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ESTIMATION OF BEARING CAPACITY OF CIRCULAR FOOTINGS ON CLAY STABILIZED WITH GRANULAR SOIL: CASE STUDY

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A B S T R A C T

Soft soils are one of the problematic soils and structures constructed on these soils are considered to be at risk due to their low shear strength and high compressibility. Therefore, construction on soft soils requires soil improvement techniques. The partial replacement of these problematic soils with granular fill layers is one of soil improvement techniques. In this paper, numerical analyses will be carried out to obtain the bearing capacity of circular footings on clay stabilized with different granular compacted fill depths and lengths. The results show that the use of granular fill over clayey soils has a significant effect on the bearing capacity characteristics of footings.

1.0 Introduction

A shortage of the availability of suitable construction sites in cities, due to economic and social development of the populations, has led to an increasing demand to construct structures on problematic areas which were previously considered inappropriate for construction. Normally consolidated or slightly over consolidated clays are classified as one of the problematic soils. Such soils exhibit poor strength, high compressibility and the problems of stability and deformation to structures founded on them. For example, shallow footings, when built on these soils, have low bearing capacity and can undergo excessive settlements. Various techniques have been developed over the past decades to improve load-settlement behavior of soft soils. In the field, provision of well compacted granular-fill materials just below a footing would be a very economical solution to a foundation problem concerned with these problematic soils.

The behavior of problematic soil can be improved by totally or partially replacing unsuitable soils with compacted granular-fill layers. Several experimental and numerical studies have been described about the reinforcement of weak problematic soils (Love et al., 1987;Ochiai et al., 1996;Adams and Collin, 1997;Okamura et al., 1997; Yin, 1997;Otani et al., 1998;Alawaji, 2001;Borges and Cardoso, 2001;Dash et al., 2003;Thome et al., 2005;Yetimoglu et al., 2005; Chen, 2007;Deb et al., 2007;El Sawwaf,2007;Nazirand Azzam,2010; Abhishek et al., 2015). Adams and Collin (1997) performed 34 large model load tests to estimate the advantages of geosynthetic-reinforced foundations. They concluded that the soil–geosynthetic system formed a composite material that prevented the development of the soil-failure wedge beneath the foundation. Alawaji (2001) studied the effects of reinforcing the sand pads over collapsible soils and observed a reduction in the collapse settlement. Dash et al. (2003) conducted model tests to study the response of the reinforcing granular fill overlying soft clay beds and observed the improvement of footing bearing capacity. Ochiai et al. (1996) studied the geosynthetic reinforcement effects of fills over soft grounds in Japan. Otani et al. (1998) investigated the behavior of a stripfoundation constructed on reinforced clay and found that settlement is reduced by increasing the reinforcement size, the stiffness and the number of layers. Yetimoglu et al. (2005) conducted laboratory CBR tests on fiber- reinforced sand fills and reported that ultimate bearing capacity and settlement can be improved using these fibers. Abhishek et al. (2015) reported that a granular bed below the footing in soft ground stabilized with granular trench increases the bearing capacity of the footing considerably.

On the other hand, numerical methods, such as finite element method (FEM) and finite difference method (FDM), are well-established numerical analysis techniques used widely in many civil engineering applications that can model behavior of soils. The present study investigates the improvement in the bearing capacity of circular footings with different diameters and thicknesses rested on natural clay deposits stabilized with compacted granular-fill layers using finite element method (FEM). Numerical analyses were conducted using two-dimensional finite element program.

2.0 Validation

In geotechnical engineering, physical modeling can be performed through either a full or a small-scale model. Full-scale modeling is performed with the real site conditions. Large and full-scale in-situ tests, despite their operational and financial disadvantages, give more accurate and reasonable results. However, most of the experimental studies on soils have been performed using small-scale laboratory tests. Small-scale or laboratory-model tests are easier to perform due to their small sizes and their low cost in comparison with full-scale field tests. Therefore, small-scale laboratory tests are considered to be preferable for studying the behavior of soil and are widely applied in geotechnical practice.

In order to evaluate the validity and performance of the proposed finite element analysis, the results of physical modeling of small-scale circular footing carried out by Ornek et al. (2012) were selected. They determined bearing capacity of small-scale circular footing resting on clayey soil stabilized by granular fill. Figure 1 shows schematic view of test set-up, loading, reaction system and typical layout of instrumentation.

