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TECHNICAL PAPER

Interference of Surface and Embedded Three Strip Footings in Undrained Condition

Saif Alzabeebee [1]

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Abstract
The closed-form solutions for the undrained bearing capacity of shallow footing have been derived considering only single footing due to difficulties associated with adding the effect of nearby footings. However, the footing, in reality, may be separated or bounded by other footings from one side or two sides, and hence, the interference effect should be considered. This study has been conducted to understand the influence of the presence of existed footings on the undrained bearing capacity of a new footing that is placed between the existed footings. Validated numerical analyses have been conducted for single and interference footings to clearly understand the effect of the spacing between the footings on the obtained bearing capacity and the associated failure mechanism. The influence of the embedment ratio and the undrained cohesion has also been considered in these analyses to illustrate the combined influence of all of the factors. It was found that the undrained cohesion does not remarkably influence the trend of the relationship of the bearing capacity ratio and the distance ratio between the old and the new footings, while the embedment ratio has been found to have a remarkable impact on the trend of the aforementioned relationship. The average maximum percentage increase of the bearing capacity of the new footing due to the interference effect is found to be ranged between 6% to 23% depending on the embedment ratio and the distance between the footings. Importantly, the embedment ratio is found to influence the critical distance at which the maximum bearing capacity of the new footing is achieved.

Keywords Undrained bearing capacity · Interference effect · Finite element analysis · Embedment ratio

✉ Saif Alzabeebee
Saif.Alzabeebee@gmail.com; Saif.Alzabeebee@qu.edu.iq

[1] Department of Roads and Transport Engineering, College of Engineering, University of Al-Qadisiyah, Al Diwaniyah, Al-Qadisiyah, Iraq

1 Introduction

The closed-form solutions for the undrained bearing capacity of shallow footing have been developed considering a single footing that is not bounded by old footings (Venkatramaiah 2006; Mabrouki et al. 2010). However, the footing may be separated or bounded by other footings from one side or more than one side. Due to this, the problem of the presence of nearby existed footings should be assessed by studying the interference effect of these footings on the bearing capacity. However, despite the importance of this topic, there are very limited studies that address this issue for undrained condition (Griffiths et al. 2006; Shu et al. 2021), while all of the other studies focused on the drained conditions (Stuart 1962; West and Stuart 1965; Kumar and Ghosh 2007; Ghazavi and Lavasan 2008; Kumar and Bhoi 2009; Lee and Eun 2009; Kouzer and Kumar 2010; Mabrouki et al. 2010; Vivek 2011; Naderi and Hataf 2014; Noorzad and Manavirad 2014; Schmüdderich et al. 2020).

Stuart (1962) was the first researcher to study the interference of the footings, where he examined the effect of interference of two shallow surface footings resting on sandy soil using the limit equilibrium method. He presented the effect of the interference in terms of the efficiency factors ξq, $\xi \gamma$, and $\xi q \gamma$. He found that the efficiency factors $\xi \gamma$ and ξq increased when the distance between the footings was decreased. Also, he validated the results of the limit equilibrium analysis with the results of a small-scale laboratory model. West and Stuart (1965) used the stress characteristics method to analyze the interference of two footings resting on medium dense sandy soil. They found a little difference in the results from those reported earlier by Stuart (1962). Griffiths et al. (2006) examined the undrained bearing capacity of two closely spaced strip footings. They used the random finite element method where the undrained cohesion was assumed to be distributed randomly with the aid of Monte Carlo methodology. Kumar and Ghosh (2007) studied the ultimate bearing capacity of two interfering strip footings resting on sand by using the stress characteristics method. Ghazavi and Lavasan (2008) investigated the interference of shallow footings resting on homogenous sandy soil reinforced with geosynthetics. They used the finite difference method (FDM) in their analysis, where they compared the results of the FDM with field results collected from the literature and found a good agreement between the numerical predictions and the field results. Kumar and Bhoi (2008) investigated the interference of three footings resting on sand using laboratory model tests. The study concerned with the effect of distance between the footings on the bearing capacity and concluded that the bearing capacity of the footings increased as the spacing between the footings decreased. Kumar and Bhoi (2009) studied the bearing capacity of two strip footings resting on dry sand using a 1-g small-scale model. They found that the interference increased the bearing capacity of the strip footings. Furthermore, they noticed that the rate of improvement of the bearing capacity increased with the rise of the relative density of the sandy soil. Lee and Eun (2009) investigated the bearing capacity of multiple footings resting on sand using series of plate load tests. From their results, they conclude that the effect of the interference on the bearing capacity became insignificant when the spacing between the footings was equal to or more than three times the width of a single footing. Kouzer and Kumar (2010) studied the interference between old and new strip footings placed on a cohesionless soil using the upper bound finite element analysis (FEM). They found that the existence of the old footing enhanced the bearing capacity of the new footing. Kumar and Bhattacharya (2010) examined the bearing capacity of multiple smooth and rough footings that are loaded to failure. The lower bound FEM was used in the analyses. They noticed that the bearing capacity of the spread (single) footing is always lower than that of a footing that is part of a group. They also found that the bearing capacity of the footing in a group continuously increased as the distance between the footings decreased.

