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BEHAVIOURAL ASSESSMENT ON INFLUENCE OF ADJACENTLY PLACED STRIP FOOTINGS AT DIFFERENT EMBEDMENT LEVEL

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Abstract
The footings laid in close proximity imposes a definite change in the behaviour of the adjacent footing, subsequently changing the behaviour of the nearby footings. The present study emphasises the behaviour of the nearby strip footings embedded at a different level by adopting the commercially available finite element analysis program, ABAQUS. The load-settlement behaviour, ultimate bearing capacity (*UBC*), and the failure patterns of adjacent strip footings are assessed by considering the Mohr-Coulomb failure criterion. The *UBC* is of the nearby footings (left and right) are estimated and represented in terms of interference factors (ξ_L/ξ_R) defined as the *UBC* of a footing in the presence of adjacent footing to that of same considered for equivalent isolated footing. The results reveal that a significant influence of the adjacent footing is experienced when the spacing between the footings (S/B) is lesser, and they behave as the single footing of greater width at S/B = 0.25 irrespective of the level of embedment depth. Furthermore, the influence of interference increases with the increase in the embedment depth of adjacent footing. It is found that the ξ_L is significantly more for a lower level of embedment depth, and the same increases with an increase in the embedment depth of the right footing but on the contrary ξ_R decreases. The increase in the peak interference factor, $\xi_{L\text{-}max}$ for D_L/B = 0.5 is 2.1% and 4.2% when D_R/B = 0.75 and D_R/B = 1.0, respectively.

Keywords: **Interference of footings; Embedment depth; Ultimate bearing capacity; Load-settlement behaviour.**

1. INTRODUCTION

The load transfer for numerous civil engineering constructions occurs through the sub-structures termed the foundations. On several occasions, such as rapid urbanisation and population growth, the buildings are constructed nearby; thus, foundations are built up in close proximity. In such a situation, the stress distribution due to the adjacency and subsequent effects imposed by a group of foundations changes the behaviour of the footings as it should be. The characteristic behaviour beneath the foundation changes, bringing about deviant behaviour compared to the theory postulated by foundation engineering pioneers. The effect leads to the modifications in load-settlement characteristics, ultimate bearing capacity, settlement behaviour and the failure mechanism. Several researchers coined such modifications as interference of footings and attracted quite a few geotechnical engineers.

Several reports are published after the pioneering work reported by Stuart [1] using different analytical/numerical methods and experimental observations.