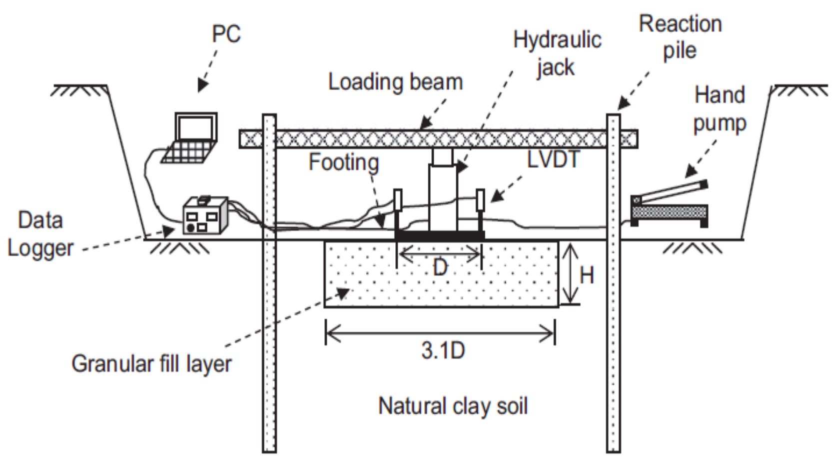


Figure 1:The general layout of the test setup by Ornek et al. (2012)

They used a hydraulic jack for applying the downward load and carried out the testing procedure according to the ASTM D 1196-93 (1997). They measured load and footing settlement by pressure gauge and linear variable displacement transducers (LVDTs), respectively.This small-scale circular footing with D= 0.9 m and H= 0.33D was numerically modeled in this study, where D and H are diameter of the circular footing and granular-fill depth, respectively.

3.0 Numerical Analysis (Case Study)

The comparison depicts a good agreement between the results. It should be mentioned that in Figure 2, the bearing capacity of footing is shown by (q). In addition, the settlement ratio (s/D) is defined as the ratio of the footing settlement (s) to the footing diameter (D).

The behavior of soils can be modeled with numerical analyses. In the finite-element method, the continuous media is divided into finite elements with different geometries. Due to the capabilities of the finite element method, it is possible to study the behavior of shallow footings. In this section, the bearing capacity of circular footings rested on natural Babol clay, from a city in north of Iran, stabilized with compacted granular-fill layers is studied. The granular-fill material was obtained from the Babolsar region situated south of the Caspian Sea (Figure2).

Figure 2: The region considered in this study

Numerical modeling was performed using the Plaxis program. Plaxis is a two-dimensional (2-D) finite element computer program which is available commercially to analyze deformation and stability of various geotechnical problems. The program can be used in plane strain as well as in axisymmetric modeling (Brinkgreve et al., 2004). An elastic-plastic user-friendly Mohr Coulomb model was selected for the clay and granular-fill material behavior. The circular footing is modeled as an elastic plate. Table 1 shows Mohr-Coulomb model parameters. These parameters are based on the results of laboratory and field tests. According to the Unified Soil Classification System (USCS), the granular-fill material was classified as well-graded, gravel-silty gravel (GW-GM).

Figure 3 shows the numerical modeling of a circular footing resting on clayey soils stabilized with compacted granular-fill layers. As seen in Figure 4, the side and bottom boundaries are located far enough from the footing so that the effects of boundaries on its response would be insignificant. The side boundaries are free vertically and restricted in the horizontal direction, while the bottom boundary is fixed in both horizontal and vertical directions. To eliminate boundary effects, the horizontal and vertical dimensions were taken as 5D and 4D, respectively. Since the problem of bearing capacity of circular footing has symmetry about the vertical axis, the axisymmetric option is used for this three dimensional problem in order to reduce the number of elements in the solution procedure. Therefore, only one half of the soil-footing system is considered. A fine finite mesh was used with 15-node triangular elements, as shown in Figure4.