Mabrouki et al. (2010) studied the behavior of two interfering strip footings constructed on sandy soil using the FDM. Vivek (2011) studied the interference effect on the response of two strip footings resting on uniform and layered c-ø soils using the FEM. Drained condition was considered in Vivek's (2011) study, where he noticed that the interference increased the bearing capacity of the strip footings. For the uniform c-ø soil, the maximum increase occurred when the spacing between the footings was 1.0 m and the percentage increase was found to be equal to 40%. For the layered c-ø soil, the maximum percentage increase was found to be equal to 37%, which occurred also when the distance between the footings was 1.0 m. Naderi and Hataf (2014) analyzed the effect of interference of closely spaced ring and circular footings resting on an unreinforced and geogrid reinforced sand using the FEM and experimental models. They found a good agreement between the numerical and the experimental results. They also found that the interference improved the achieved bearing capacity. However, they also noticed that the improvement of the bearing capacity decreased with the increase of the spacing between the footings. The maximum improvement of the bearing capacity is reported to be equal to 27% for circular footings resting on unreinforced sand, 31% for circular footings resting on reinforced sand, 18% for ring footings resting on unreinforced sand, and 14% for ring footings resting on reinforced sand. Noorzad and Manavirad (2014) studied the interference effect on the bearing capacity of footings resting on unreinforced and reinforced soft clay using the FEM. Drained condition was assumed in the FEM analysis utilizing elastic perfectly plastic Mohr-Coulomb model and hardening soil model. Noorzad and Manavirad (2014) found that reinforcing the ground with geogrid increased the beneficial effect of the interference. Also, they found that increasing the number of reinforcement layers and the axial stiffness of the geogrid layer raised the beneficial effect of the interference. Boufarh et al. (2019) studied the interference of two adjacent footings resting on two layers of Tebessa sand using a small-scale laboratory model. The study mainly focused on the effect of the distance between the footings and the relative difference of the relative density of the sand layers.

Alzabeebee (2020a) studies the behavior of two nearby machine footings subjected to vertical vibration and resting on sand using the FEM. Alzabeebee (2020a) noticed that the critical distance after which the interference effect terminated depends on the stiffness of the soil and the frequency of vibration. Anaswara and Shivashankar (2020) studied the interference behavior of two footings resting on a granular soil that contains a void using the FEM. Two conditions have been considered by Anaswara and Shivashankar (2020). The first condition involved loading the two footings at the same time to simulate the case of the interference of two new footings. The second condition involved loading the first footing in a separate stage and the other footing in the next stage to simulate the case of old and new footings. Anaswara et al. (2020) examined the performance of two and three nearby strip footings resting on unreinforced and reinforced medium dense sand. The cases considered in the study have been investigated using laboratory tests and FEM. Similar to Anaswara and Shivashankar

(2020) study, two scenarios have been considered, where in the first scenario all of the footings have been loaded at the same time (for both the two and three interference footings). The second scenario considered the effect of the existed footing/s (footing/s of an existed building/s) on the response of the new footing. The second scenario was analyzed only using the FEM. Saraf and Pusadkar (2020) reported the bearing capacity of four interference footings resting on reinforced coarse-grained soil. Similar to previous studies, they found that the bearing capacity surged as the distance between the footings decreased. They also noticed that the trend of the stress–settlement relationship is the same for the footing in a group in comparison to a single footing. Schmüdderich et al. (2020) investigated the bearing capacity of a new footing placed near an existing footing and resting on a cohesionless (friction) soil using the finite element limit analysis. They used elastic perfectly plastic Mohr-Coulomb model in the simulation. Schmüdderich et al. (2020) found that the presence of the old footing increased the bearing capacity of the new footing, where the percentage increase was found to be increased when the spacing between the footings decreased or when the angle of internal friction of the soil increased. Finally, Shu et al. (2021) investigated the problem of the interference between two closely spaced strip footings in an undrained condition. The spatial variability of the undrained shear strength was modeled in this study using the Monte Carlo simulations. They found an increase in the bearing capacity due to the interference effect.

As it is clearly evident in this review, the problem of the interference of three footings in an undrained condition has not been addressed in the literature. Thus, this research aims to study the bearing capacity of a new footing that is constructed between two existed (old) footings to address this gap in the state of the art. A robust finite element model has been developed to address the aim of the research.

2 Statement of the Problem Considered in this Study

Three strip footings are considered in this study to investigate the effect of the interfering of the footings on the bearing capacity for soft, medium, and stiff clays. The considered problem involves the study of the bearing capacity of a new strip footing bounded by two existed (old) strip footings from the left and right sides as shown in Fig. 1. All of the strip footings are with width (B) of 3.0 m and thickness (H)

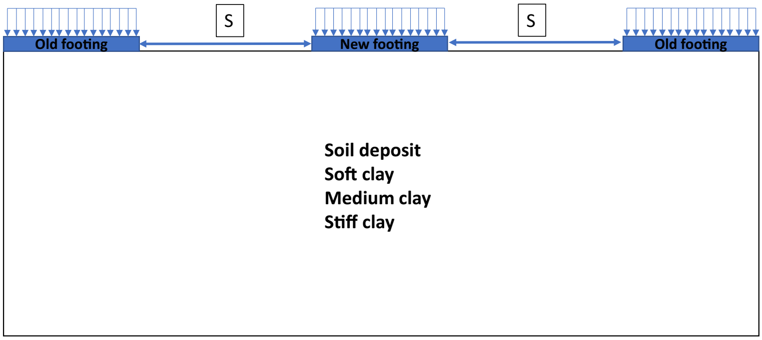


Fig. 1 A schematic diagram of the problem

of 0.5 m. The spacing of the nearby footings (S) and the embedment depth are changed, and the finite element analysis is carried out for each case. The values of S are taken equal to 0.25 B, 0.50 B, 1.00 B, 1.50 B, 2.00 B, and 2.50 B, while the values of the embedment depth are taken equal to 0.00 B, 0.25 B, 0.50 B, and 1.00 B.