The studies offering the understanding of two or multiple interfering footings using analytical/numerical methods use upper and lower bound limit analysis [2–7], finite difference method [8–10], finite element method [11–18] and analytical method [19, 20], the probabilistic method [21] and others [22]. Then several experimental studies [23–29] have been reported on the interference of surface footings. Lavasan et al. [30] studied the behaviour of two adjacent rigid, rough strip footings laid on the surface of sand by employing finite difference method (FDM) and kinematic element methods (KEM). The ultimate bearing capacity was determined using finite difference based code $FLAC^{3D}$ by modelling soil domain using non-associated flow rule obeying Mohr-Coulomb failure criterion. The 2-dimensional KEM is developed by using the associated flow rule. A failure mechanism was proposed by considering several rigid elements bounded by plane boundaries with translational movement, restricting possible rotations. Ghosh *et al.* [20] conducted a small strain problem analysis using the Pasternak model by considering linear and non-linear elastic analysis to determine the interference effect of two closely placed strip footings experiencing a uniformly distributed load on the settlement response. In the analysis, the parameters such as the width of the right footing (by keeping the left footing constant), load on the foundation, and the rigid base's depth were varied. The results were presented in terms of interaction factors. Yang *et al.* [3] presented the investigations on the ultimate bearing capacity factor (N_γ) and failure mechanism of multiple interfering footing employing upper bound finite-element analysis considering the rigid translatory moving elements. The footings were placed at equal spacing on the surface of the soil. The footings were assumed to fail simultaneously. Lavasan *et al.* [31] performed the investigation to determine the ultimate bearing capacity of two closely spaced rough, rigid, surface strip footings. The numerical analysis is carried out using enhanced limit equilibrium, plastic limit analyses, and finite-difference solutions and two different failure mechanisms are proposed. The failure mechanism was based on the limit equilibrium, with an assumption of a non-symmetrical triangular elastic wedge trapped under the base of the footing, wherein the failure mechanism corresponds to minimum collapse load by integrating an optimisation algorithm for any given friction angle. Besides, kinematic limit analyses were based on a quadrilateral-shaped trapped non-plastic wedge beneath the footings. Shokoohi *et al.* [32] applied the finite element method and limiting equilibrium method to estimate the bearing capacity of adjacently placed surface strip footings. They presented the limit equilibrium solution to estimate the bearing capacity by including the correction factors associated with the interference of footings. Using the finite element analysis, the shear stress failure pattern of closely spaced footings was determined and compared with the theoretical solution provided by Stuart [1]. It was observed that at close proximity, the triangular passive zone was formed between the two footings, and the zones of shear failure increased in size. As the spacing was further reduced, the two footings were found to act as a single unit of double the width. In order to provide a bearing capacity equation, they assumed a relatively rigid soil block entrapped in a region between the two footings, which increases its resistance to the applied load. Fuentes *et al.* [14] performed the numerical analysis aided by a 3-dimensional boundary value finite element problem to study the interference behaviour of closely spaced shallow square footing using the software ABAQUS. They considered different embedments of the footing by prescribing an equivalent surcharge load rather than modelling the embedded footing in the soil. The spacing between the footings on the surface of granular soil was varied. They considered the extended Drucker-Prager constitutive model to model the soil behaviour. Further, the results obtained from finite element analysis were used to fit the linear regression analysis model for multiple variables. Using the variable parameters such as the effect of embedment depth and spacing between the footings, they proposed a relation to determine the bearing capacity of closely spaced square footings. Nainegali *et al.* [12] studied the interference phenomenon on the response of bearing capacity and settlement characteristics at permissible/working range of proposed newly constructed footing placed in the proximity of an existing footing. By considering an identical width of both footings, they varied the spacing between the footings and assumed that the footings were loaded simultaneously to failure. The effect of interference is observed to be reasonably higher for dense sand in terms of bearing capacity.

Chenari and Mohafezatkar [33] proposed reducing undesirable settlements due to buildings' adjacency. By carrying out numerical analysis using $FLAC^{3D}$, the parameters such as the limits to the storeys and embedment depth of the nearby new foundations are a few ways of improving the *UBC* of soil beneath both old and new foundations. Jayamohan et al. [34] investigated the additional settlements experienced by a strip footing due to the loading on adjacent strip footing using finite element analyses program, PLAXIS 2D. The additional settlement experienced by nearby footings were further reduced by increasing the spacing between the footings and by introducing micropiles underneath the interfering footings. It was further observed that the additional settlement is occurring due to the relative embedment depth of the footings. Eslami and Moghaddasi [35] presented case studies of domestic buildings constructed in a proximity wherein severe damages were observed due to footings laid up in spacing lesser than the critical. An improvement in the design for the foundation system has been proposed owing to the damages occurring due to tilt in the foundations and serviceability issues. Shahein and Hefdhallah [36] presented a case history of 28 auxiliary buildings of an Electrical Power plant near Cairo, Egypt. By keeping the settlement as the criteria, analyses were carried out by considering the influence of elastic stresses due to adjacent loaded areas at the foundation level by integrating vertical strains of the layered ground. They reported that the influence of neighbouring footing could not be ignored for the settlement computations.

From the ongoing discussion, it is identified that the results reported are those of surficial footings; however, in practice, the footings are seldom found to be laid on the ground level. The interference of footings in an embedment state is rarely acknowledged. Besides, the two adjacent footings may not be laid at the same embedment level considering the nearby footings due to different structures. The present Study addresses the interference effect of two nearby strip footings embedded in a homogenous cohesionless foundation medium at a different level.

