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Experimental Investigation of Strip Footings on Weak Clay with a Granular Trench

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ABSTRACT

The necessity for moderate improvements in the stress-strain behavior of soft soil is common in geotechnical engineering. One effective method for stabilizing such soil involves the installation of a granular trench. This experimental study examines the performance of strip footings supported by granular trenches in soft soil, focusing on the effects of trench size, shape, and the friction angle of the trench material on bearing capacity and settlement. Results indicate that a significant enhancement in bearing capacity, up to four times, and a settlement reduction of approximately 54% were achieved when the trench depth and width were 4 and 2.5 times the footing width, respectively. Beyond these dimensions, improvements in load-bearing capacity and reductions in settlement became negligible. It was also observed that the greatest settlement reduction occurred when trench sides were inclined outward by 30º from the vertical, whereas the maximum bearing capacity improvement was noted with vertical trench sides. The friction angle of the trench material had a substantial impact on settlement and a moderate effect on bearing capacity. This investigation provides valuable insights for optimizing granular trench design to enhance the performance of strip footings on weak clay.

1. INTRODUCTION

Along with the rapid growth of new construction in limited urban areas in large cities around the world, construction on soft, weak soils is inevitable. Such soils, in many situations, can be considered problematic because they result in low bearing capacity and high compressibility. In the last decades, many treatment techniques have been suggested and developed to enhance the load-settlement characteristics of soft soils, such as soil stabilization (i.e., mechanical, admixture, hydraulic, thermal, and biological), soil reinforcement (i.e., inclusion of geosynthetics, piling, stone columns, and nailing), and substitution of problematic soils with non-problematic soils [1-3]. Various factors may control and affect the selection of the suitable treatment technique for the soft soil in the field, such as time of treatment, cost, environment, material availability, required equipment, the availability of experience, and skilled local labor.

One of the most commonly used techniques to improve the load-settlement behavior of the soft soil, due to its simplicity and cost-effectiveness, is to use granular piles, which serve as stiffness elements while accelerating the dissipation of excess pore water pressure in a short period of time. A granular trench is a specific instance of a two-dimensional plane strain variation of granular piles. In this situation, a layer of densely packed granular material is laid on top of the soft soil layers to serve as a sturdy foundation. Various analytical, numerical, and experimental studies have investigated the enhancement in bearing capacity of foundations using the granular trench technique. The pioneering work on this topic was presented in 1978 by Madhav and Vitkar [4], who employed the upper bound kinematic approach to suggest a theoretical solution to estimate the bearing capacity of a strip footing on weak soils improved by a granular trench. Hamed [5] performed a series of experimental tests on a small model of strip footings on soft clay improved by a sand trench. The effects of the sand trench and the footing width on bearing capacity were studied. It was reported that the maximum improvement in bearing capacity was obtained at a trench depth of 2.5 to 3 times the footing width, and the improvement was considered insignificant afterwards. Michalowski and Shi [6] employed the kinematic limit approach to examine the enhancement in the load-bearing capacity of clay reinforced by a granular trench. The results showed that the bearing capacity could not be further improved at a critical thickness, which is the ratio of the granular trench depth to the width of the footing. Artificial neural network analysis was adopted by Ornek et al. [7] to estimate the load-bearing capability of circular footings on soft clay reinforced with a granular fill. The findings revealed that the thickness of the granular fill and the dimensions of the footing are the primary factors influencing the enhancement of bearing capacity. Ornek et al. [8] investigated numerically the scale effect and the behavior of circular footings resting on natural clay stabilized with granular fill. The results showed that increasing the thickness of the granular fill up to two times the footing diameter increased the bearing capacity to its maximum value. Ibrahim [9] conducted field loading tests and used the finite element tool PLAXIS to perform numerical computations. The purpose was to examine the bearing ability of a circular foundation on granular soil situated above soft clay. The relationship between the bearing capacity and the depth of the granular layer was demonstrated. Nevertheless, in the case of small-sized footings, the increase in bearing capacity is considered insignificant when the depth of the granular material exceeds twice the width of the footing. For large surface footings, the improvement in performance is observed up to a depth of four times the width of the footing. In the case of embedded footings, this improvement is observed up to a depth of six times the width of the footing. Abhishek et al. [10] proposed a theoretical method to calculate the bearing capacity of a strip footing on cohesive soil reinforced by a granular trench. The researchers determined that the angle of friction has a greater impact on improving the bearing capacity compared to the breadth of the granular trench. Fattah et al. [11] conducted a series of experiments to explore the increase in the load-bearing capacity of shallow footings on soft clay using the approach of partial soil replacement. According to their statement, the greatest increase in bearing capacity can be attained when the width and depth of the trench are equivalent to 2 and 1.5 times the width of the footing, respectively. Kumar and Chakraborty [12] used finite element analysis to investigate the behavior of circular foundations on layered sand-clay media. The results indicated that there is an optimum depth of sand fill thickness for each value of $c_u/\gamma.B$, where c_u is the clay shear strength, γ is the clay density, and B is the foundation diameter. The optimum depth of sand fill thickness increases with an increase in the internal friction angle. On the other hand, it decreases with an increase in the $c_u/\gamma.B$ ratio. In 2017, Bhattacharya and Kumar [13] employed a hybrid approach involving lower bound plane strain and axisymmetric limit analysis, finite elements, and an optimization process to investigate the load-bearing capability of foundations on soft clay with granular columns and trenches. The enhancement in bearing capacity was evaluated using a non-dimensional metric called the efficiency factor (EF), which represents the ratio of the bearing capacity of the better ground to that of the non-improved ground. The study results demonstrate that the enhancement in bearing pressure is directly proportional to the increase in trench width, depth, and internal friction angle of granular materials. However, the improvement in bearing capacity diminishes as the ratio of cohesion to unit weight multiplied by trench width ($c_u/\gamma.B$) grows. The findings derived by Bhattacharya and Kumar [13] are highly consistent with those documented by Kumar and Chakraborty [12]. Ranjbar and Golshani [14] conducted a numerical analysis to examine how the depth of the granular trench affects the bearing capacity of shallow strip foundations on soft ground. The results demonstrate that the bearing capacity increased by 80% when the depth of the granular trench was five times the width of the footing. Chua and Nepal [15] suggested a novel method using finite elements to create design charts for calculating the bearing capacity of strip footings on a geogrid-stabilized granular layer atop cohesive soil.

