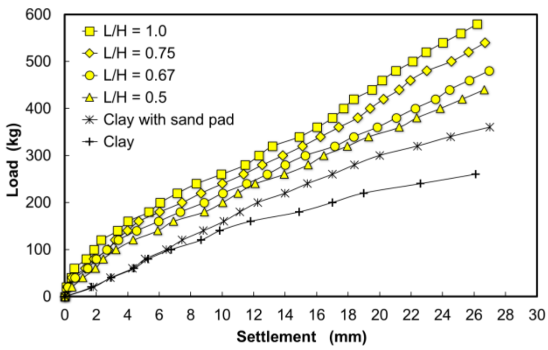


Figure 7: Effect of basalt pile length corresponding to soft clay depth on the load - settlement relationship. (Ar=33%).

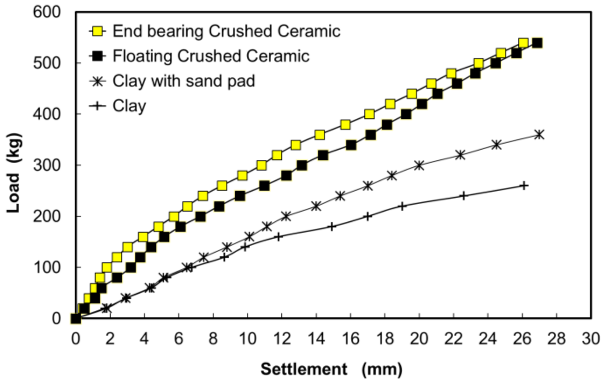


Figure 8: Effect of pile type on the load - settlement relationship in case of using crushed ceramic pile (Ar=15%).

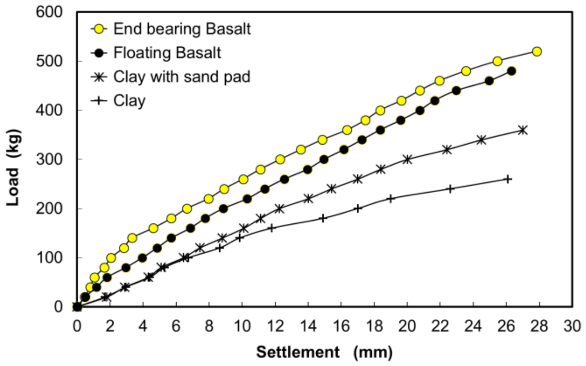


Figure 9: Effect of pile type on the load - settlement relationship in case of using basalt pile (Ar=15%).

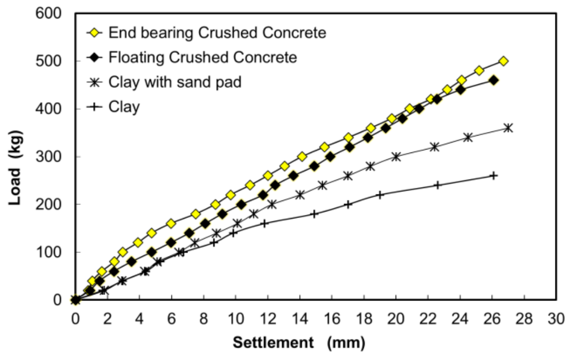


Figure 10: Effect of pile type on the load - settlement relationship in case of using crushed concrete pile (Ar=15%).

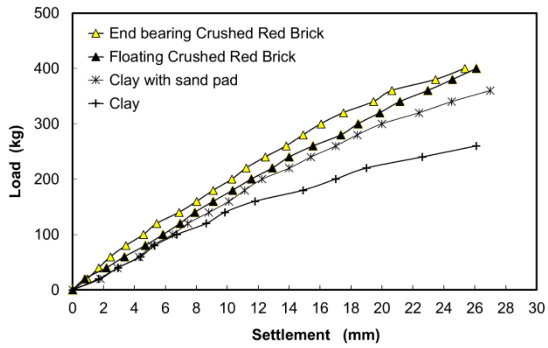


Figure 11: Effect of pile type on the load - settlement relationship in case of using red brick pile (Ar=15%).

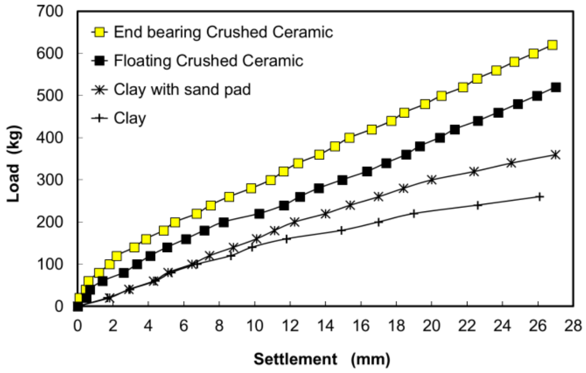


Figure 12: Effect of pile type on the load - settlement relationship in case of using crushed ceramic pile (Ar=33%).