3 The Numerical Modeling of the Problem

The problem of this research has been modeled using Plaxis 2D (Bringkgreve and Vermeer 2004) considering a plane-stain condition. Six-node isoperimetric triangular elements with three stress points are used to model the soil. The extension of the soil domain in both the horizontal and vertical directions has been taken equal to 30 B to eliminate the boundary effect especially for the models with S/B of 2.50. These dimensions have been determined based on a sensitivity study. The left and right edges of the finite element model have been restrained against the horizontal movement only while the bottom edge of the model has been restrained against the horizontal and vertical movements. These boundary conditions have been utilized based on the recommendation of many previous studies in the literature (Alzabeebee et al. 2017; Van Baars 2018; Azzam and Basha 2018; Chavda and Dodagoudar 2018; Ouahab et al. 2018; El-Soud and Belal 2019; Haddad and Choobbasti 2019; Schweiger et al. 2019; Ekbote and Nainegali 2019a, b; Anaswara and Shivashankar 2020; Alzabeebee 2020a, b, c, 2021).

The footings have also been modeled using six-node isoperimetric elements. The load carried by the footings has been simulated as a uniformly distributed pressure over the whole width for each footing. Extremely fine elements have been utilized in forming the mesh for both the soil domain and the footings to ensure robust analysis. The total number of elements used in the analysis is 41,584 with an average area of element equal to 0.420 m. These numbers are changed slightly in each model due to the automatic mesh generation technique in Plaxis 2D.

The linear elastic model has been used to model the footings, while the Mohr-Coulomb elastic perfectly plastic soil model has been used to represent the behavior of the soil. The material properties used in the analyses and the justification to use the Mohr-Coulomb elastic perfectly plastic soil model are discussed in detail in the next section.

The water table is modeled at the surface before calculating the in situ stresses. The finite element mesh of the problem is shown in Fig. 2. Three stages have been considered in the analysis as follows:

Stage 1: In this stage, the in situ stresses and initial pore water pressure have been calculated depending on the unit weight of the soil and the lateral earth pressure (k_o), where k_o has been determined using the equation proposed by Jacky (1944) which is:

$$k_o = 1 - Sin\ Ø \tag{1}$$

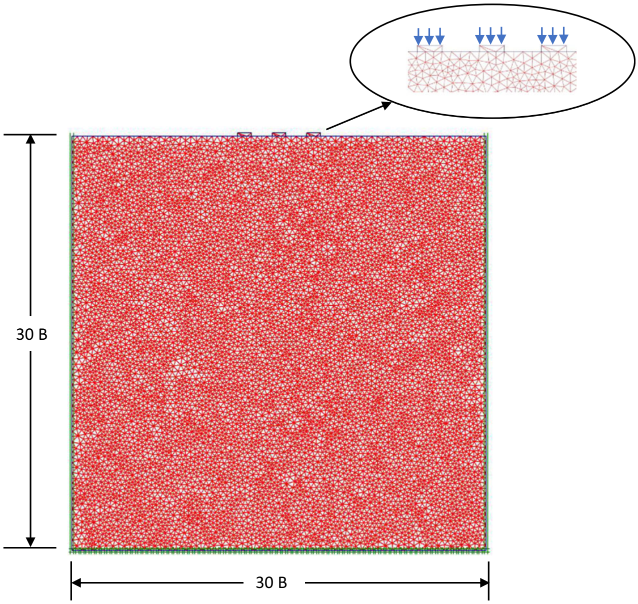


Fig. 2 The mesh of the problem

Stage 2: In this stage, the left and right existed (old) footings (the old footings) have been loaded with a uniform stress equal to the allowable bearing capacity of a single strip footing. The allowable bearing capacity has been determined as the ultimate bearing capacity of a single footing divided by 3.0 (i.e., the factor of safety).
Stage 3: In this stage, the middle footing (the new footing) has been loaded until reaching the ultimate condition, where the bearing capacity of the footing is taken equal to the stress at failure (i.e., the stress at which the settlement continuing to increase without any change in the applied stress).

It is worthy to add that the methodology to model the old (existed) footings in a stage and then applying the load of the new footing in the next stage has also been used by Kouzer and Kumar (2010), Anaswara and Shivashankar (2020), Anaswara et al. (2020), and Schmüdderich et al. (2020). Hence, this methodology is robust and provides a realistic simulation of the problem considered in this study.

4 Material Properties

As mentioned in the previous section, the footings have been assumed to behave as a linear elastic material with the properties shown in Table 1 (Alzabeebee 2019, 2020c), while the undrained clayey soils have been modeled using an elastic perfectly plastic model obeying the Mohr-Coulomb failure criteria. This soil constitutive model has been utilized as its robustness has been demonstrated in previous studies (Benmebarek

Table 1 Material properties used in finite element analysis

Material	Soft clay	Medium clay	Stiff clay	Concrete
Material behavior	Undrained	Undrained	Undrained	Non-porous
Unit weight (γ) (kN/m^3)	15	16	17	24
Undrained cohesion (Su) (kPa)	25	60	100	–
Poisson's ratio	0.49	0.49	0.49	0.20
Modulus of elasticity (E) (kPa)	12,500	30,000	50,000	20,000,000

et al. 2017; Ouahab et al. 2018, 2020). This soil constitutive model has also been utilized in many previous studies to investigate the undrained bearing capacity problems (Merifield and Nguyen 2006; Nguyen and Merifield 2011, 2012; Lee et al. 2016; Benmebarek et al. 2017; Ouahab et al. 2018; Zhang et al. 2019; Chi and Lin 2020; Ouahab et al. 2020; Birid and Choudhury 2021). Importantly, this model is practical and usually used in practice as its parameters can be obtained easily from routine laboratory tests or empirical correlations.