It should be mentioned that most of the previous studies have contributed to the theoretical understanding of the bearing capacity of strip footings on soft clay improved by granular trenches. However, experimental studies are limited on this topic, and there is still no consistency on which depth and width of the granular trench are the optimum values. In addition, although it is difficult to achieve a vertical trench in most of the cases in practice and the trench has to be inclined outward from the footing, the effect of a sloping trench has not been considered in any of the previous studies. Therefore, this study aims to determine the effect of the shape and dimensions of the granular trench and the relative density of granular materials on both the bearing capacity and the settlement experimentally, thereby addressing the aforementioned gaps in the literature. Therefore, a series of experimental laboratory tests were performed on a strip footing model rested on soft clay supported by a granular trench at various shapes, dimensions and relative densities. After presenting and discussing the obtained results, the main findings and conclusions were summarized in this study.

2. LABORATORY MODEL TESTS

2.1 Test box and footing model

The experiment in this study aims to investigate the stress-strain behavior of strip footings rested on soft clay soil stabilized with a granular trench. The apparatus used in this investigation mainly includes a steel box, a steel horizontal beam over the box, a loading system, and a steel footing model. The rigid steel box, with dimensions of 1200 mm×1200 mm ×1000 mm (width×length×depth), was used to carry out a total of 61 experimental tests of the strip footing model on clay improved by a granular trench. In order to maintain plane strain conditions, a steel plate of 4 mm thickness was used to build the test box, with all faces welded to accommodate the soil and minimize any plane displacement. All the inside surfaces of the steel box were polished smoothly by a sand block to minimize as much friction with the soil as possible. The horizontal beam was braced to two steel columns which are fixed to the laboratory ground by several bolts. The main roles of the horizontal beams are to carry and support the loading system. The loading system consists of two parts: a hand-operated hydraulic jack and a proving ring. The load is applied through a loading shaft centered on a platform with nine legs to transfer the load to the footing model at a constant rate of 1.0 kPa per second. The platform legs transfer the load through nine bearing balls placed on the footing model's upper surface at grooved points. Three dial gauges with a precision of 0.001 mm were mounted on the footing model's upper surface and fixed to the steel box wall by a magnetic connector to measure the settlement during each test. A plane strain footing with dimensions of 1200 mm in length and 150 mm in width was used in this study as a footing model. Three rows of grooves were made on the top surface of the footing model to accommodate bearing balls. The bottom face of the footing model was treated with epoxy glue and rolled in rough sand to achieve a rough base condition in the experimental tests. The steel footing model used in this study has a yield strength of 250 MPa, an ultimate tensile strength of 450 MPa, an elasticity modulus of 200 GPa, and a density of 7850 kg/m^3. A schematic view of the experimental apparatus is shown in Figure 1.

2.2 Test materials

The trench granular material utilized in this investigation is categorized as well-graded gravel (GW) according to the Unified Soil Classification System (ASTM D2487) [16]. The material was washed, dried, and sorted based on particle size. The well-graded gravel consists of 60% gravel, 37% sand, and 3% silt and clay. Figure 2 displays the grain size distribution of the granular material utilized. The effective diameter (D_{10})

is 0.72 mm, the coefficients of uniformity (C_u) and curvature (C_c) are 9.0 and 2.6, respectively, and the specific gravity (G_s) is 2.62. Table 1 provides a summary of the further physical characteristics of the material found in the trench. The cohesive soft soil utilized in this study is categorized as lean clay (CL), and its particle size distribution is illustrated in Figure 3. The weakly cohesive soil consists of 12% sand, 61% silt, and 27% clay. The specific gravity (G_s) of 2.71, the liquid limit (LL) of 41% and the plasticity index (PI) of 18.5% were found, respectively. Additional attributes are displayed in Table 2.