2. PROBLEM STATEMENT

Figure 1 illustrates the problem of two adjacent strip footings, marked as left and right footing, embedded in isotropic, homogenous, semi-infinite cohesionless soil medium. The footings are considered a width, B placed at a clear spacing, S from each other and loaded with uniform pressure, q. The adjacent footings are embedded at different depths, entitled D_L for left footing and D_R for right footing. The analysis is to be carried out to assess the effect of interference on load-settlement behaviour, ultimate bearing capacity, and failure envelope of the adjacently placed strip footings. A parametric study is accomplished by varying the clear spacing for different combinations of embedment depths of the left and right footings. The mechanical properties and the varying parameters considered in the analysis are presented in Table 1.

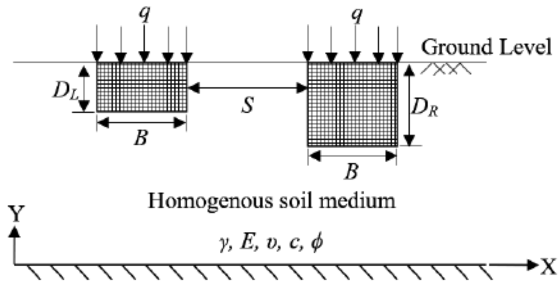


Figure 1.
Geometrical representation of problem definition

Table 1.
Mechanical properties of soil and varying parameters considered in the analysis

Mechanical properties of soil	
Parameters	**Values**
Young's Modulus (E), MPa	32
Poisson's ratio (υ)	0.3
Cohesion (c), kPa	2
Soil friction angle (ϕ), °	30°
Unit weight (γ), kg/m^3	1600
Dilatancy angle (ψ), °	15°
Range of varying parameters	
D_L/B	0.50, 0.75, 1.0
D_R/B	0.50, 0.75, 1.0
S/B	0.25, 0.50, 0.75, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0

3. METHODOLOGY

The Study implicates the finite element analysis of nearby embedded strip footings to assess the effect of interference considering the embedment differences. The analysis is carried out using the commercially available program, ABAQUS. The cohesionless soil domain follows a linear elastic, perfect plastic Mohr-Coulomb failure criterion obeying the non-associated flow rule and the footings are considered as a linear elastic material. The mechanical properties considered for the soil is tabulated in Table 1, and for the footings, the Young's Modulus, E and Poisson's ratio, υ as 25GPa and 0.2, respectively. The problem at hand is taken up as a plane strain problem due to the length of strip footing assumed to be large compared to the width. Henceforth, the domain approximation for analysis has been carried out considering the quadratic continuum plane strain elements (CPE8R). The interface between the soil and the footing is modelled using the interaction feature available in