Table 1: Mohr-Coulomb model parameters used in this study

Parameter	Babol clay	Babolsar granular-fill material
Unit weight (kN /m^3)	18	21
Stiffness (kN /m^2)	8500	40000
Cohesion (kN /m^2)	70	1
Poisson's ratio	0.35	0.2
Friction angle (degrees)	0	43
Dilatancy angle (degrees)	0	13

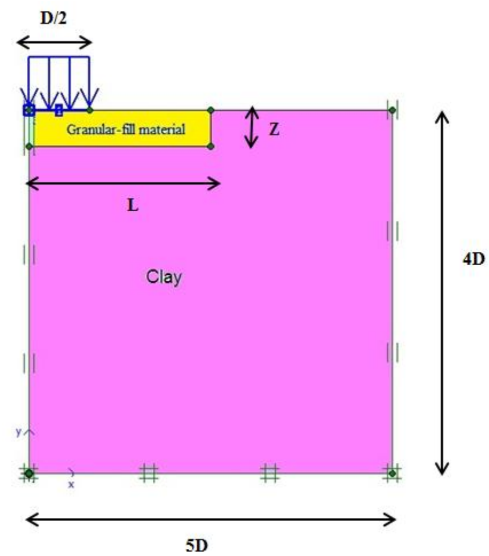


Figure 3: Numerical modeling

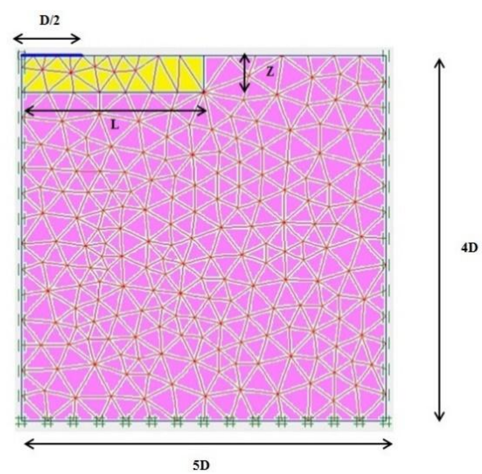


Figure 4: The typical finite element mesh used in the study

Footings of different diameters (D = 5, 10 and 15m) and thicknesses (d = 0.5, 0.8 and 1m) were modeled in this numerical study. Tangents were drawn from the initial and end points of the load–settlement curves and the point of intersection of these tangents was defined as the ultimate bearing capacity. One such exercise has been indicated in Figure5.

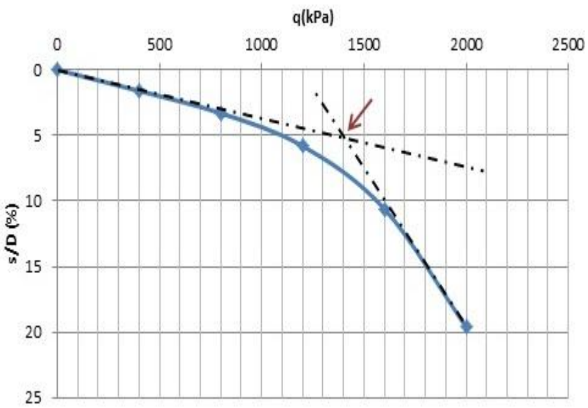


Figure 5: Typical determination of the ultimate bearing capacity value

This procedure has been followed throughout in the present study to obtain the ultimate bearing capacity from the load–settlement curves and all numerical results were interpreted using this method. It should be noted that in Figure5, the horizontal and vertical axes show the ultimate bearing capacity (q) and the settlement ratio (s/D), respectively.

4.0Effect of the Partial Replacement of Clay with Granular-Fill Layer

In this section, the effect of granular-fill on the bearing capacity of circular footing resting on natural clay is studied. The clay is partially replaced by firmer granular soil. Figures 6 to8 show the variation of ultimate bearing capacity of circular footings (q) with granular-fill depth to footing diameter ratio (z/D). It should be noted that in these Figures, L is the length of reinforcement and d is the footing thickness.