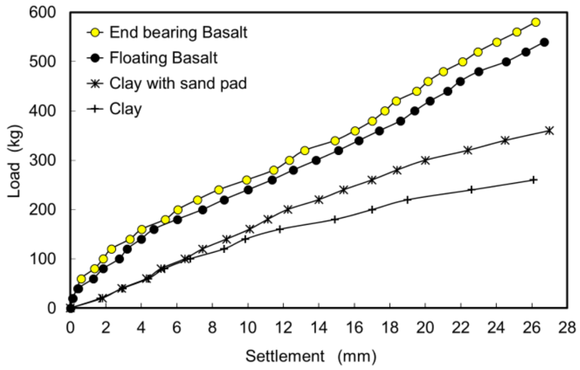


Figure 13: Effect of pile type on the load - settlement relationship in case of using basalt pile (Ar=33%)

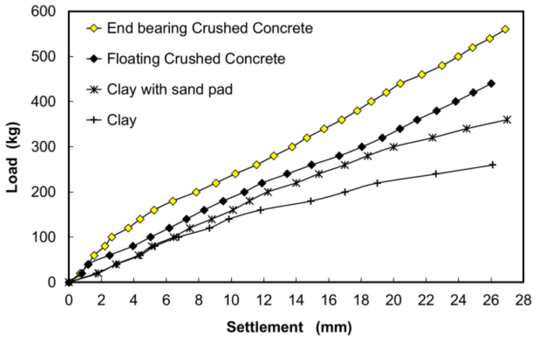


Figure 14: Effect of pile type on the load - settlement relationship in case of using crushed concrete pile (Ar=33%).

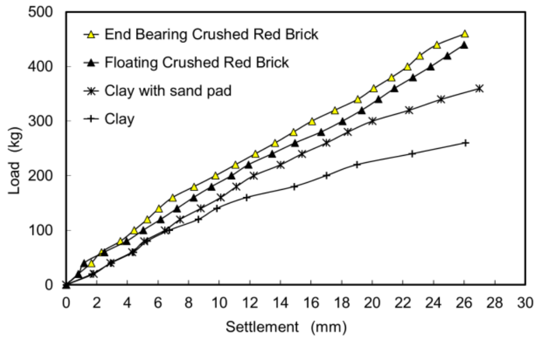


Figure 15: Effect of pile type on the load - settlement relationship in case of using crushed red brick pile (Ar=33%).

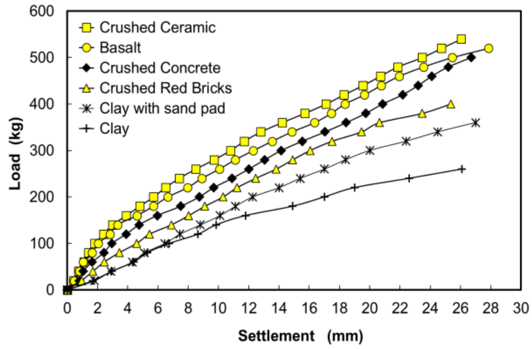


Figure 16: Effect of pile material on the load - settlement relationship in case of using end bearing pile (Ar=15%).

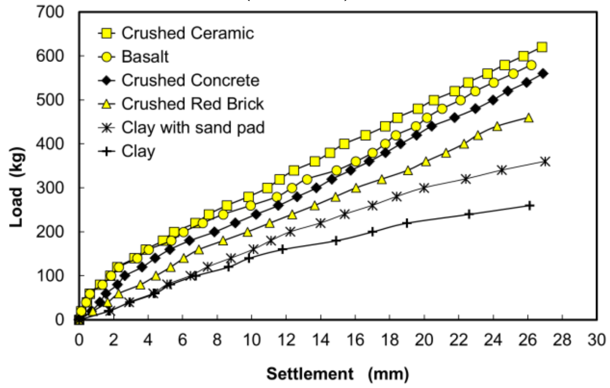


Figure 17: Effect of pile material on the load - settlement relationship in case of using end bearing pile (Ar=33%).