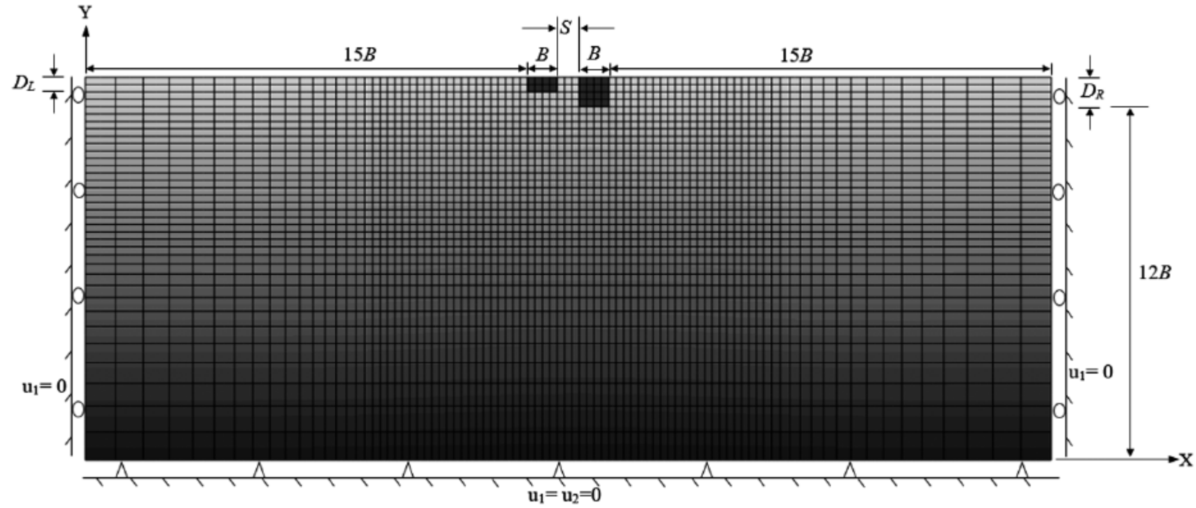


Figure 2.
Discretisation of domain and boundary condition

the ABAQUS (surface-to-surface, master-slave contact option). Using this feature, one surface provides a master surface, and another surface provides a slave surface. Thus, a group of contact elements is generated automatically by defining such surfaces. The interaction simulation consists of normal to the surface and tangential to surface components. The interface in the normal direction is assumed as hard contact with no separation allowed between the surfaces. The tangential component is defined using the Coulomb's friction law by virtue of which tangential behaviour between the contact surfaces is defined using a coefficient of friction, μ, which is equal to the tangent of soil friction angle, ϕ ($\mu = \tan\phi$). The extreme boundaries are prescribed with appropriate conditions following Nainegali *et al.* [11, 12] and Ekbote and Nainegali [15, 17]. The roller supports are considered along with the far end vertical boundaries to restrict the horizontal displacement ($u_1 = 0$) and to allow any possible vertical displacement (u_2) then, the horizontal boundary is considered to be fixed to restrict both horizontal and vertical displacements ($u_1 = u_2 = 0$). The domain discretisation and the associated boundary condition of the problem at hand are illustrated in Figure 2. The size of the domain, discretisation, and size of elements have been adopted by following Ekbote and Nainegali [17]. The size of 15*B* on either side of the footings and 12*B* from the base of the footings has been adopted.

4. RESULTS AND DISCUSSION

The load-settlement (p-δ) behaviour of two adjacently positioned strip footings embedded at different levels is obtained using the finite element analysis tool ABAQUS to comprehend the ultimate bearing capacity and the failure pattern. The p-δ behaviour is obtained for different embedment depths of the adjacent footings and various clear spacing between the footings. The ultimate bearing capacity (*UBC*) is represented in terms of unitless interference factors (ξ_L/ξ_R) for left and right footings presented in equation 1 and are defined as the ratio of UBC of left footing ($q_{u\text{-}L}$) or UBC of right footing ($q_{u\text{-}R}$) to that of UBC of equal isolated footing (q_u) placed at the identical embedment depth.

$$\xi_L = \frac{q_{u-L}}{q_u} \tag{1a}$$

$$\xi_R = \frac{q_{u-R}}{q_u} \tag{1b}$$

The p-δ behaviour of left and right footings when $D_L/B = 0.5$ for $D_R/B = 0.5$, 0.75 and 1.0 is presented in Figure 3, 4, and 5, respectively. Similarly, the p-δ behaviour of left and right footings when $D_L/B = 1.0$ for $D_R/B = 0.5$, 0.75 and 1.0 is presented in Figures 6, 7, and 8, respectively. The p-δ behaviours illustrated in Figure 3 and Figure 8 are those of the symmetrical footings and are found to be in line with the results reported by Ekbote and Nainegali [15]. Moreover, the p-δ behaviours presented in Figure 4 to Figure 7 represent the case of the asymmetry with respect to the embedment depth for left and right footing and a significant divergence in the behaviour may be observed. The extent of clear spacing (S/B) at which the maximum *UBC* is obtained varies for left and right footing. The maximum *UBC* for the symmetrical case of the footings is obtained at $S/B = 0.5$ for both left and right footings embedded at $D_L/B = D_R/B = 0.5$, 0.75 and 1.0. However, the maximum *UBC* is obtained at higher S/B i.e., $S/B = 0.75$ and $S/B = 1.0$ for $D_R/B = 0.75$ and 1.0, respectively when $D_L/B = 0.5$. The influence of adjacent footing is substantially experienced in the vicinity. Similar observations can be made for Figure 6, Figure 7 and Figure 8. Furthermore, the p-δ curves are observed to deviate from isolated footing due to the inherent interference effect; however, it is relatively more when the adjacent footing is at a higher embedment depth.