All the models are analyzed using Plaxis 2D utilizing the undrained parameters (Bringkgreve and Vermeer 2004). The water table is assumed to be at the surface to consider the most stringent condition. The properties of the saturated clayey soils are shown in Table 1. It is worth mentioning here that the modulus of elasticity of the clayey soils used in the analyses has been determined using the equation reported by Das (2010), which correlates the modulus of elasticity with the undrained cohesion, where $E = (250 - 500)\ Su$. In addition, the undrained cohesion for soft clay, medium clay, and stiff clay is considered equal to 25, 60, and 100 kPa, respectively (Atkinson 2007; Barnes 2010; Das 2010).

5 Model Validation

Finite element analyses of a single strip footing resting on soft, medium, and stiff clays have been carried out in the initial stage of the research and the results have been compared with the results of the bearing capacity that are calculated using closed-form solutions to validate the developed model and to ensure that the methodology used in the analysis is corrected and produces reasonable results. The closed-form solutions have been obtained using the well-known bearing capacity equation utilizing Terzaghi bearing capacity factors and Hansen bearing capacity factors (Bowles 1996). The stress settlement curves obtained from the finite element analyses conducted in this section are shown in Fig. 3. The FEM bearing capacity has been considered as the stress at which the settlement increases without any increase in the applied stress. Table 2 shows the comparison of the obtained bearing capacity values and those calculated using Terzaghi and Hansen bearing capacity factors. It is clear from the table that the obtained FEM values are very close to those calculated using Terzaghi bearing capacity factors, where the percentage difference ranges between 1 and 6%. In addition, the percentage difference between the FEM bearing capacity values and those predicted using Hansen bearing capacity factors ranges between 12 and 16%, which also illustrates a reasonable match. It is also worthy to mention that Griffiths et al. (2006) and Gourvenec et al.

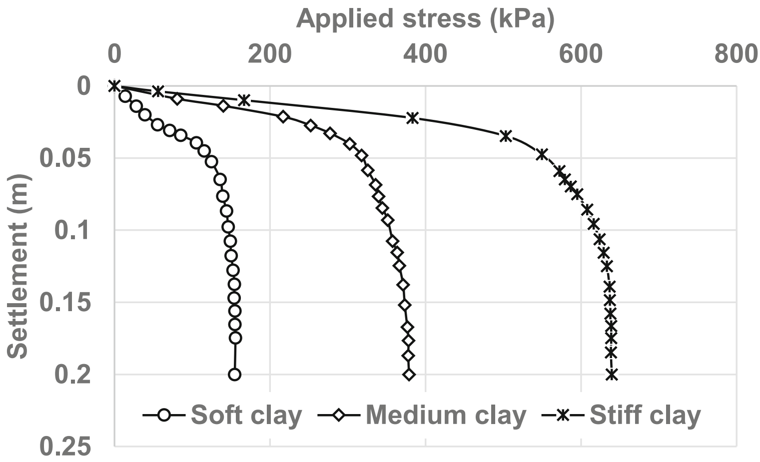


Fig. 3 Stress settlement curves for single strip footing constructed on soft, medium, and stiff clays

(2006) also noticed a slight overestimation of the bearing capacity predicted using the finite element analysis compared with closed-form solutions. Thus, it is evident that the model developed in this research is valid and can be used with certainty to achieve the objectives of the study.

6 Parametric Study

A parametric study has been carried out to study the effect of the distance ratio (S/B), embedment ratio (D/B), and the undrained cohesion on the bearing capacity of the new footing. Table 3 summarizes the cases considered in this study.

To clearly evaluate the effect of the interference on the bearing capacity, a non-dimensional parameter called the bearing capacity ratio (ξ) has been obtained by dividing the bearing capacity of the new footing by the bearing capacity of a single footing (obtained from the validation stage) as shown in Eq. 2.

$$\xi = \frac{q_u\ of\ \ the\ new\ footing}{q_u\ of\ \ a\ single\ footing} \tag{2}$$

Table 2 Predicted and calculated values of the bearing capacity

Soil type	Present study (kPa)	Closed-form solution using Terzaghi bearing capacity factors (Bowles 1996) (kPa)	Percentage difference (%)	Closed-form solution using Hansen bearing capacity factors (Bowles 1996) (kPa)	Percentage difference (%)
Soft clay	154	152	1	135	12
Medium clay	378	363	4	324	14
Stiff clay	641	604	6	540	16

Table 3 Summary of the cases considered in this research

Su (kPa)	25				60				100			
D/B	0.00	0.25	0.50	1.00	0.00	0.25	0.50	1.00	0.00	0.25	0.50	1.00
S/B	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50

The relationship between the bearing capacity ratio (ξ) and the distance ratio (S/B) has been plotted for all undrained cohesion and embedment ratio values to provide a clear understanding of the interference effect in the undrained condition. The following subsections discuss the effect of the distance ratio and the effect of the embedment ratio based on the bearing capacity ratio.

