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Assessment of two nearby interfering strip footings of different embedment depths in saturated cohesive soils

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Abstract. There are instances where foundations are closely spaced, such as around railroad sleepers and foundations close to property lines. In such circumstances, the stress isobars of the separate footings may interact and combine to generate an overlapping stress isobar that affects a wider zone of the foundation soil and alters the individual foundations behavior, which would be different from that of the isolated footings. As a result, an examination of such issues should be conducted by taking into account all the variables that realistically affect the interference behavior of such closely spaced footings. This paper has been conducted to understand the behaviour of closely placed strip footings of different depths embedded in saturated cohesive soils under various factors such as the groundwater table, soil undrained shear strength, footing depth, and the spacing between footings using a three-dimensional finite element model (Midas GTS-NX). The evaluated ultimate bearing capacity (UBC) and settlements are represented in terms of non-dimensional efficiency factors for UBC: ξ_L/ξ_R (Left/Right). It was concluded that when the spacing between footings is increased from S/B = 1 to 2, there would be an increase in the UBC of both footings when D_{fr}/D_{fl} increases, then the bearing capacity decreases when S/B is increased to 4. For footings of different embedment depths, when the ground water table is deep (at 4 m depth), the values of UBC ratio ξ_R increase with S/B while ξ_L decreases. This is because of various embedment between the two adjacent footings. In all cases, when the ground water table is at the ground surface, lower values in ξ_L are at Cu = 60 kPa, while the higher values in ξ_R are found at this strength.

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1. Introduction

One significant design factor to take into account is the settlement of foundations under working load situations. Designed effectively foundations cause the soil to develop stress-strain conditions that are neither linearly elastic nor perfectly plastic [1]. Settlements usually prioritize footing construction over bearing capacity when working with soft clay and sand. Therefore, for the construction of shallow foundations, settlement calculations are crucial. The impact of nearby footings is usually disregarded while assessing isolated footing capacity when taking permissible settlement requirements into account. In this regard, numerous studies using both experimental and numerical methods have been performed to determine the interference impact of two nearby shallow foundations [2].

According to Kumar and Ghosh (2007) [3], an upper bound limit analysis was used to ascertain the ultimate bearing capacity (UBC) of two closely spaced strip footings installed on a cohesionless medium that were loaded simultaneously to failure at the same magnitude of the failure load. Each footing edge was assumed to have a logarithmic spiral radial shear zone made up of many triangular rigid blocks. The ultimate bearing capacity was discovered to correspond to a specific essential spacing between the two footings. For spacing greater than the critical, it was discovered that the bearing capacity decreased continuously as the distance increased. The obtained results indicate a reasonable degree of agreement with the available experimental and theoretical data.

In the article [4], an attempt has been made to simulate the settling behavior of two strip footings situated near each other on a layered soil deposit, featuring a strong upper layer and a weaker lower layer. The governing differential equations were derived using the theory of elasticity and then solved using the finite difference analysis. Many parameters have been investigated on the settlement behavior of closely spaced footings, such as the footing load, clear distance between the footings, and the elastic moduli and thickness of the two layers. The results of the theoretical investigation show that the settlement of closely spaced footings is larger than that of a single isolated footing and that the settlement decreases as the spacing between the footings increases.

The interaction of two closely spaced rigid strip footings resting on a homogeneous soil bed was examined in [2] using finite element analysis (FEA) in order to find their UBC and settlement behavior subjected to inclined loading. The foundation soil was modeled as elastoplastic material obeying the Mohr-Coulomb failure criterion. Numerous parametric studies were performed by varying the angle of inclination of load and clear spacing between the footings. The findings showed that both bearing capacity and settlement of interacting footings compared to that of an isolated footing increased with decrease in spacing, whereas the effect on the UBC for footings was not significant.

On the other hand, the performance of two closely spaced strip footings resting on the surface of the semi-infinite clay soil medium was examined [4]. Two-dimensional plane strain FEA was used to observe the effect of interference on characteristic behavior such as bearing pressure, tilt, and settlement. A parametric study has been conducted by altering the clear spacing and depth of the footings and examining the impact of these changes on the load-settlement characteristic, bearing pressure, and settlement variation with clear spacing. The study concluded that the interference impacted the isolated footing's performance. In contrast, the study observed an increase in settlement compared to the isolated footing, and a decrease in bearing pressure as the clear spacing between the footings decreased.

Parametric studies were done in [6] for two foundations by varying the spacing between the foundations and the footing width. In the first instance, both footings were simultaneously loaded up to failure. In the second instance, an already existing footing was loaded with half of the estimated failure load of single independent strip footing and second adjacent footing was loaded up to failure. The interference effect was observed to be particularly significant in terms of the settlement and tilt. In addition, it was observed that the presence of shear keys has a significant effect on interference between footings when compared to not having them, particularly in reducing foundation tilt.

However, the impact of the embedment on the interaction of closely spaced footings is seldom highlighted. In order to better understand the effect of footing depth on the interference effect, two adjacent interfering strip footings at different depths in saturated cohesive soils were studied.

In this study, two strip footings are considered to investigate the effect of their interference on the bearing capacity of saturated cohesive soils. The strip footings have 0.3 m of thickness (H) and 2.0 m of width (B), as shown in Fig. 1. In addition, the depth of footings (Df), the spacing between footings (S), the undrained shear strength of the clay (Cu), and the groundwater table level (GWT) are changed. As a result, FEA is applied to each case. Table 1 lists the parametric studies considered in this analysis.