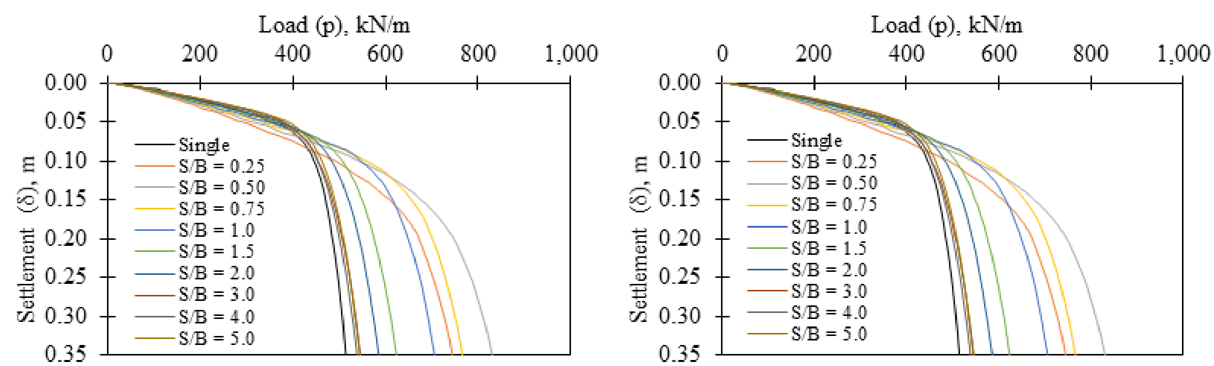


Figure 3.
p-δ behaviour for $D_L/B = 0.5$ and $D_R/B = 0.5$

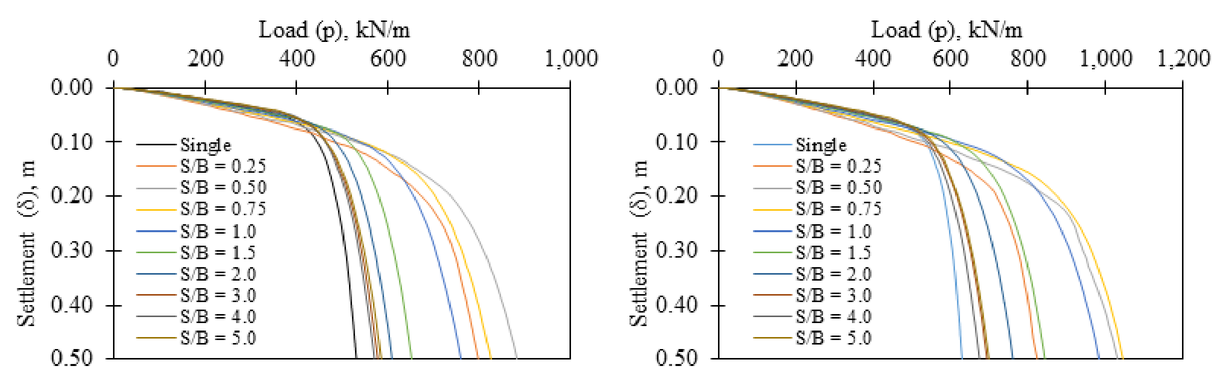


Figure 4.
p-δ behaviour for $D_L/B = 0.5$ and $D_R/B = 0.75$

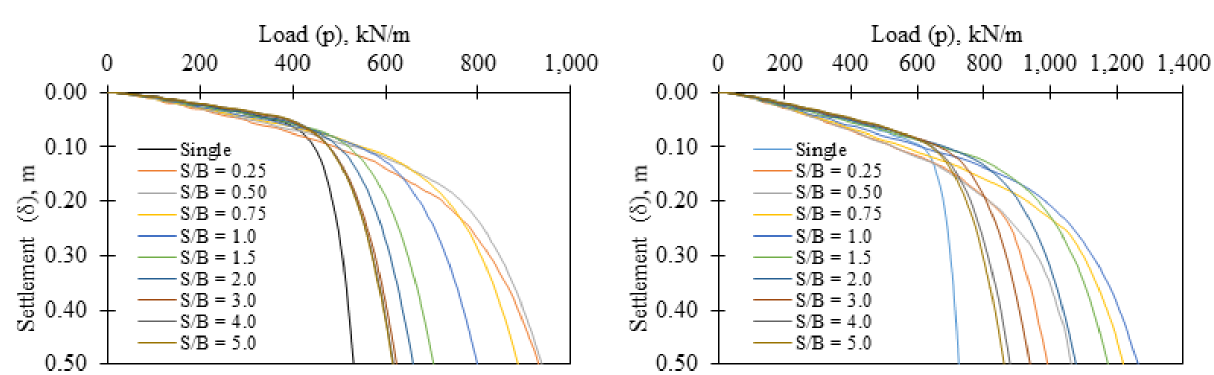


Figure 5.
p-δ behaviour for $D_L/B = 0.5$ and $D_R/B = 1.0$

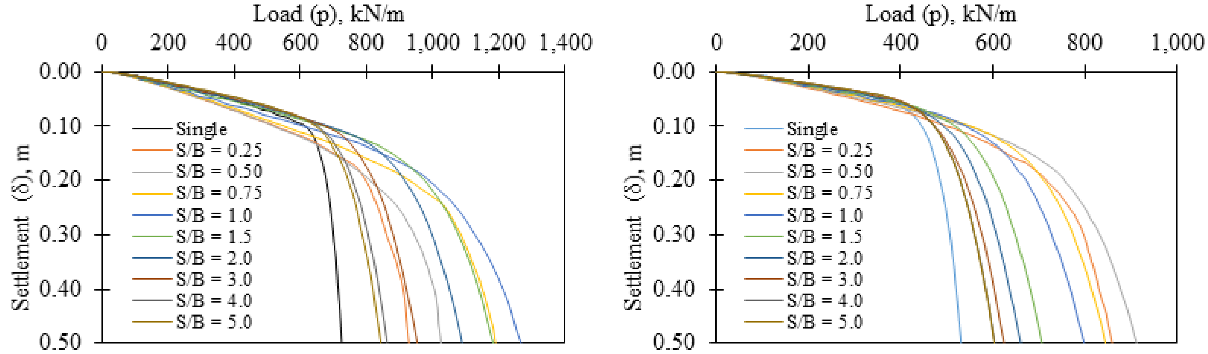


Figure 6.
p-δ behaviour for $D_L/B = 1.0$ and $D_R/B = 0.5$

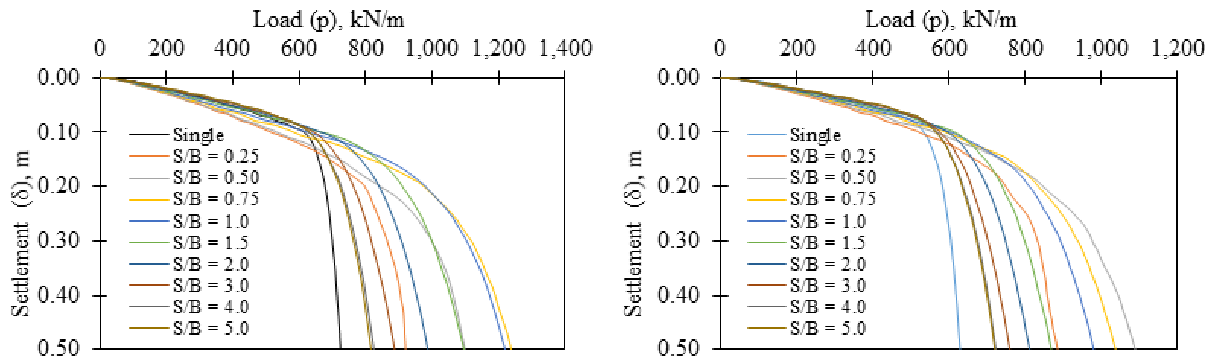


Figure 7.
p-δ behaviour for $D_L/B = 1.0$ and $D_R/B = 0.75$

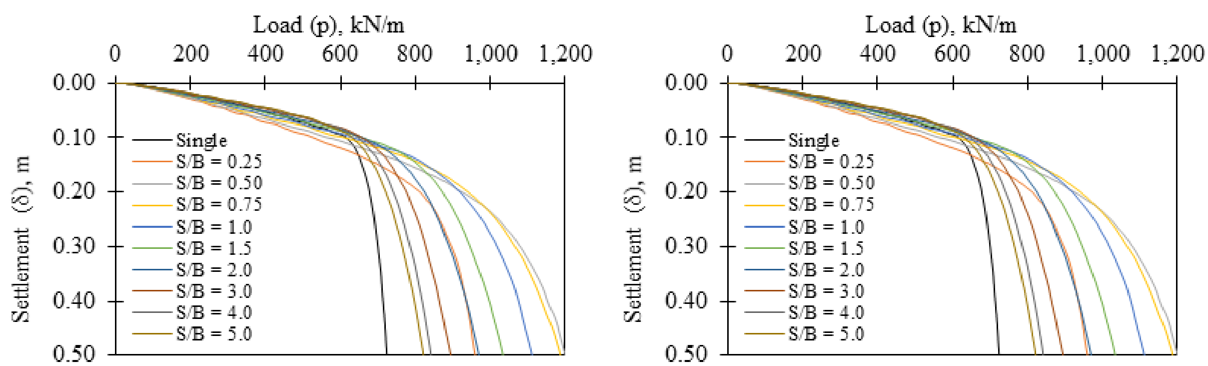


Figure 8.
p-δ behaviour for $D_L/B = 1.0$ and $D_R/B = 1.0$

The variation of interference factors (ξ_L/ξ_R) with various S/B and D_R/B is presented in Figure 9, Figure 10 and Figure 11 for $D_L/B = 0.5$, 0.75 and 1.0, respectively. It is observed that the variation trend for the interference factors is