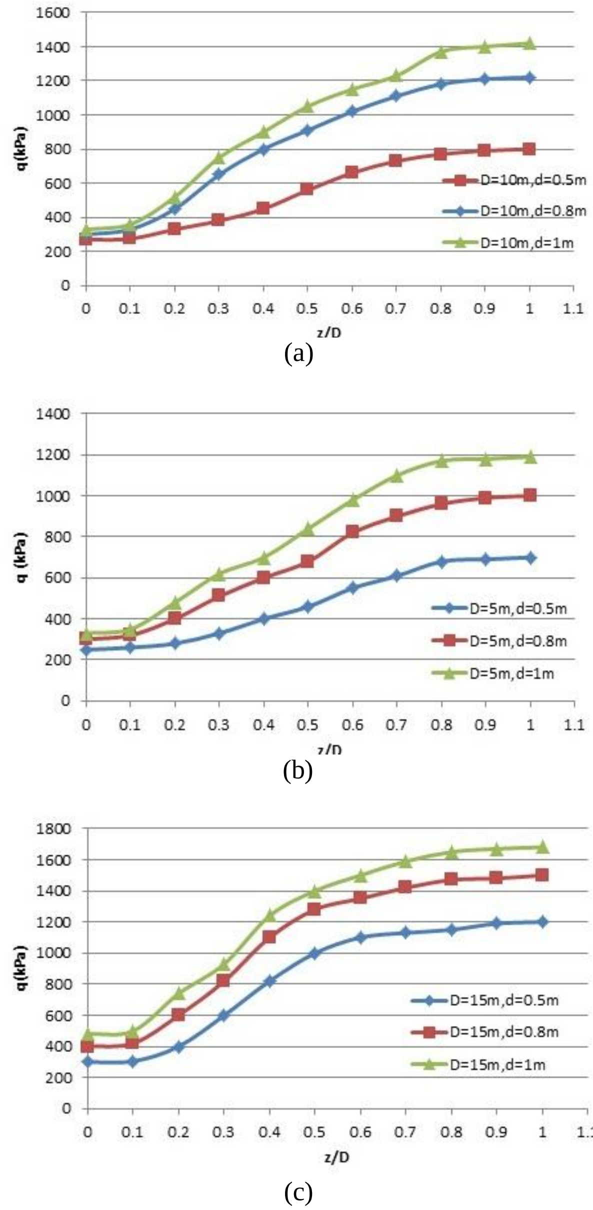
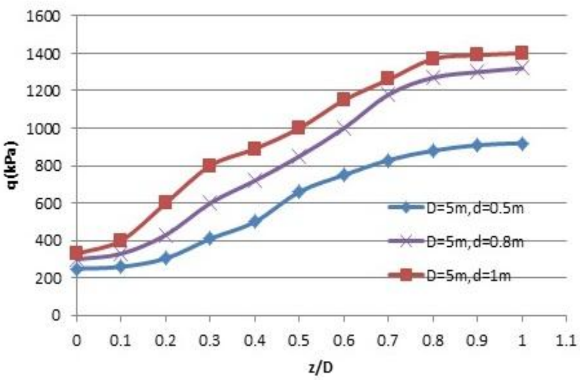
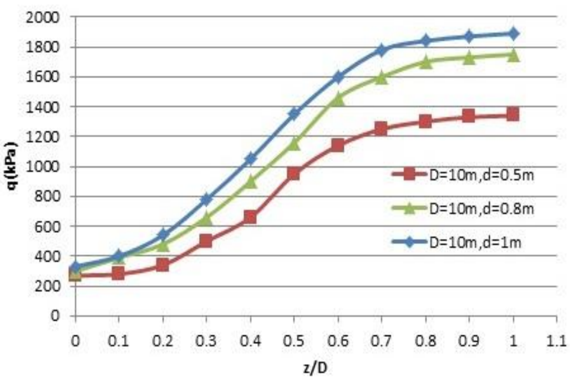


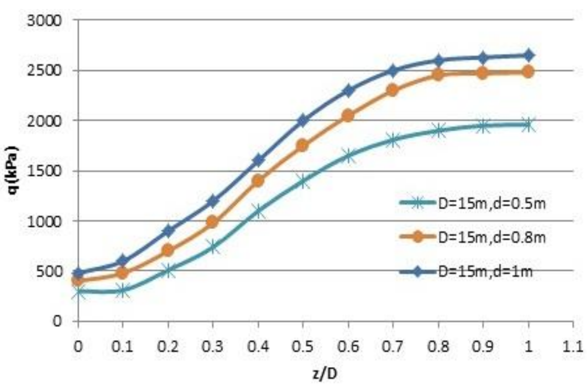
Figure 6: Variation of ultimate bearing capacity (q) with the ratio of granular-fill depth to footing diameter (z/D) for L=0.5D



(a)