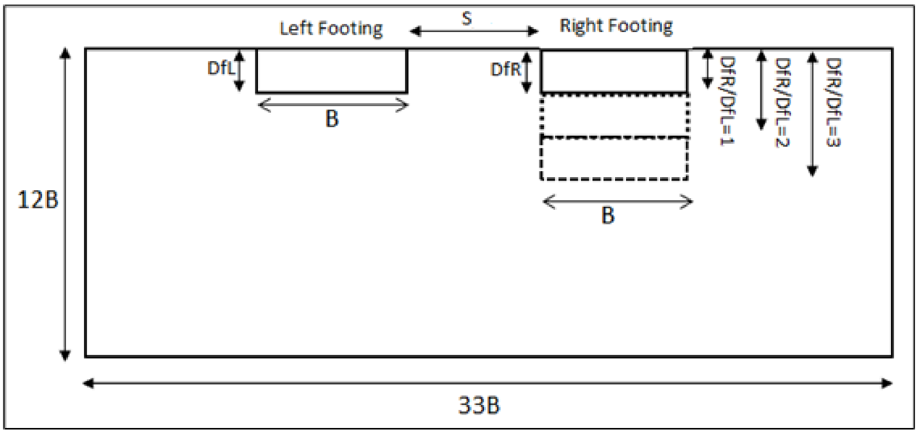


Figure 1. Schematic representation of nearby footings.

Table1. Soil properties, footings, and parametric studies.

Parameters	γ, kN/m³	Cu, kN/m²	E, kN/m²	υ
Clay	18	40	40000	0.3
		60	60000	
		100	100000	
Footings	24		25x10⁶	0.2
Range of varying parameters				
S/B	0.5	1	2	4
GWT	0	2	4	
Cu	40	60	100	
Special Case: Footings of different depths				
Depth of left footing, Dfl		1 m	1 m	1 m
Depth of right footing, Dfr		1 m	2 m	3 m
Dfr/Dfl		1	2	3

2. *Methods*

2.1. *Finite Element Method*

In this study, the behavior of closely spaced strip footings embedded in saturated cohesive soils is examined numerically using a finite element analysis (Midas GTS-NX). The model size was 33B x 12B in both horizontal and vertical directions, with B representing the width of the strip footings. These dimensions were sufficient to reduce boundary effects in numerical modeling, as increasing mesh size did not affect the study results. Furthermore, the mesh simulation was conducted using a reasonably fine mesh close to the strip footings and a coarser mesh further away from these zones. The boundary condition assumed that the bottom surface was hinged to prevent both horizontal and vertical movement and that a roller had been applied to the right and left sides of the soil to permit only vertical movement [7-10]. Fig. 2 displays the geometrical boundaries and plane strain mesh. It is important to note that the load on each footing is applied with uniform pressure. The mesh of this model has 6591 components and 6706 nodes. Due to the auto mesh generating method used by the Midas GTS-NX program, it should be noted that the numbers of elements and nodes in each model differ slightly.

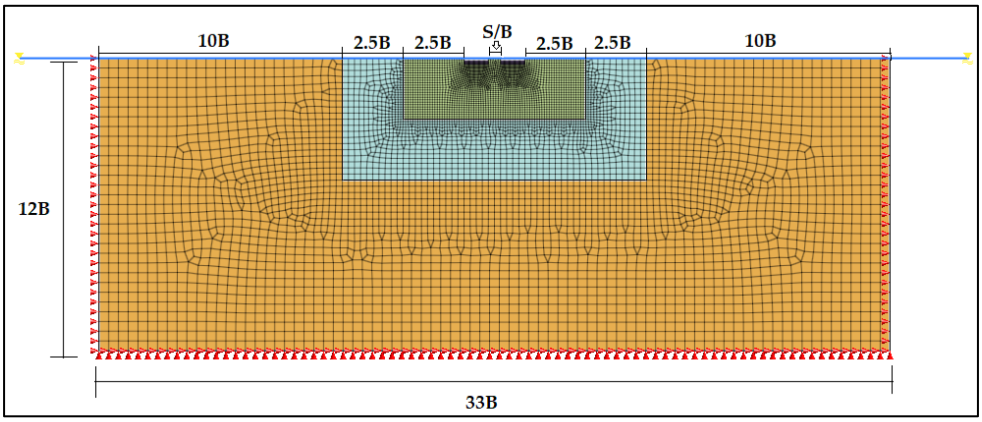


Figure 2. Finite element mesh of the problem and boundary conditions.

The soil was simulated using the Mohr-Coulomb constitutive model because of its simplicity and correctness [11]. This model is widely used in the FEA of geotechnical engineering, including the undrained bearing capacity problems [12–22]. In addition, a linear elastic model was used to simulate the footings. Table 1 presents the required soil and footing parameters.