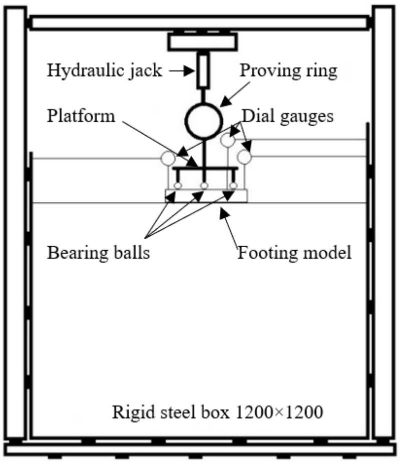

Figure 1. Schematic layout of the laboratory model apparatus (not to scale)

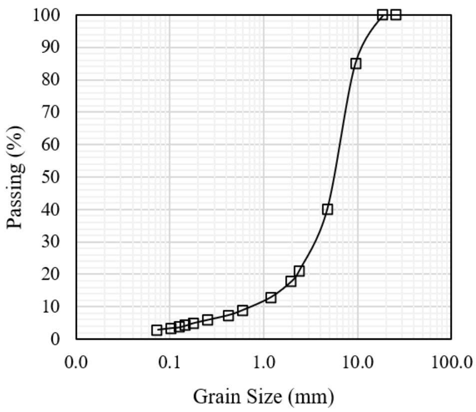

Figure 2. Particle size distribution of the granular material used in the tests

Table 1. Properties of the granular material used in the tests

Property	Value	Value	
Gravel		60	
Sand		37	
Silt and clay		3	
Effective diameter (D_{10})		0.72 mm	
Coefficient of uniformity (C_u)		9.0	
Coefficient of curvature (C_c)		2.6	
Specific gravity (G_s)		2.62	
Minimum density		15.4 kN/m^3	
Maximum density		21.21 kN/m^3	
Relative density (R_d)	40%	58%	80%
Dry density	17.30 kN/m^3	18.31 kN/m^3	19.72 kN/m^3
Residual angle of internal friction	33.2°	37.5°	41.2°

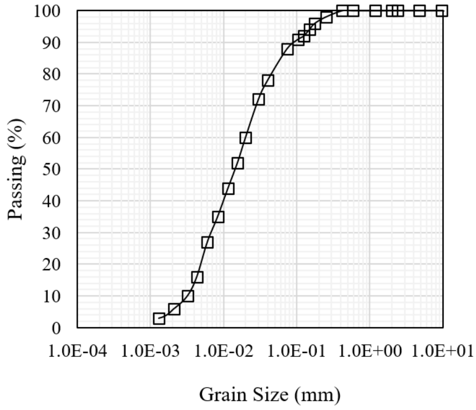

Figure 3. Particle size distribution of the cohesive soil used in the tests

Table 2. Properties of the cohesive, soft soil used in the tests

Property	Value
Gravel	00.0
Sand	12.0
Silt	61.0
Clay	27.0
Specific gravity (G_s)	2.71
Maximum dry density	16.8 kN/m^3
Optimum moisture content	14.5%
Natural moisture content	27.4%
Liquid limit (LL)	41%
Plasticity index (PI)	18.5%

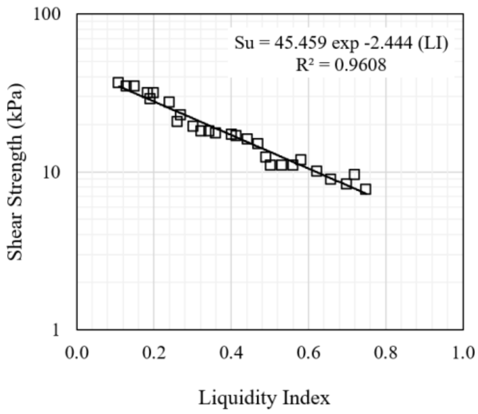

Figure 4. Correlation of the shear strength and the liquidity index of the cohesive soft soil

According to the proposal by Wroth and Wood [17] and Kuriakose et al. [18], a series of tests were conducted to determine the connection between the shear strength of clay and its water content. These tests aim to establish the correlation between shear strength and liquidity index (LI), as depicted in Figure 4. In this study, the presented correlation was utilized to determine the optimal water content percentage necessary to attain the desired shear strength of the cohesive soil beds.