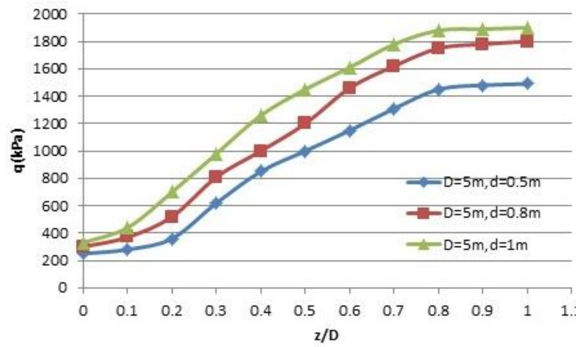


(b)

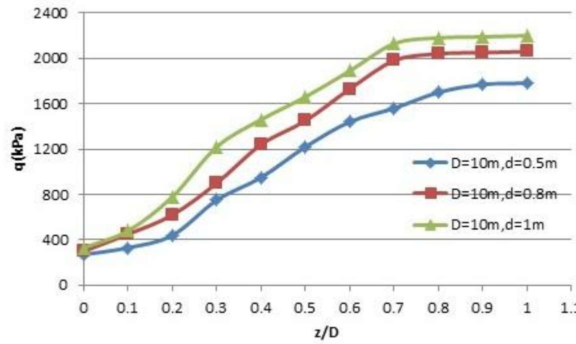


(c)

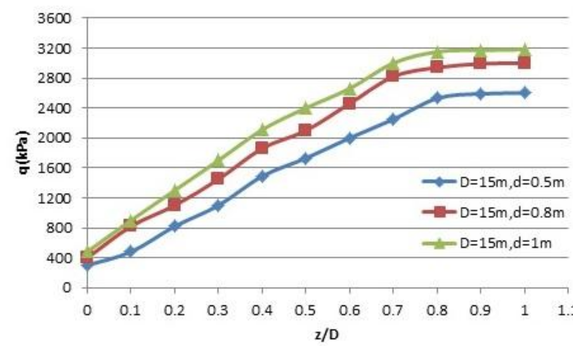
Figure 7: Variation of ultimate bearing capacity (q) with the ratio of granular-fill depth to footing diameter (z/D) for L=1.5D



(a)



(b)



(c)

Figure 8: Variation of ultimate bearing capacity (q) with the ratio of granular-fill depth to footing diameter (z/D) for L=2.5D

As seen in Figures6 to 8, for given values of z/D and d, the bearing capacity increases with increasing footing diameter. For instance, as observed in Figures 7(a) - (c), for a footing with z/D=0.7 and d =0.5m, the bearing capacity values are 610, 730 and 1130 kPa for D=5, 10 and 15m, respectively. The ultimate bearing capacity is clearly a function of z/D (Madhav and Vitkar, 1978;Hamed et al., 1986). For low z/D values, the increase in the bearing capacity is insignificant. However, with increasing z/D, the bearing capacity of footings increases. It can be concluded that at small z/D values, the shear failure zone of soil developed beneath the footing extended into the soft clay. Hence, bearing capacity values are low at initial stages. With an increase in the depth of the granular-fill, an increasing portion of the shear failure zone was developed within the granular fill. Therefore, bearing capacity values increase significantly.

Granular-fill materials are stiffer and stronger than the natural clay and partial replacement of clay with these materials can redistribute the applied load to a wider area and reduce the intensity of stresses transmitted to the underlying ground. The granular-fill layer helps to increase the load-bearing capacity of the circular footing and distributes the load into the underlying ground. The main reason for this subject is that the depth of the granular-fill material is increasing and this material is being more effective.

It can be concluded that granular-fill materials covers the depth of failure zone beneath the circular footings gradually. However, for the values of z > 0.8D, the bearing capacity values increase with smaller rate and the effect of the soil-replacement depth is decreased. When the depth of the granular-fill reaches a value of z/D = 0.8, the entire shear failure surface is developed and completely contained within the granular-fill materials, at which the bearing capacity reaches the maximum. Thereafter, any further increase in granular-fill depth beyond this optimum value can not substantially improve the bearing capacity because the failure surface is always confined within the granular-fill. Therefore, z = 0.8D can be considered as the optimum depth of granular compacted fill. The obtained results are in a good agreement with the results reported by Das (1988). He conducted laboratory model test to determine the ultimate bearing capacity of a surface strip foundation installed in soft ground supported by a granular trench. The ultimate bearing capacity of the footing increased with increasing the depth of the granular trench to a maximum value and then remained constant.