6.1 Effect of the Distance Ratio (S/B)

Figure 4 presents the relationship between the bearing capacity ratio (ξ) and the distance ratio (S/B) for the case of a surface footing resting on soft, medium, and stiff clays. It is clear from the figure that the undrained cohesion has a very minor influence on the relationship between the bearing capacity ratio and the distance ratio. In addition, the figure also shows that the presence of the left and right (old) footings remarkably increase the bearing capacity of the middle footing for distance ratios of 0.25 and 0.50, where the percentage increase ranges between 20 and 24% for a distance ratio of 0.25 and 21 to 23% for a distance ratio of 0.50. The improvement of the bearing capacity is due to the beneficial effect of adding the surcharge (loads of the old footings) on the top

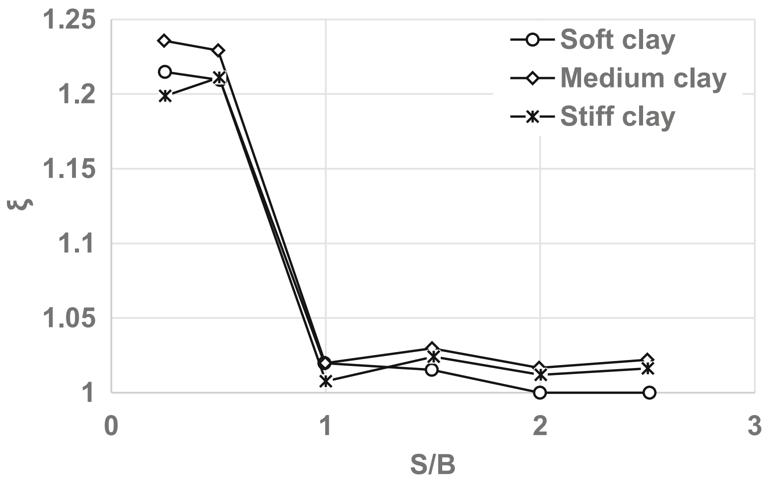
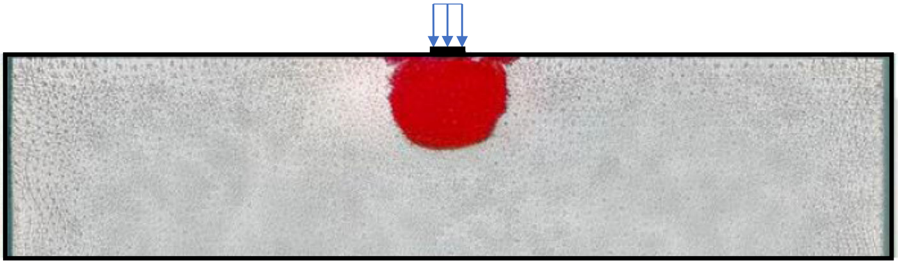


Fig. 4 Relationship between the bearing capacity ratio and the distance ratio for surface footing

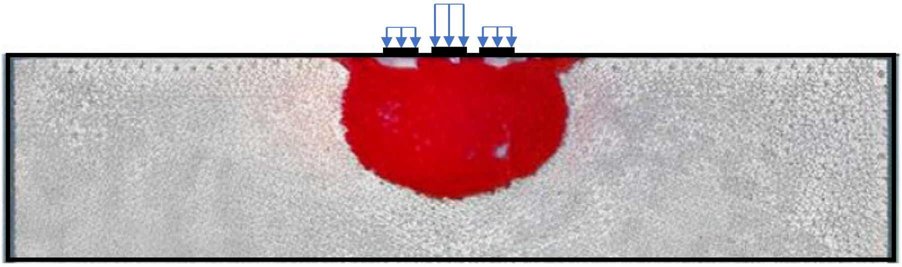
of the passive wedges, which is developed due to loading the middle footing to the failure. The presence of these surcharge loads on the left and right sides of the new footing confines the passive wedges and hence increases the load the ground can handle before failure. This justification has been made considering that the Prandtl-type failure mechanism is also valid for undrained analysis based on the observation of Gourvenec et al. (2006), who compared the failure mechanism produced in the undrained analysis with that proposed by Prandtl (1921) (which is adopted later by Terzaghi in the derivation of his famous bearing capacity solution). However, it can also be observed from Fig. 4 that the improvement in the bearing capacity remarkably decreases as the distance ratio increases to S/B of 1.0 and becomes unpronounced beyond this distance ratio, which indicates that the nearby footings become far from the passive wedge and hence, their beneficial influence on the bearing capacity will be decreased. It is worthy to also state that the increase in the bearing capacity due to the interference may also be justified by the blocking effect (Naderi and Hataf 2014; Noorzad and Manavirad 2014; Ghazavi and Dehkordi 2021), where the combined system of the interference footings will move downward as a single unit due to this effect and hence, the area of this system becomes greater than that of a single footing. Therefore, the bearing capacity will be increased due to the increase of the bearing area (i.e., the area over which the load is distributed). This effect can be seen clearly in Fig. 5, which compares the failure zone (which is represented by red color) of a single footing and interference footings at the ultimate condition. The figure shows that for the interference footings, the failure zone is extended in the horizontal and vertical directions in an area greater than that of single strip footing, although the left and right footings are loaded only to the allowable load and only the middle footing is loaded to the ultimate load. It is also clear from Fig. 5 that the failure zone is extended outside of the nearby footings for the case of S/B equal to or less than 0.5, while it is restricted to the edges of the nearby footings for greater S/B values.