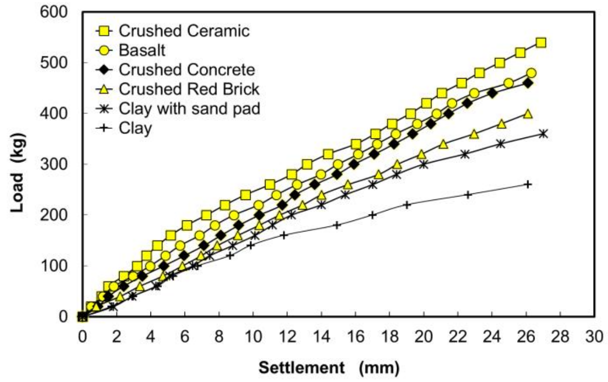


Figure 18: Effect of pile material on the load - settlement relationship in case of using Floating pile (Ar=15%).

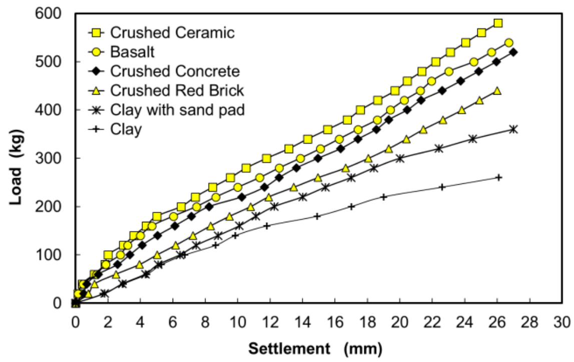


Figure 19: Effect of pile material on the load - settlement relationship in case of using Floating pile (Ar=33%).

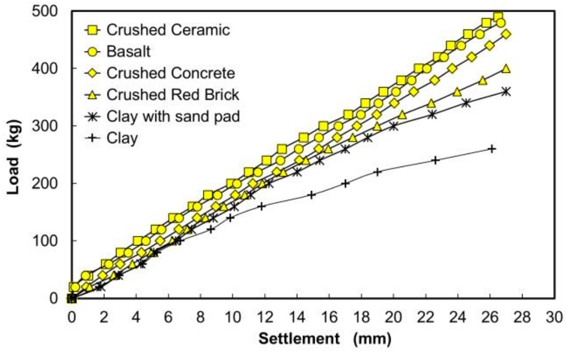


Figure 20: Effect of pile material on the load - settlement relationship in case of using Floating pile (Ar=15%, L/d=9, L=45cm).

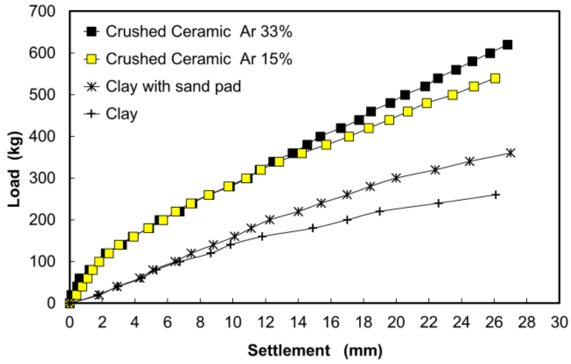


Figure 21: Effect of (Ar) on the load - settlement relationship in case of using end bearing crushed ceramic pile.

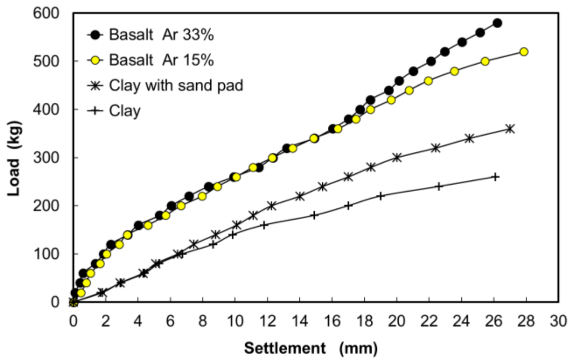


Figure 22: Effect of (Ar) on the load - settlement relationship in case of using end bearing basalt pile.

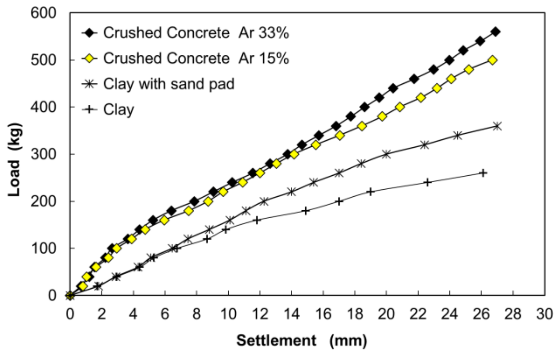


Figure 23: Effect of (Ar) on the load - settlement relationship in case of using end bearing crushed concrete pile.