3. PREPARATION OF THE TEST MATERIALS

The clay beds were prepared by pouring the cohesive soil in layers at a moisture content value of 31.19%. This moisture content was calculated and specified from a liquidity index value of 47%, which was drawn with respect to the previous correlation shown in Figure 4 to represent a clay shear strength of 15 kPa. This shear strength value was obtained to represent the soft clay condition in the field. However, the soil was divided into five layers, with each layer having a depth of 200 mm. It is worth mentioning that the soil was prepared in three stages (drying, crushing, and pulverizing). In the first stage, the soil was dried in an oven at a temperature of 110°C until a constant weight was reached. In the second stage, the soil was crushed into smaller pieces using a jaw crusher. Then the crushed soil was ground into a fine powder using a mechanical pulverizer. Finally, the appropriate quantity of water was incorporated to be mixed with the soil according to Eq. (1):

$$w_w = \frac{w_S . w_c}{1 - w_c} \quad (1)$$

where, w_w is the amount of water required to be added to the soil amount (w_s) to achieve a moisture content (w_c).

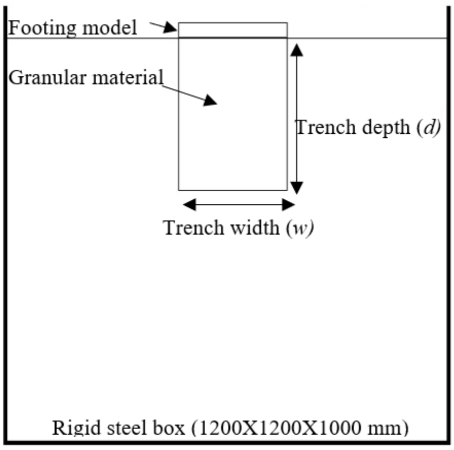

Figure 5. Schematic layout of the granular trench under the footing model

Moreover, several vane-shear tests were conducted to check if the targeted shear strength of the clay was achieved. Regarding the granular trench preparation, the clay soil was removed from the center of the testing box in a careful manner until the required width and depth were reached. Then the granular soil was filled into the trench in layers. A vibratory technique was used to compact the soil layer in the trench. This technique consists of a small vibrator, which was used to apply a uniform vibrator to a stiff, thin steel plate for each sand layer for a manipulated duration to achieve the target relative densities of 0.40 (loose soil), 0.58 (medium-dense soil), and 0.80 (dense soil). To achieve the relative density in question, three small, known-volume aluminum cups were placed randomly in each layer for all tests to measure the relative density. However, the granular material layers were compacted in layers of 50 mm until reaching the desired elevation. In the final preparation step, the hydraulic jack was used to apply an incremental load until failure was reached. The settlement of the footing model was recorded in a careful manner for each load increment after stabilization was reached. A schematic layout of the granular trench under the footing model on the cohesive soft soil is displayed in Figure 5.

4. TESTING PROGRAM

An extensive experimental program of 61 tests was carried out to investigate the behavior of a strip footing on soft clay beds reinforced with a granular trench. The tests include four series, as shown in Table 3. Initially, the first series includes the response of the model footing supported on a soft clay bed without any granular trench.

Table 3. Test program

Series	Constant Parameters	Variable Parameters
1	No trench	S_u=15 kPa
2	S_u=15 kPa, R_d=80%	d/B=1.0, 2.0, 3.0, 4.0, 5.0, 6.0 w/B=1.0, 1.5, 2.0, 2.5, 3.0, 3.5
3	S_u=15 kPa, d/B=2.0, w/B=1.0	λ=10°, 30°, 45°, 60° R_d=80%, 58%, 40%
4	S_u=15 kPa, w/B=1.0	d/B=1.0, 2.0, 3.0, 4.0, 5.0, 6.0 R_d=58%, 40%

Note: λ is the inclination angle of the trench sides from the vertical

The second test series was performed to investigate the effect of the granular trench geometry (width and depth) at a relative density of 80% of the granular material for strip footing models resting on soft clay beds. Two variable parameters, w and d, were expressed non-dimensionally as a function of footing width (B), denoted as w/B and d/B, respectively, to describe the width and depth of the trench. In the second series, only vertical granular trenches were considered. The third series was conducted to study the effect of the granular trench inclination on the stress-strain behavior of strip footing models resting on soft clay beds at various relative densities of the granular fill. Three relative density values (0.40, 0.58, and 0.80) were adopted in this series to describe the loose, medium-dense, and dense soil conditions of the granular material. The fourth series was performed for the vertical granular trench at different relative densities and various depth ratios, aiming to investigate the effect of the internal friction angle of the trench material on the bearing capacity and the settlement of strip footing models on soft clay beds. It is worth noting that the dimensions of the trench were chosen in the laboratory models to reflect the reality of their possibility of field application, as the proportions of w/B and d/B were chosen to be suitable for their practical application in reality.

A few tests were repeated more than three times at the same conditions to examine the accuracy of the measurements and the reliability of the results and, finally, validate the consistency of the test data. The relationship between strain and stress varied less than 5%, which is considered insignificant.