In the current study, all the models are simulated using Midas GTS-NX utilizing the undrained parameters. Consequently, the dilation angle (ψ) and friction angle (φ) are equal to zero under undrained conditions. Moreover, the undrained modulus of clays (E_u) is estimated using the following equation, which is suggested by [23]:

$$E = (100 - 1000)Cu. \tag{1}$$

Fundamental to note that the undrained Poisson's ratio for soil undrained is used with 0.495 rather than 0.50 to evade any numerical issues. In addition, the drainage parameter is selected with the third option: Undrained (Effective stiffness/Undrained strength) in Midas GTS-NX. Furthermore, the lateral earth pressure coefficient at rest $\left(k_0\right)$ has been computed as 1.00, using the following equation:

$$k_0 = \frac{v}{(1-v)}, \tag{2}$$

where v is undrained Poisson's ratio.

2.2. Construction Stages

The two-dimensional model was constructed using the same soil characteristics and footing elements stated in Table 1. The stages are summed up as follows:

1. Initial Stage (I.S): this stage starts with applying the gravity load to create the initial soil stress prior to the installation of strip footings. Also, the boundary conditions were activated in this stage.
2. Stage 1 (S1): Both footings are installed. Moreover, the displacements were reset to zero at this stage to begin calculating the bearing capacity resulting from the applied loads alone.
3. Stage 2 (S2): the loads were applied using Forty incremental loading steps to simulate the load-settlement behavior.

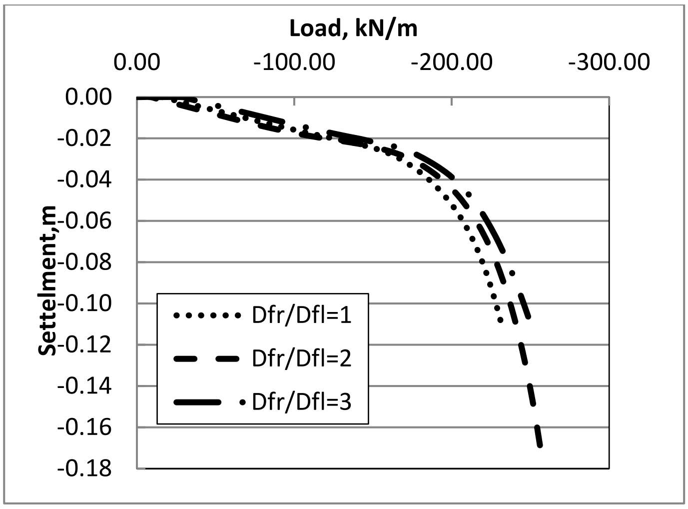
2.3. Definition of Bearing Capacity Ratio (ξ)

The evaluated UBC $\left(q_u\right)$ and settlements are represented in terms of non-dimensional efficiency factors for UBC: ξ_L/ξ_R (Left/Right).

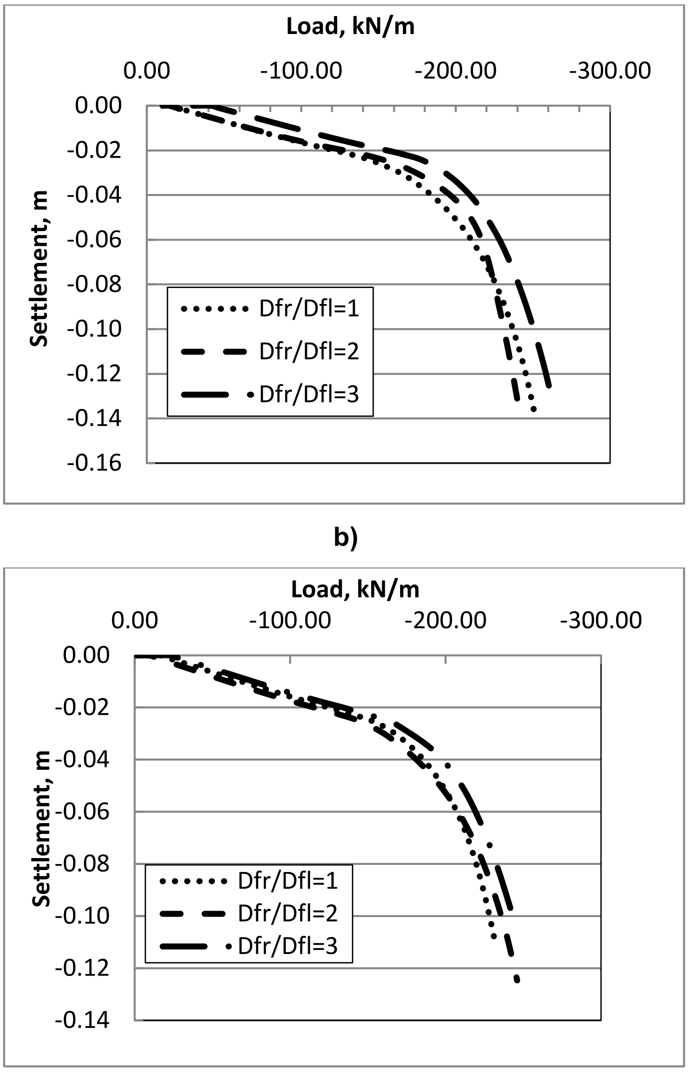
$$\xi_L/\xi_R = \frac{q_u \text{ of left/right footing in presence of right/left footing}}{q_u \text{ of identical isolated footing}}. \tag{3}$$

3. Results and Discussions

Fig. 3 shows the load-settlement curves for the two nearby footings in clayey soil with Cu = 40 kPa of different embedment depths and water table level. The values of bearing capacity of all the cases analyzed in this study are summarized in Table 2.



a)



b)

c)

Figure 3. Load settlement curve on soil with Cu = 40 kPa for left and right footing with S/B=0.5 and a) GWT= 0, b) GWT = 2 m and c) GWT = 4 m.