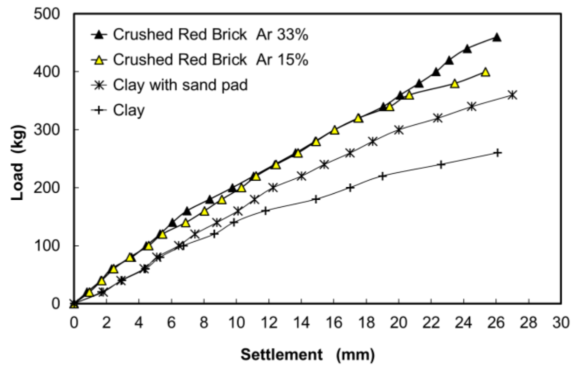


Figure 24: Effect of (Ar) on the load - settlement relationship in case of using end bearing crushed red brick pile.

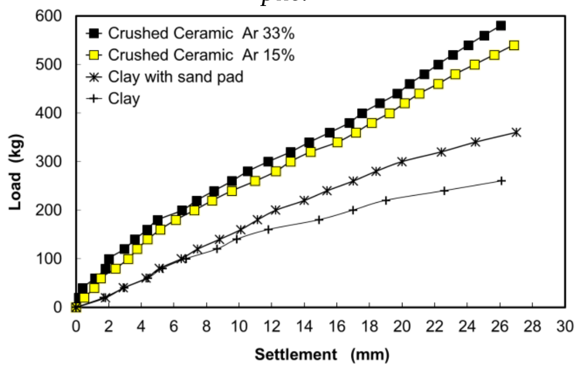


Figure 25: Effect of (Ar) on the load - settlement relationship in case of using floating crushed ceramic.

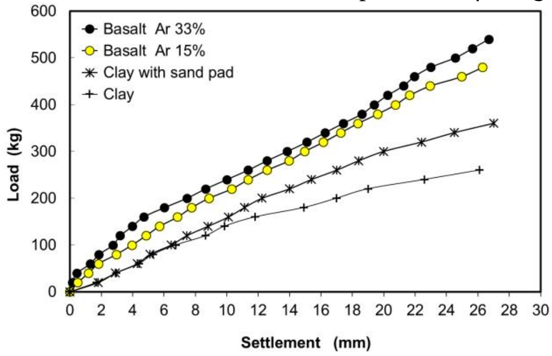


Figure 26: Effect of (Ar) on the load - settlement relationship in case of using Floating basalt pile

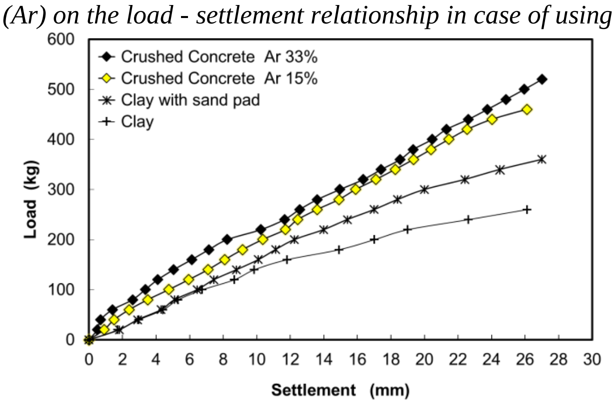


Figure 27: Effect of (Ar) on the load - settlement relationship in case of using floating crushed concrete pile.

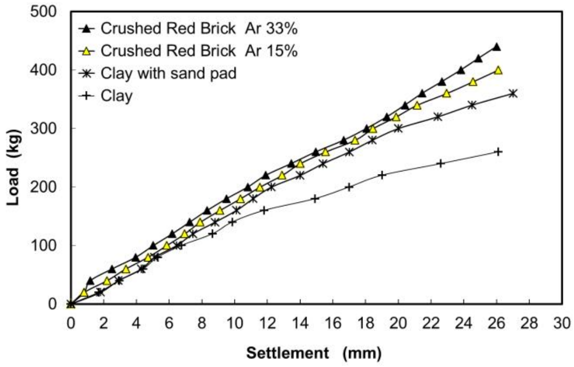


Figure 28: Effect of (Ar) on the load - settlement relationship in case of using floating crushed red brick pile.