5. RESULTS AND DISCUSSION

A total of 61 tests were conducted on a strip footing model supported and unsupported by a granular trench resting on a soft soil bed. The effects of the trench dimensions, shape, and relative density of the granular material on the bearing capacity and settlement were investigated. The enhancement achieved by the inclusion of the granular trench was expressed using a non-dimensional parameter called EF, which is a measure of the increase in bearing capacity of a footing when a granular trench is included compared to the condition where no trench is present. The tangent intersection approach was used to estimate the bearing capacity based on the stress-settlement relationship for each test in this study. This approach estimates the bearing capacity by finding the load at the place where two tangents cross. These tangents were drawn from the start and final segments of the stress-settlement relationship. The *EF*, according to the definition, can be expressed in Eq. (2):

$$EF = \frac{q_{ult,T}}{q_{ult}} \tag{2}$$

where, $q_{ult,T}$ and q_{ult} are the maximum load-bearing capacities of the footing with and without a granular trench.

The stress-settlement behavior of the strip footing model on soft, cohesive soil beds without any granular trench is presented in Figure 6. The bearing capacity of the strip footing model on soft clay strata was determined to be 85 kPa.

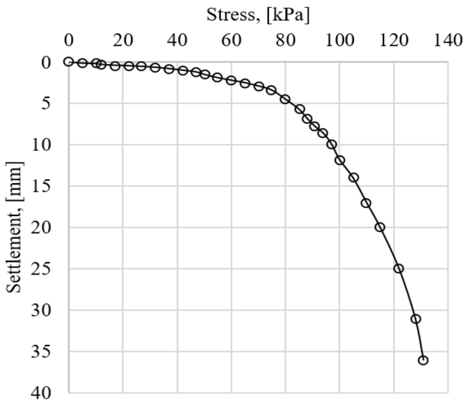

Figure 6. Stress-settlement relationship for footing model on soft cohesive beds without any trench

5.1 Effect of the trench width and depth

A total of 36 experimental tests were performed to investigate the effect of the width and depth of a vertical granular trench on the bearing capacity and settlement of strip footing models on soft clay beds. The shear strength of the soft clay beds and the relative density of the trench granular material were kept constant at 15 kPa and 80%, respectively. The depth ratio (*d/B*) of the granular trench varied between 1.0, 2.0, 3.0, 4.0, 5.0, and 6.0 at various trench width ratios (*w/B*) of 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5. Figure 7 presents the variation of the stress with the settlement of the strip footing model for different granular trench width ratios at a depth ratio (*d/B*=1.0) and a relative density (R_d) of the granular material of 80%.

The results, as depicted in Figure 7, demonstrate that the utilization of a granular trench enhanced the bearing pressure and minimized the settlement. For example, at a settlement level of 10 mm, the bearing pressure is 78 kPa for the strip footing on soft clay without a granular trench. However, it increases by 75.3% when a granular trench with a width ratio (*w/B*=1.0) and a depth ratio (*d/B*=1.0) is utilized. In addition, at a bearing pressure of 78 kPa, the recorded settlement for the footing model on soft clay is 10 mm. However, the settlement reduces by 80% by utilizing a granular trench with a width ratio (*w/B*=1.0) and a depth ratio (*d/B*=1.0). As shown in Figure 7, the enhancement in bearing capacity and the reduction in settlement tend to be less intense after a width ratio (*w/B*) of 2.5.

Moreover, the variation of the EF with the trench depth ratio at different trench width ratios is presented in Figure 8. It can be clearly seen that the EF increases when the trench depth increases. However, the enhancement tends to be less intense beyond a depth ratio of 2.0. For example, the bearing capacity, in the case of using a trench width ratio of 3.5, increases to 4.0 when the trench depth is two times the footing model width. However, it barely increases to 5.0 when the trench depth extends to six times the footing model width. The improvement in bearing capacity beyond a trench depth ratio of 4.0 can be considered insignificant (Figure 9).

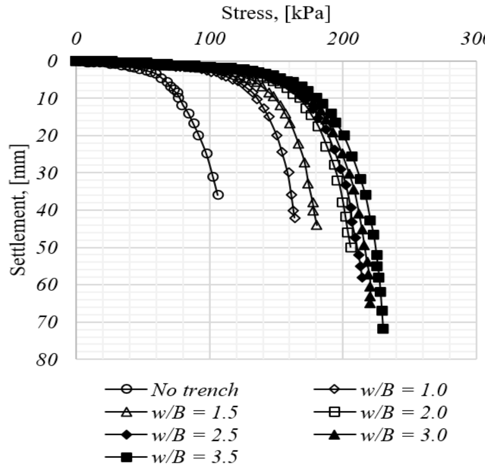

Figure 7. Stress-settlement relationship for the strip footing model for various trench width ratios (*w/B*) on soft cohesive beds (S_u=15 kPa, R_d=80%, *d/B*=1.0)