Table 2. Ultimate bearing capacity of footings based on the load settlement curves.

Cu, kPa	GWT m	S/B	D_{fr}/D_{fl}	q_u kPa	Cu kPa	GWT m	S/B	D_{fr}/D_{fl}	q_u kPa	Cu kPa	GWT m	S/B	D_{fr}/D_{fl}	q_u kPa
40	0	1	1	280	60	0	1	1	350	100	0	1	1	588
			2	285				2	365				2	594
			3	290				3	375				3	600
		2	1	250			2	1	340			2	1	580
			2	260				2	350				2	587
			3	275				3	365				3	596
		4	1	245			4	1	338			4	1	575
			2	250				2	347				2	582
			3	265				3	355				3	588
	2	1	1	290		2	1	1	375		2	1	1	592
			2	294				2	383				2	597
			3	300				3	390				3	605
		2	1	255			2	1	365			2	1	585
			2	265				2	374				2	592
			3	278				3	380				3	598

Cu, kPa	*GWT* m	*S/B*	D_{fr}/D_{fl}	q_u kPa	*Cu* kPa	*GWT* m	*S/B*	D_{fr}/D_{fl}	q_u kPa	*Cu* kPa	*GWT* m	*S/B*	D_{fr}/D_{fl}	q_u kPa
		4	1	253			4	1	360			4	1	580
			2	260				2	367				2	585
			3	269				3	375				3	592
	4	1	1	295		4	1	1	390		4	1	1	595
			2	300				2	395				2	600
			3	305				3	403				3	607
		2	1	275			2	1	383			2	1	590
			2	280				2	390				2	594
			3	287				3	397				3	601
		4	1	265			4	1	378			4	1	585
			2	270				2	384				2	593
			3	280				3	390				3	597

It is noticed that the bearing capacity values increase with the increase of the undrained shear strength, depth of footing, and water table depth.

When the spacing between footings is increased from S/B = 1 to 2, there would be an increase in UBC of both footings when Dfr/Dfl increases. In addition, the bearing capacity decreases when S/B is increased to 4. This can be illustrated as follows. When S/B = 1, there must be some interlocking between the failure slip surfaces of the nearby footings, which decreases the ultimate bearing capacity, such interlocking is overcome when S/B becomes 2. As the spacing ratio increases to S/B = 4, the footings act separately and the effect of confinement vanishes.

According to test results obtained by [24, 25], the presence of a bounding wall has a significant impact on bearing capacity, improving it by varying percentages depending on the wall's depth and distance from the edge of the footing. This improvement is caused by an increase in soil confinement beneath the footing.

3.1. *Footings of Different Depths*

Fig. 4–7 present the variation of bearing capacity ratio for the left and right footings with Cu for different spacing between footings and water table level. Table 3 summarizes the values of ξ_L and ξ_R for different S/B values when Cu = 40 kPa. Table 4 present the values for footings with Cu = 60 and 100 kPa. In all cases, when the ground water table is at the ground surface, lower values in ξ_L are at Cu = 60 kPa, while the higher values in ξ_R are found at this strength.

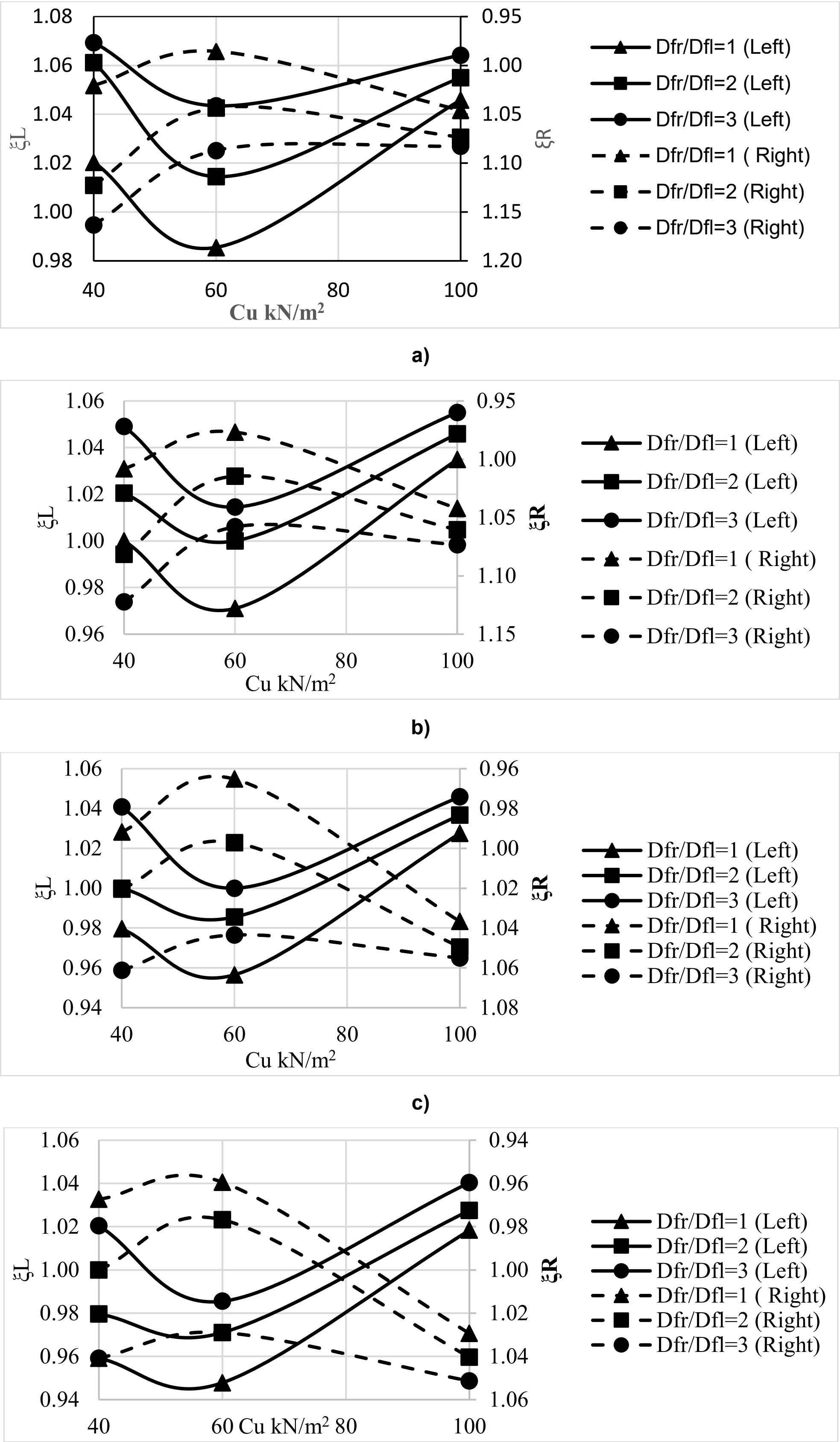
Table 3. Variation of ξ_L and ξ_R with S/B for D_{fr}/D_{fl}, Cu = 40 kPa.