Figures 6 and 7 present the bearing capacity ratio-distance ratio relationship for embedment ratios of 0.25 and 0.50, respectively. Both figures show that the undrained cohesion (clayey soil strength) has very marginal effect on the relationship between the bearing capacity ratio and the distance ratio, similar to the observation noted for the surface interference footings. It is also clear that the trend of the relationship for both embedment ratios is similar, where the bearing capacity ratio increases as the distance ratio increases from 0.25 to 0.50 and then gradually decreases as the distance ratio rises. The figures evidently show that the maximum improvement in the bearing capacity is achieved when the distance ratio is equal to 0.50 for both embedment ratios, where the average percentage increase of the bearing capacity at this distance ratio is equal to 23% and 21% for embedment ratio of 0.25 and 0.50, respectively. In addition, the average percentage increase of the bearing capacity at a distance ratio of 0.25 is equal to 16% and 17% for the embedment ratio of 0.25 and 0.50, respectively. Importantly, the figures show that the interference effect diminishes as the distance ratio increases beyond S/B of 1.0 as the improvement of the bearing capacity becomes less than 10%. This is due to the reduction of the beneficial effect of the interference as the loads applied by the old footings shift from the passive wedges developed due to loading the middle footing to the ultimate conditions.

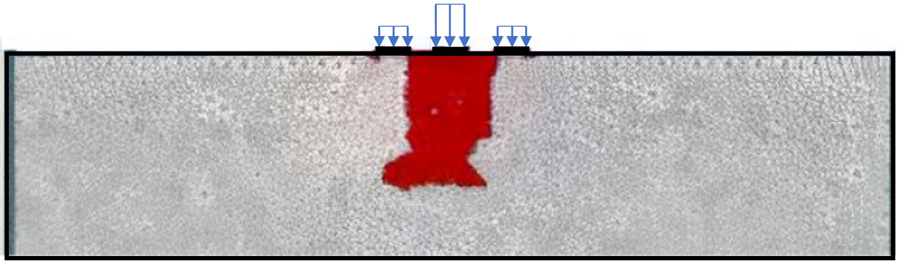
Figure 8 illustrates the effect of the interference on the bearing capacity of the middle footing for an embedment ratio of 1.0. It is obvious from the figure that the



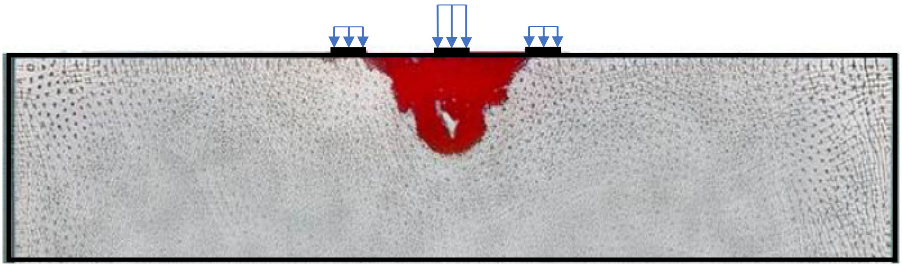
a) Single footing



b) Interference footings with S/B of 0.50



c) Interference footings with S/B of 1.00



d) Interference footings with S/B of 2.00

Fig. 5 Failure zone (red color) at the ultimate condition for a single surface and interfering footings resting on medium clay. **a** Single footing. **b** Interference footings with S/B of 0.50. **c** Interference footings with S/B of 1.00. **d** Interference footings with S/B of 2.00

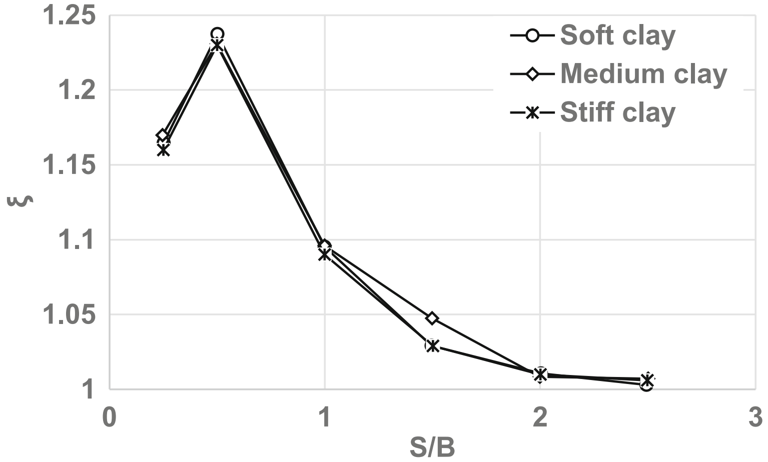


Fig. 6 Relationship between the bearing capacity ratio and the distance ratio for an embedment ratio of 0.25

interference effect becomes very marginal for this embedment ratio, where the maximum percentage improvement for this embedment ratio is equal to 6% recorded at a distance ratio of 1.50. In addition, the trend of the relationship for this embedment ratio is different from other embedment ratios, where the bearing capacity ratio marginally increases as the distance ratio increases up to 1.50 and then gradually decreases. This observation will be discussed in detail in the next subsection, which specifically focuses on the effect of embedment.