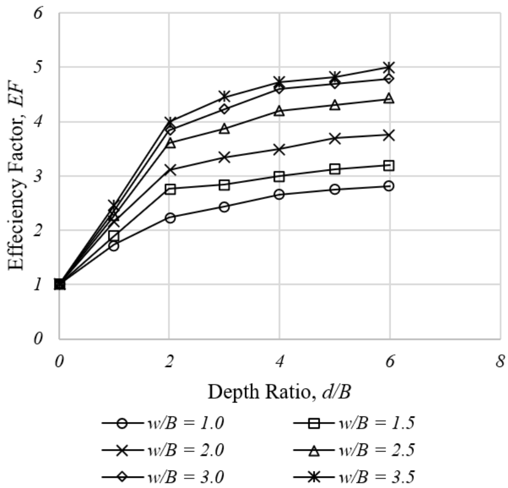

Figure 8. The variation of EF with depth ratio (*d/B*) at various width ratios (*w/B*) (S_u=15 kPa, R_d=80%)

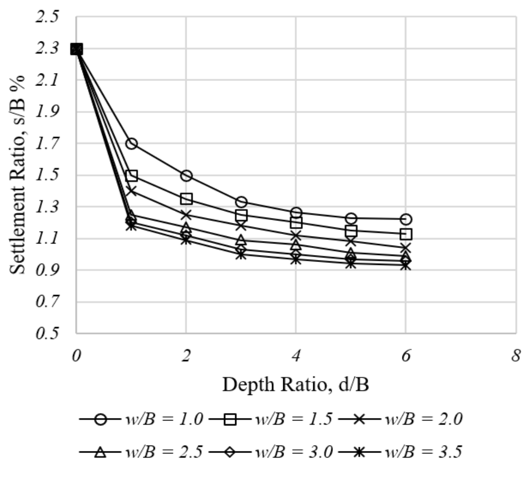

Figure 9. Variation of settlement ratio (*s/B*) with depth ratio (*d/B*) at various width ratios (*w/B*) (S_u=15 kPa, R_d=80%) based on bearing capacity from the two tangents approach

5.2 Effect of the trench inclination angle

In many situations, when footings are proposed to be constructed on soft soil beds, it is not possible to excavate a granular trench vertically. Therefore, the sides of the trench may be inclined by an angle (λ), as illustrated in Figure 10.

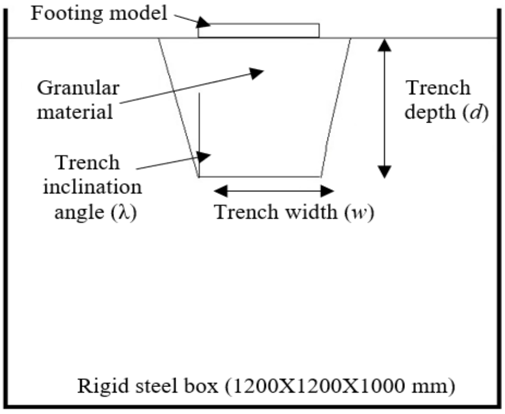

Figure 10. Schematic layout of the sloping granular trench under the footing model

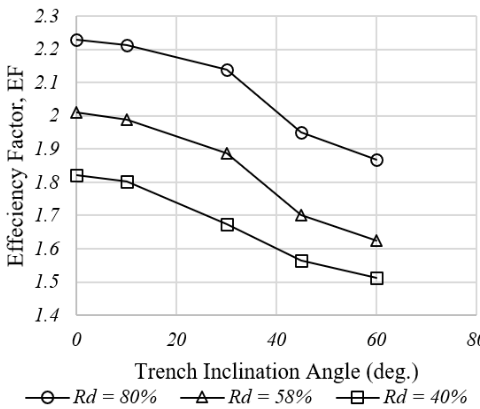

Figure 11. The effect of the trench inclination angle on the EF at different relative densities of the granular materials (w/B=1.0, d/B=2.0)

In order to investigate the effect of the trench inclination on the behavior of the stress-settlement relationship, 12 experimental tests were conducted, as presented in Table 3. The inclination angle of the granular trench varied at 10°, 30°, 45°, and 60° at three different relative density values of the trench granular material (R_d=80%, 58%, and 40%). The relative density values were adopted to reflect the granular material internal friction angles of 41.2° (dense soil), 37.5° (medium-dense soil), and 33.2° (loose soil), respectively. To minimize the effect of other parameters on the results, both depth and width ratios were kept constant at 2.0 and 1.0. The variation of the EF with the trench inclination angle (λ) is presented in Figure 11.

When the inclination angle increases, the EF values decrease. Hence, the rate of reduction in the EF becomes more intense beyond an inclination of 30°. For example, in the case of dense material (R_d=80%), when the inclination angle is 30°, the EF reduces by 4% compared to its maximum value when the trench is vertical, while the reduction reaches 12.5% for an inclination angle of 45°. The same behavior occurs for medium-dense and loose trench granular material, as shown in Figure 11.