GWT (m)	*S/B*	D_{fr}/D_{fl}	ξ_L	ξ_R
0	1	1	1.00	1.01
		2	1.02	1.08
		3	1.05	1.12
	2	1	0.98	0.99
		2	1.00	1.02
		3	1.04	1.06
	4	1	0.96	0.97
		2	0.98	1.00
		3	1.02	1.04
2	1	1	0.99	1.00
		2	1.03	1.05
		3	1.05	1.08
	2	1	0.98	1.00
		2	1.02	1.04

GWT (m)	S/B	D_{fr}/D_{fl}	ξ_L	ξ_R
		3	1.04	1.06
	4	1	0.98	0.97
		2	1.01	1.02
		3	1.02	1.05
4	1	1	0.99	1.00
		2	1.03	1.05
		3	1.05	1.08
	2	1	0.98	1.00
		2	1.02	1.04
		3	1.04	1.06
	4	1	0.98	0.97
		2	1.01	1.02
		3	1.02	1.05

Table 4. Extent of variation of ξ_L and ξ_R with S/B for D_{fr}/D_{fl}, Cu = 60 and 100 kPa.

Cu (kPa)	GWT (m)	S/B	D_{fr}/D_{fl}	ξ_L	ξ_R	Cu (kPa)	GWT	S/B	D_{fr}/D_{fl}	ξ_L	ξ_R
60	0	1	1	0.97	0.98	100	0	1	1	1.03	1.04
			2	1.00	1.01				2	1.05	1.06
			3	1.01	1.06				3	1.06	1.07
		2	1	0.96	0.97			2	1	1.03	1.04
			2	0.99	1.00				2	1.04	1.05
			3	1.00	1.04				3	1.05	1.06
		4	1	0.95	0.96			4	1	1.02	1.03
			2	0.97	0.98				2	1.03	1.04
			3	0.99	1.03				3	1.04	1.05
	2	1	1	0.96	0.97		2	1	1	1.02	1.03
			2	0.99	1.00				2	1.03	1.05
			3	1.01	1.03				3	1.04	1.06
		2	1	0.95	0.96			2	1	1.01	1.02
			2	0.97	0.99				2	1.02	1.04
			3	1.00	1.01				3	1.03	1.06
		4	1	0.94	0.95			4	1	1.00	1.02
			2	0.96	0.98				2	1.01	1.04
			3	0.97	1.00				3	1.02	1.05
	4	1	1	0.95	0.96		4	1	1	1.02	1.03
			2	0.99	1.01				2	1.03	1.04
			3	1.01	1.02				3	1.04	1.05
		2	1	0.94	0.95			2	1	1.01	1.02
			2	0.97	0.98				2	1.02	1.03
			3	0.99	1.00				3	1.03	1.04
		4	1	0.93	0.94			4	1	1.00	1.01
			2	0.96	0.97				2	1.01	1.02
			3	0.98	0.99				3	1.02	1.04