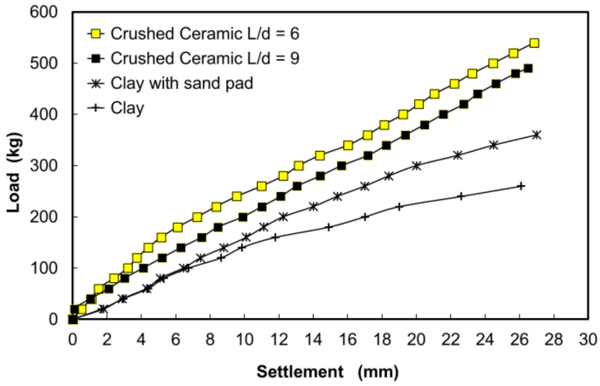


Figure 29: Effect of slenderness ratio on the load - settlement relationship in case of using floating crushed ceramic pile (Ar=15%).

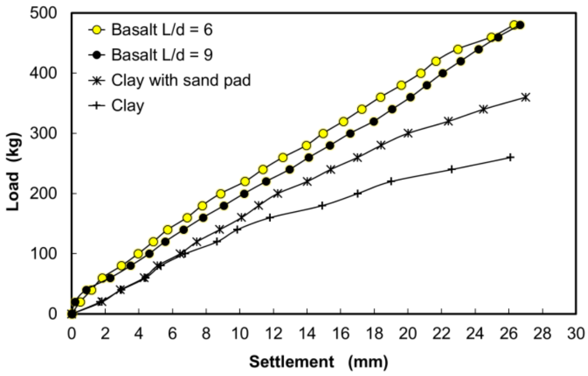


Figure 30: Effect of slenderness ratio on the load - settlement relationship in case of using Floating basalt pile (Ar=15%).

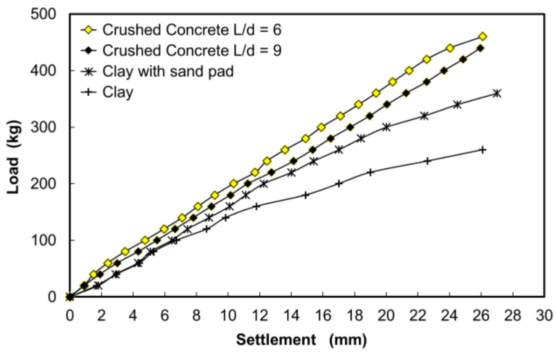


Figure 31: Effect of slenderness ratio on the load - settlement relationship in case of using floating crushed concrete pile (Ar 15%).

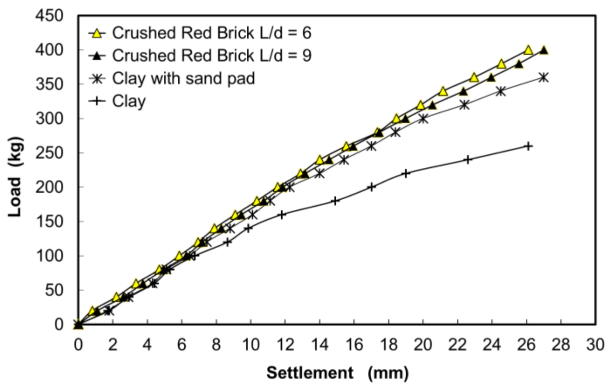


Figure 32: Effect of slenderness ratio on the load - settlement relationship in case of using floating crushed red brick pile (Ar=15%).

Conclusions

Experimental investigations were carried out to study the behavior of soft clay soil reinforced by granular piles using different materials. Load tests were conducted on soft clay soil reinforced with granular piles using the unit cell concept. Floating granular piles were compared to end bearing granular piles. Based on those tests, the following conclusions can be drawn:

- Using a sand pad reduces the settlement and increases the ultimate load of soft clay soil.
- The case of end bearing granular pile has the best performance in reducing the amount of settlement and increasing the load carrying capacity of soft clay soil at different replacement ratios.
- Using a floating granular pile with L/H = 0.75 is nearly close to end bearing granular pile in reducing settlement.
- For all suggested granular pile materials used, the ultimate load improves compared to clay without reinforcement.
- Granular piles using recycled aggregates can be successfully used to improve the ultimate load and to decrease the settlement of soft clay soil beds. Using crushed ceramic is the most efficient then using crushed concrete and finally using crushed red brick.
- Increasing the area replacement ratio improves the ultimate load of soft clay soil, especially in case of the floating granular pile (*in the range of this study*).

Finally, it can be concluded that using floating granular piles of L/H = 0.75 is efficient enough compared to using end bearing piles from the economic point of view. Also, using recycled aggregates as a material for granular piles in soft clay soils is efficient as well as natural aggregates *(in the range of this study)*.

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