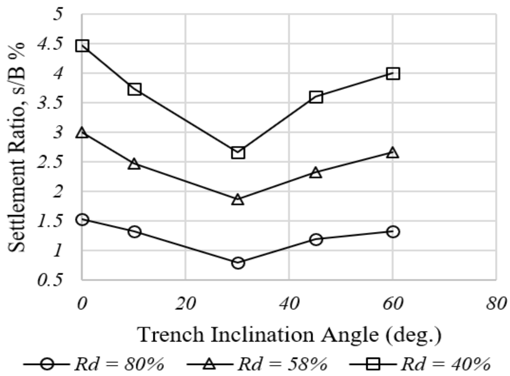

Figure 12. Impact of the trench inclination angle on the settlement ratio at different relative densities of the granular materials (w/B=1.0, d/B=2.0) based on bearing capacity from the two tangents approach

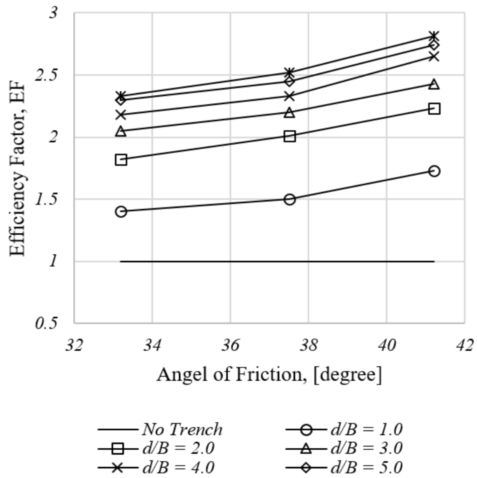

Figure 13. The variation of EF with the friction angle of the granular material at depth ratios (d/B) (w/B=1.0)

The settlement ratio (s/B) values are plotted against the trench inclination angle (λ) for different relative densities (R_d) in Figure 12. Values of settlement ratio (s/B) decrease continuously with λ and R_d to a certain value of λ equal to 30°, after which the s/B values increase. The settlement values were selected according to the bearing capacity determined by the tangent intersection approach. The same behavior occurs again for the medium-dense and loose granular material of the trench.

Therefore, based on the results presented in Figures 11 and 12, the maximum EF is achieved when the granular trench is vertical, and the maximum reduction in settlement can be attained when λ is equal to 30°. Based on practical considerations, it can be concluded that the optimum trench inclination angle is preferred to be in the range of 20° to 30°.

5.3 Effect of the friction angle of the trench granular material

Figure 13 shows the variations in the EF values of a strip footing model on a soft clay bed with a trench width ratio (w/B=1.0) and varied depth ratios (d/B) of 1.0, 2.0, 3.0, 4.0, 5.0, and 6.0 across different granular material friction angles of 33.2°, 37.5°, and 41.2°. The values of EF exhibit a modest increase when the friction angle values of the granular material increase. In general, based on the results depicted in Figure 13, when granular dense material with a friction angle of 41.2°, instead of loose material with a friction angle of 33.2°, is used in the trench under the strip footing model on a soft cohesive bed, the EF increases by approximately 20% to 25%. The same behavior is noticed for all depth ratios (*d/B*), as shown in Figure 13.

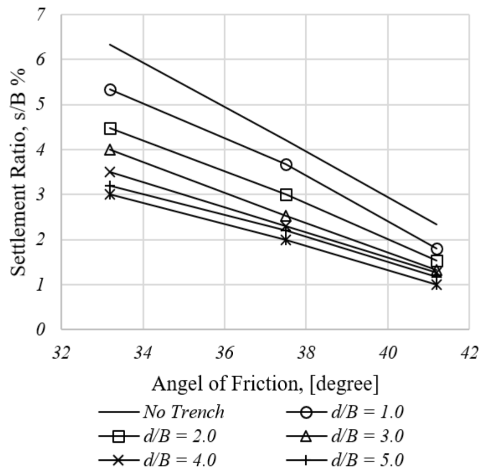

Figure 14. Variation of settlement ratio with friction angle of the granular material at various depth ratios (*d/B*) (*w/B*=1.0) based on bearing capacity from the two tangents approach

Figure 14 shows the variations in the settlement ratios of the strip footing model with the friction angle of the granular trench material for the aforementioned test series. Based on the results presented, it is evident that an increase in the friction angle of the granular material used in the trench leads to a noticeable reduction in settlement. Compared with using a granular material with a friction angle of 33.2°, the settlement reduction obtained by utilizing a granular material with friction angles of 41.2° and 37.5° is approximately 65% and 35%, respectively. Once again, the same pattern is observed for all depth ratios (*d/B*), as depicted in Figure 14.

5.4 Comparisons with literature

The results obtained from this study were compared with several results reported in the literature. Figure 15 presents the EF values for strip footing models resting on soft, cohesive clay reinforced by a granular trench at *w/B*=1.0 for varied depth ratios.

For the trench with dense granular material, the results of this study show higher values of EF than those reported by Hamed [5]. However, a good agreement between the results is noticed in Figure 15. In the case of the medium-dense granular material, the EF values provided by Hamed [5] are 22% lower than those of this study, yet the same trend is evident. However, it is worth mentioning that the length-to-width ratio of the footing model used by Hamed [5] is 4:1, while the ratio is 8:1 in this study because it was specifically designed to describe strip footings.