in line with the literature. However, the peak interference factors ($\xi_{L\text{-}max}/\xi_{R\text{-}max}$) are attaining at different S/B due to adjacent embedment depth. It is noticed that for a given value of D_L/B, $\xi_{L\text{-}max}$ is observed to be increasing with an increase in D_R/B. For an instance for $D_L/B = 0.5$, the $\xi_{L\text{-}max}$ increases by 2.1% and 4.2% when $D_R/B = 0.75$ and $D_R/B = 1.0$, respectively. On the contrary, the value of $\xi_{R\text{-}max}$ decreases by 1.25% and 2.03% when $D_R/B = 0.75$ and $D_R/B = 1.0$, respectively. Furthermore, the value of $\xi_{R\text{-}max}$ will be attained at the value of S/B = 0.75 and S/B = 1.0, respectively when $D_R/B = 0.75$ and $D_R/B = 1.0$ for $D_L/B = 0.5$. Further, for given value of $D_L/B = 0.75$, the value of $\xi_{L\text{-}max}$ decreased by 2% and 1.3% when the D_R/B = 0.5 and D_R/B = 1.0. Correspondingly, the value of R-max increased by 2.8% and 2.4% when the D_R/B = 0.5 and D_R/B = 1.0, respectively for a D_L/B = 0.75. In a similar course, for the given value of D_L/B = 1.0, $\xi_{L\text{-}max}$ increases by 6.7% and 2.2% and R-max increases by 8.3% and 2.5% for D_L/B = 0.5 and D_L/B = 0.75. From the ongoing discussion, it may be perceived that there is a significant influence embedment level on the adjacent footing. It is a well-known fact that, with the increase in embedment depth of the footing, the *UBC* increases due to the increased resistance to passive shear zone; in addition to that confinement effect of the adjacent footing also implicates a significant effect. The footing at lesser embedment depth experiences a considerable effect due to passive pressure impended by the footing embedded at a higher embedment depth.