As stated before, it is also clear from Figs. 4, 6, 7, and 8 that the undrained cohesion of the soil does not have a remarkable impact on the relationship between the interference factor and the spacing ratio. However, there is still some minor effect that is obvious in the figures. This minor effect can be attributed to the fact that the interference factor is calculated by dividing the bearing capacity of the interference footing by the bearing capacity of a single footing. Hence, it is expected not to have the

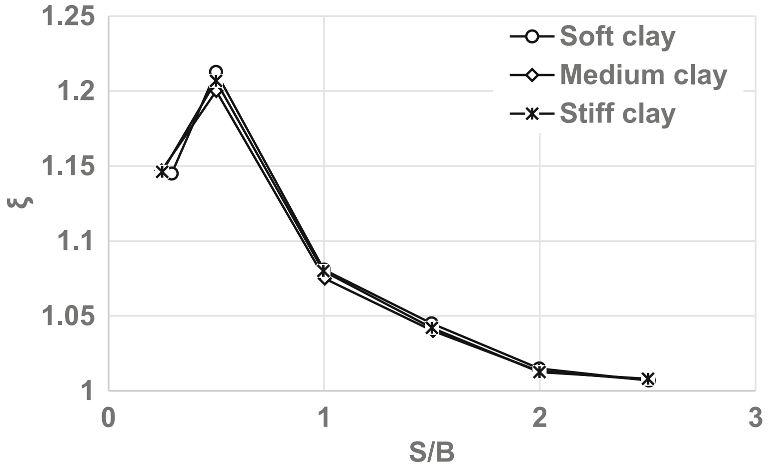


Fig. 7 Relationship between the bearing capacity ratio and the distance ratio for an embedment ratio of 0.50

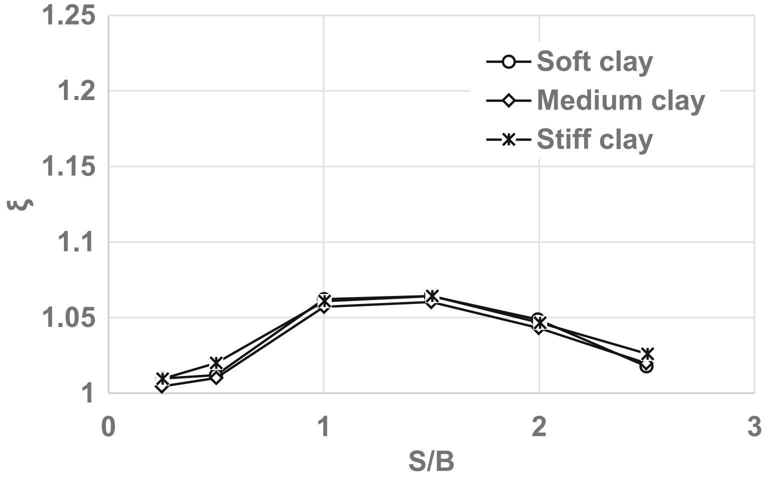


Fig. 8 Relationship between the bearing capacity ratio and the distance ratio for an embedment ratio of 1.00

relationship following a perfect trend for all cases. Nonetheless, the overall trend is obvious and enables drawing comprehensive observations.

6.2 Effect of the Embedment Ratio (D/B)

To explicitly discuss the effect of the embedment ratio, the relationship between the bearing capacity ratio and the distance ratio has been plotted for different embedment ratios for soft, medium, and stiff clays as shown in Figs. 9, 10, and 11.

Figures 9, 10, and 11 show that in general, increasing the embedment depth decreases the maximum bearing capacity ratio with the exception of the case of embedment ratio of 0.25 for S/B less than 1.50. Also, it is clear from the figures that the increase of the bearing capacity is marginal for the embedment ratio of 1.0. In general, the obtained trend can be justified by the decrease of the beneficial effect of the

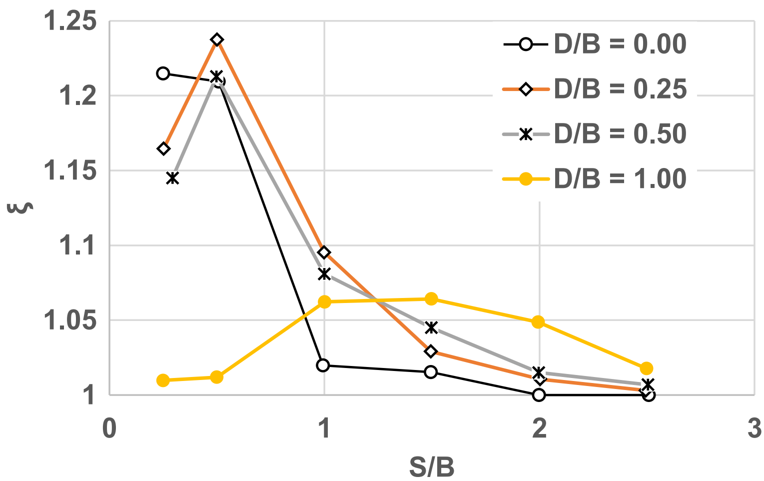


Fig. 9 The effect of the embedment ratio on the bearing capacity ratio for footing resting on soft clay

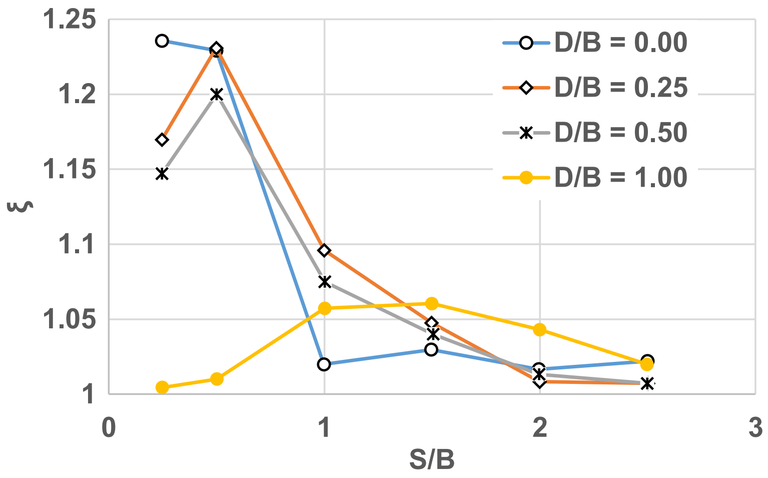


Fig. 10 The effect of the embedment ratio on the bearing capacity ratio for footing resting on medium clay

nearby footings in confining the middle footing when the embedment ratio increases as the single footing that has been considered as a reference also benefited from the confinement due to the overburden pressure when the embedment ratio rises. This justification also clearly explains the observation regarding the marginal effect of the interface for the case of embedment ratio of 1.0 (i.e., higher confinement led to less beneficial effect from the interference).