Although the effect of the footing size was not addressed in this study, it has been reported that the performance of strip footings is substantially better than that of circular footings [13]. In addition, it should be noted that the ($c_u/\gamma_{clay}\ B_f$) values of the compared results in Figure 15 are not exactly matched. The value is 4.53 for this study and is 4.96 for both the experimental study by Hamed [5] and the numerical study by Bhattacharya and Kumar [13]. However, in the comparison presented in Figure 15, it can be observed that for the medium-dense granular material of the trench, an increase in the ($c_u/\gamma_{clay}\ B_f$) value leads to a decrease in the EF values. Such a behavior illustrates that for softer clay, the improvement resulted from utilizing a granular trench provides higher EF values.

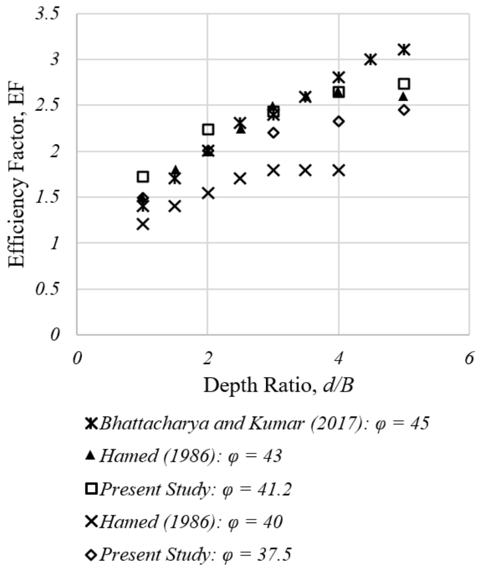

Figure 15. Comparison between the results of this study and those published by Bhattacharya and Kumar [13] and Hamed [5] in terms of the EF versus depth ratio at *w/B*=1.0

6. CONCLUSIONS

This study investigated experimentally the impact of several parameters on the bearing capacity and the settlement of a strip footing model resting on soft, cohesive soil stabilized by a granular trench. The experiments were carried out under different granular material conditions. Based on this investigation, the main findings were drawn as follows:

a) When a granular trench beneath the strip footing resting on soft clay beds was used, the bearing capacity significantly increased and the settlement was reduced.

b) An increase in the width ratio (*w/B*) of the granular trench improved the bearing capacity and reduced settlement. The optimum trench width was found to be 2.5 times the footing width, and afterwards, the improvement in the stress-strain relationship was considered negligible.

c) An increase in the depth ratio (*d/B*) of the granular trench resulted in an improvement in bearing capacity and a reduction in settlement. The ideal depth of the trench was determined to be four times the width of the footing. Beyond this point, any further increase in depth could not significantly enhance the stress-strain relationship.

d) For loose, medium-dense, and dense granular materials, the highest level of efficiency in bearing capacity was reached when the trench was constructed in a vertical position, and the greatest reduction in settlement was achieved when the trench slope angle (λ) was equal to 30°.

e) When the dense material with a friction angle of 41.2°, instead of the loose material with a friction angle of 33.2°, was used in the trench beneath the strip footing model, the EF increased by approximately 20% to 25%.

f) Compared to using granular material with a friction angle of 33.2°, the settlement reduction achieved by employing granular material with friction angles of 41.2° and 37.5° was approximately 65% and 35%, respectively.

g) An increase in the ($c_u/\gamma_{clay} B_f$) value for the medium-dense granular material of the trench resulted in a reduction in the EF values. This behavior demonstrates that the use of a granular trench is more effective in improving softer clay, resulting in higher EF values.

7. LIMITATIONS AND FUTURE RESEARCH

In this study, a small-scale footing model was utilized to investigate the effect of several parameters on the bearing capacity and settlement of strip footing on weak clay supported by a granular trench. The use of small-scale models in the laboratory to simulate large-scale footings in the field is subject to various limitations [19, 20]. The primary limitations of this study include, but are not limited to:

a) Scale effects: The behavior of soil can vary at different scales because of its inherent variability and anisotropy.

b) Boundary conditions: The effects caused by the edges of a laboratory setup can influence the results.

c) Loading condition: The manner in which loads are imposed during laboratory experiments may vary from real-site situations. Loads in the field can involve more complex and variable loading scenarios. However, loading was applied at a constant rate of 1.0 kPa per second in this investigation.

d) Instrumentation and measurement accuracy: The precise measurement of minor deformations and stresses in a controlled laboratory environment can pose challenges, and any inaccuracies or constraints in the equipment used can have a substantial impact on the outcomes.

Based on the above-mentioned limitations, future studies on this topic could include the following aspects:

a) The effect of different loading conditions, such as dynamic loads, on strip footing resting on weak clay reinforced with granular trenches could be investigated.

b) Large-scale model tests could be performed to validate the results obtained from the current work and literature.

c) An artificial neural network could be adopted to estimate the bearing capacity and settlement of the strip footing resting on soft clay supported by a granular trench.

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