The results indicate that with increasing footing thickness, the bearing capacity increases. Moreover, the effect of increasing footing thickness from 0.5 to 0.8 m on the bearing capacity is more than increasing footing thickness from 0.8 to 1 m. For example, in Figure 7 (a) and for z/D = 0.7, the bearing capacity increases from 610 to 900 kPa (rate of increase = 47.5%) with increasing the footing thickness from 0.5 to 0.8 m. However, the bearing capacity increases from 900 to 1100 kPa (rate of increase = 22.2%) with increasing the footing thickness from 0.8 to 1 m.

In addition, the effect of L/D on the bearing capacity is considerable and with increasing L/D, the bearing capacity of footing with given diameter, thickness and z/D values can increase considerably. For instance, by comparison of Figures 6 (c), 7 (c) and 8 (c) to each other, it can be seen that for z/D= 0.6, d= 0.8m and D= 15m, the bearing capacity values are 1350, 2050 and 2460 kPa for L/D= 0.5, 1.5 and 2.5, respectively. Figure 9 shows the effect of length of reinforcement to the footing diameter ratio (L/D) on the bearing capacity of circular footings with diameter (D) of 5 and thickness (d) of 0.5m.

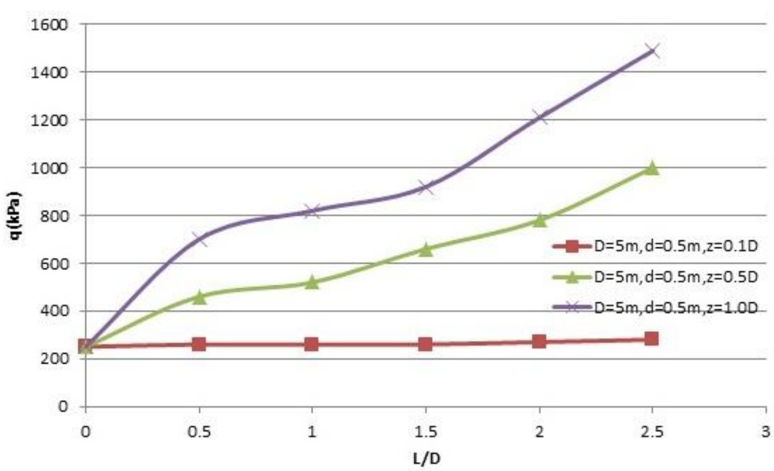


Figure 9: Variation of ultimate bearing capacity (q) with the ratio of granular-fill length to footing diameter(L/D)

It is seen that no optimum length (L) is found in the analyses. In other words, the bearing capacity values increase with increasing the length of the granular-fill material. Similar trends were observed for all other similar numerical analyses performed on footings that can be related to the improvement of the length of the soil failure zone beneath the footing by granular-fill. Also the results show that for L=0.5D and L=1D, the deformation of the footing center is more than other parts of it that can be due to footing flexibility.

5.0 Conclusions

The results of study depicted that the replacement of natural clay with compacted granular-fill layer had a significant effect on the bearing capacity of the circular footings. In the present study, a numerical modeling procedure was applied to analyze the bearing capacity of circular footings on clayey soils stabilized with granular-fill. The elasto-plastic Mohr–Coulomb model was used in the procedure. A comparison between numerical and measured results of model test showed that the agreement between results was acceptable. Numerical analyses were carried out on circular footings with different diameters and thicknesses stabilized with granular-fill. In the analyses, granular-fill depth (z) was changed depending on the footing diameter as 0.1D, 0.2D, … and 1.0D. The results indicate that granular-fill materials function as a strong base, reduce the stress concentration and facilitate increased load to be applied over it. It was found that the bearing capacity increases with an increase in the ratio of granular-fill depth to footing diameter (z/D) for all cases until it reaches a critical value, which can be considered as the optimum limit of improvement of the bearing capacity of the footing. The optimum depth of the granular-fill (z) was found to be 0.8 times the diameter of the footing (D). For the values of $z > 0.8D$, the bearing capacity values remain relatively constant and enhancement is marginal with further increase in granular- fill depth.

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