On the other hand, Figs. 9, 10, and 11 show that increasing the embedment ratio increases the distance ratio at which the peak bearing capacity ratio is recorded, where the peak bearing capacity ratio is recorded at S/B of 0.25, 0.50, 0.50, and 1.50 for embedment ratio of 0, 0.25, 0.50, and 1.00, respectively. This indicates that the passive wedge's location shifts horizontally as the overburden pressure increases. Hence, the distance ratio at which the peak bearing capacity ratio is recorded also shifts. It is worthy to state that Abd El Samee (2018) also noticed the shift of the passive wedge as

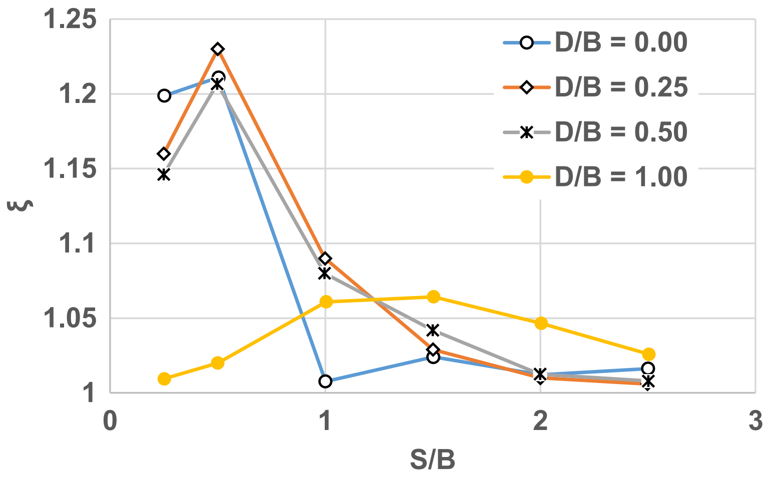


Fig. 11 The effect of the embedment ratio on the bearing capacity ratio for footing resting on stiff clay

the embedment of the foundation increases. Also, Salgado et al. (2004) and Merifield and Nguyen (2006) noticed an extension of the failure zone of the footings vertically and horizontally as the embedment of the footing rises, which also indicates a shift of the passive wedges as the embedment ratio rises.

Finally, it is worthy to stress that to the best of the author's knowledge this study is the first study that is concerned with the interference of three footings in an undrained condition. Hence, it is not possible to compare the obtained results from this study with previous studies as previous studies have either considered the drained condition (i.e., assuming a cohesionless soil) or considered only two footings in the undrained condition.

7 Conclusions

This paper investigated the bearing capacity of a new strip footing constructed between two existed (old) strip footings resting on three types of clayey soils (soft, medium, and stiff) in an undrained condition. A numerical model has been developed for this purpose. The clayey soils have been modeled using an elastic perfectly plastic model with the Mohr-Coulomb failure criteria and the footings have been modeled using the linear elastic model. The finite element model has been validated before conducting the parametric study to ensure that the results produced in this paper are robust and, hence, will be useful for future studies. The effect of the distance ratio (the distance between the new and old footings), embedment ratio, and undrained shear strength has been considered in the research to produce a thorough insight into the problem. Based on the results obtained in this study, the following conclusions can be emphasized:

1. The bearing capacity values obtained from the finite element analyses for soft, medium, and stiff clays are in fair agreement with those calculated using Terzaghi bearing capacity factors and Hansen bearing capacity factors.
2. There is no significant effect for the undrained cohesion (i.e., clayey soil strength) on the relationship between the bearing capacity ratio and the distance ratio.
3. Overall, the presence of the old footings improves the bearing capacity of the new footing as the interference footings will work as a combined system that distributes the applied load over the entire area of the interference and hence increases the area over which the applied load is distributed. Also, the loads applied from the existed footings confine the passive wedges that are developed due to loading the new footing to the failure, and hence, the confinement improves the bearing capacity of the new footing.
4. The average maximum percentage increase of the bearing capacity is equal to 22%, 23%, 21%, and 6% for embedment ratio of 0.00, 0.25, 0.50, and 1.00, respectively. This peak maximum percentage increase is recorded at distance ratio of 0.25, 0.50, 0.50, and 1.50 for embedment ratio of 0.00, 0.25, 0.50, and 1.00, respectively.
5. The embedment ratio has a dramatic impact on the trend of the relationship between the bearing capacity ratio and the distance ratio and also on the percentage increase of the bearing capacity due to the interference effect. This is due to the shift of the passive wedges of the middle footing as the embedment ratio increases.

6. The critical distance at which the peak bearing capacity ratio is achieved increases as the embedment ratio rises. Again, this is due to the extensions of the passive wedges in the horizontal direction as the embedment ratio rises.

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