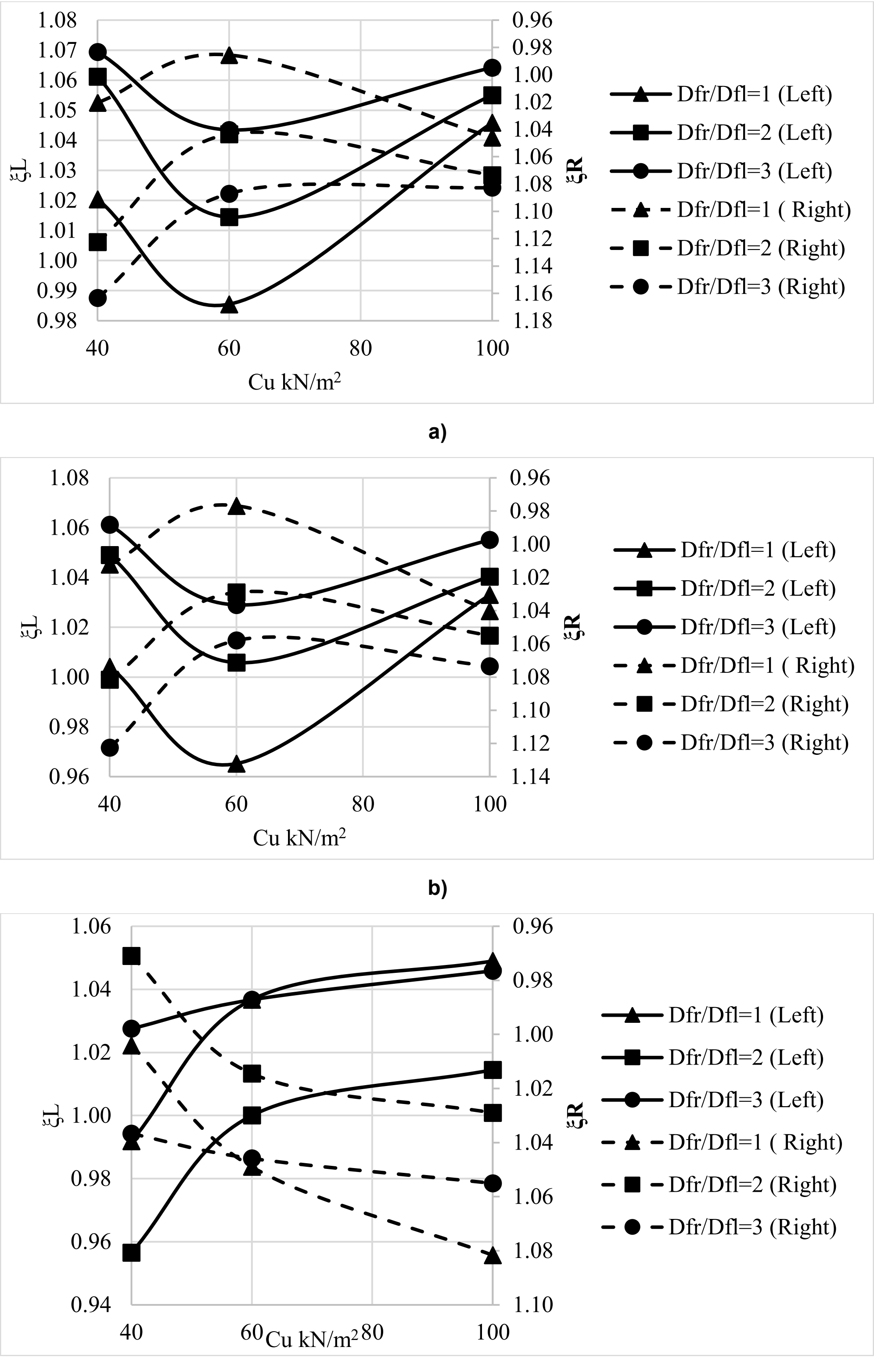
a)

b)

c)

d)

Figure 4. Variation of ξ_L ξ_R with Cu for different D_{fr}/D_{fl} (left and right footing) and GWT = 0 for a) S/B = 0.25, b) S/B = 1, c) S/B = 2 and d) S/B = 4.

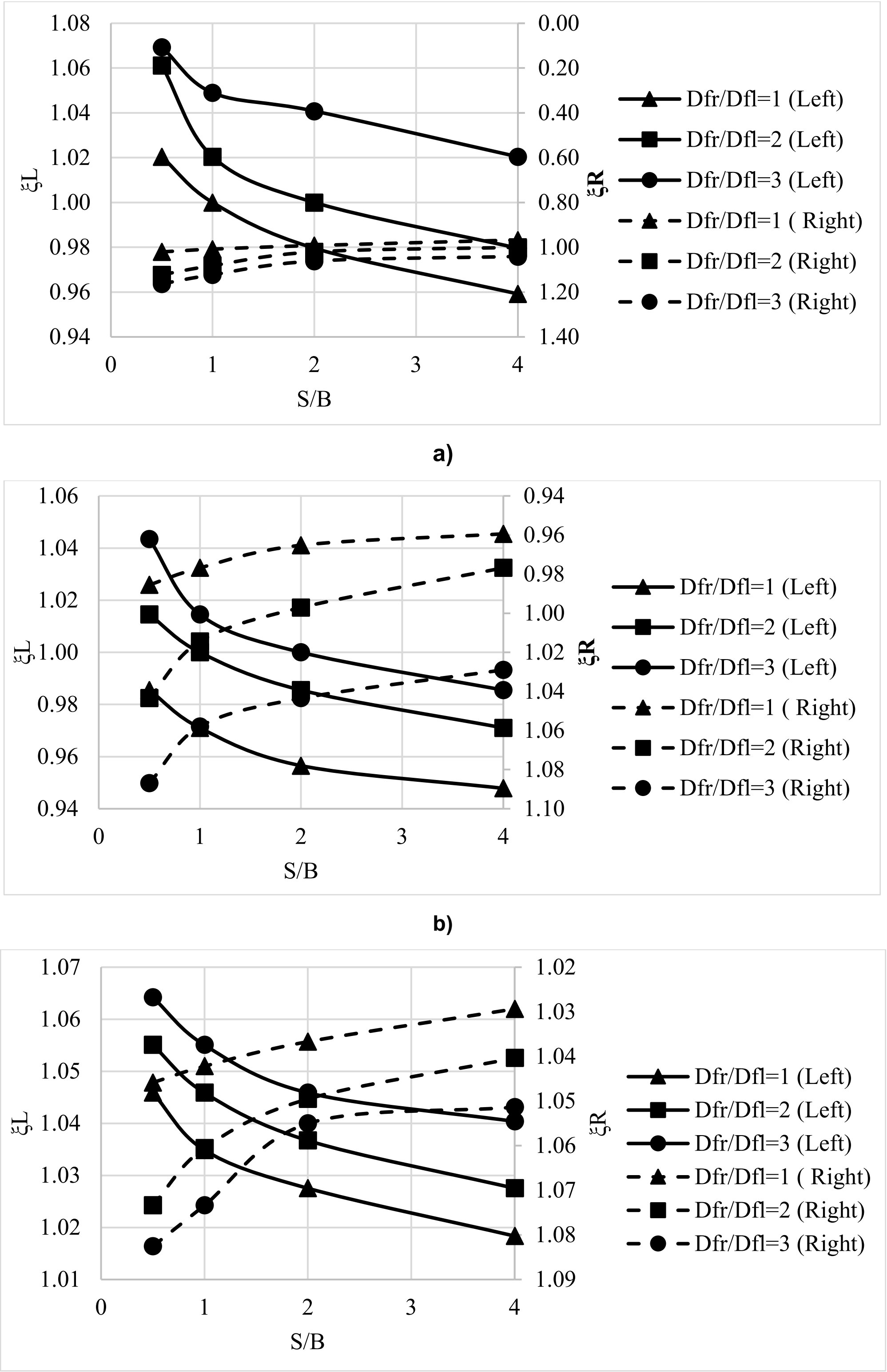


a)

b)

c)

Figure 5. Variation of ξ_L, ξ_R with Cu for different D_{fr}/D_{fl} (left and right footing) and S/B = 0.5 for a) GWT = 0, b) GWT = 2 m, and c) GWT = 4 m.

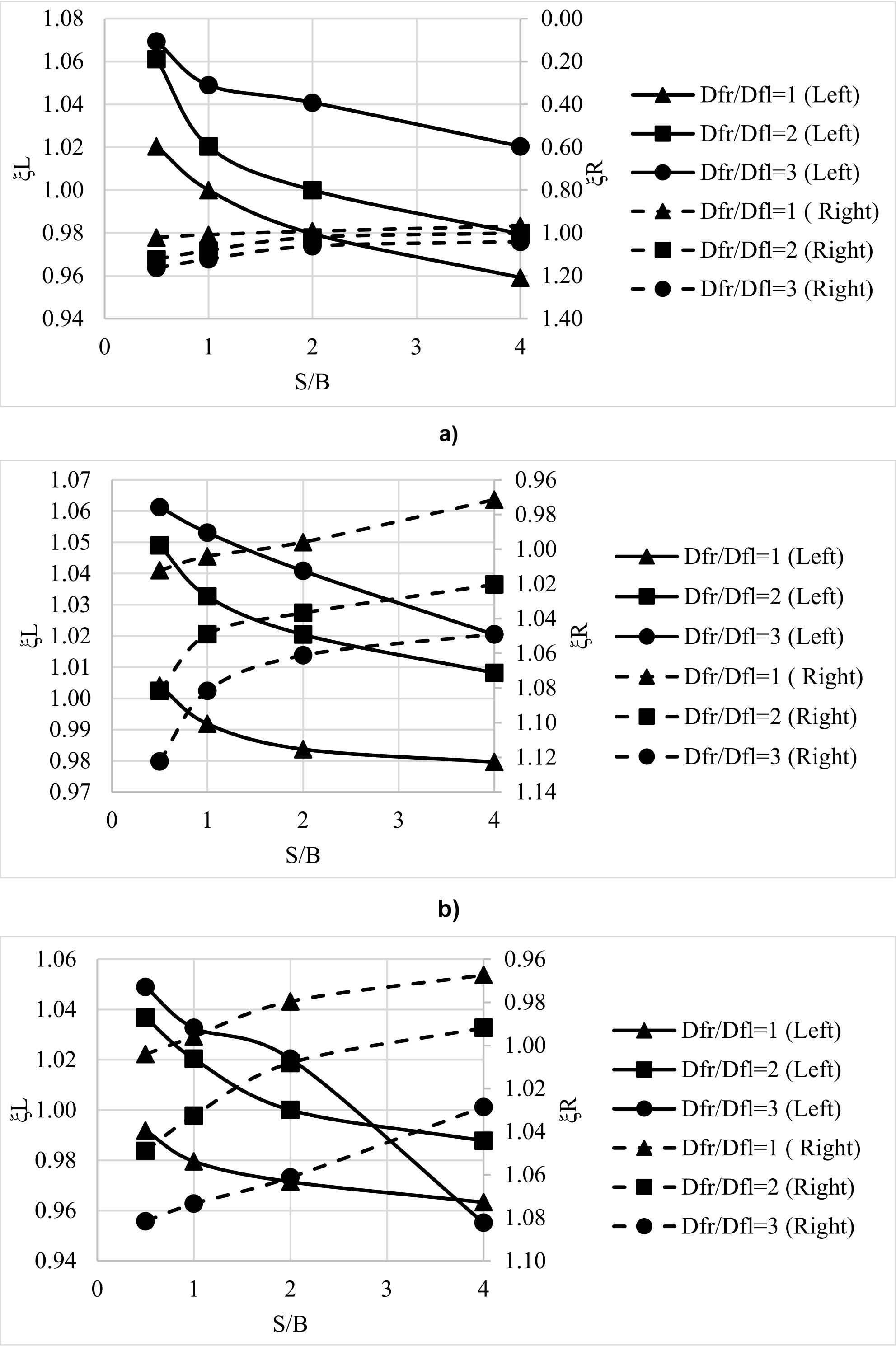


a)

b)

c)

Figure 6. Variation of ξ_L, ξ_R with S/B for different D_{fr}/D_{fl} (left and right footing) and GWT = 0 for a) Cu = 40, b) Cu = 60, and c) Cu = 100.



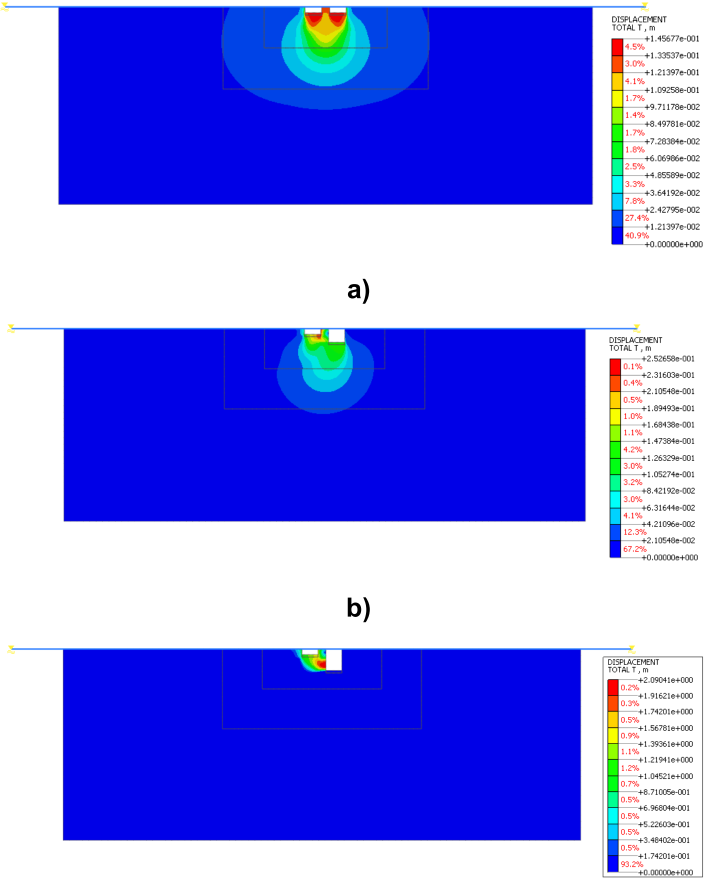
a)

b)

c)

Figure 7. Variation of ξ_L, ξ_R with S/B for different D_{fr}/D_{fl} (left and right footing) and Cu = 40 for a) GWT = 0, b) GWT = 2, and c) GWT = 4 m.

When the ground water table is deeper (at 4 m depth), the values of ξ_R increase with S/B while the values of ξ_L decrease. This is caused by the embedment of right footing. Fig. 8 displays clearly the extension of failure zones below footings when the depth of nearby footings changes from D_{fr}/D_{fl} = 1 to 2 and 3.



a)

b)

c)

Figure 8. Total-displacement contour plots for footings of different depths when Cu = 40 kPa, GWT = 0, and S/B = 0.5 for a) D_{fr}/D_{fl} = 1, b) D_{fr}/D_{fl} = 2, and c) D_{fr}/D_{fl} = 3.

4. Conclusions

This paper examined the impact of two adjacent interfering strip footings embedded in saturated cohesive soils. For this purpose, the finite element program Midas GTS-NX has been adopted. The following major conclusions can be drawn from the results:

1. The soil cohesion and the footing depth ratio have a notable influence on the interference of closely spaced footings.
2. When the spacing between footings is increased from S/B = 1 to 2, there would be an increase in the ultimate bearing capacity of both footings when D_{fr}/D_{fl} increases, then the bearing capacity decreases when S/B is increased to 4.
3. For footings of different embedment depths, when the ground water table is deep (at 4 m depth), the values of ξ_R increase with S/B, while the values of ξ_L decrease. This is caused by the embedment of right footing.
4. In all cases, when the ground water table is at the ground surface, lower values in ξ_L are at Cu = 60 kPa, while the higher values in ξ_R are found at this strength.

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