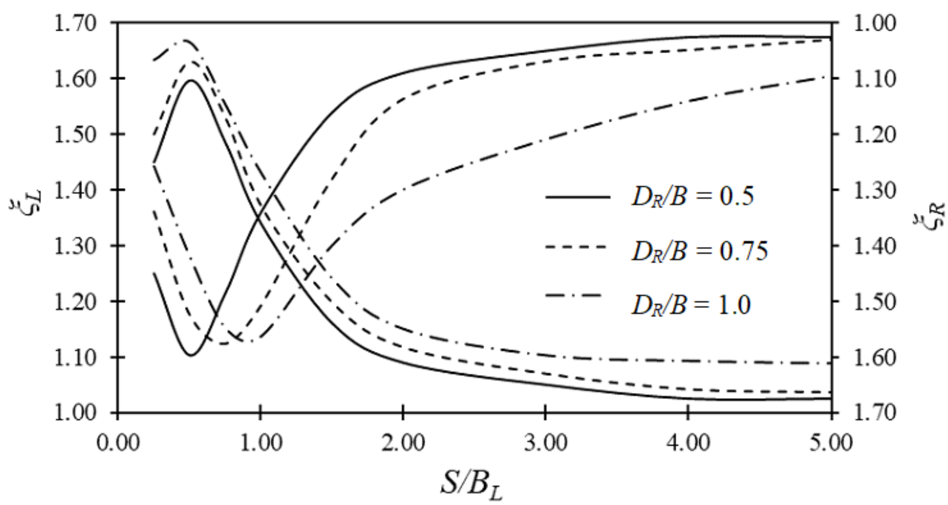


Figure 9.
Variation of ξ_L and ξ_R with S/B for D_L/B = 0.5 and D_R/B = 0.5, 0.75 and 1.0.

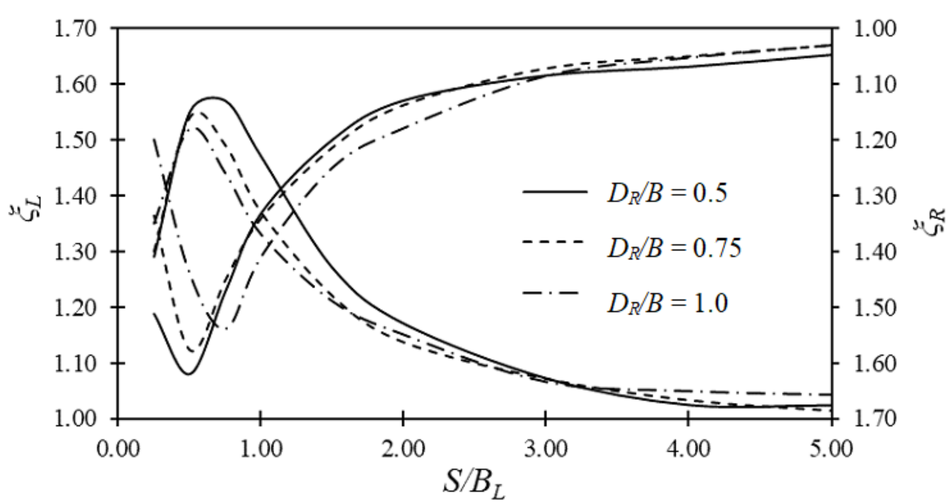


Figure 10.
Variation of ξ_L and ξ_R with S/B for D_L/B = 0.75 and D_R/B = 0.5, 0.75 and 1.0.

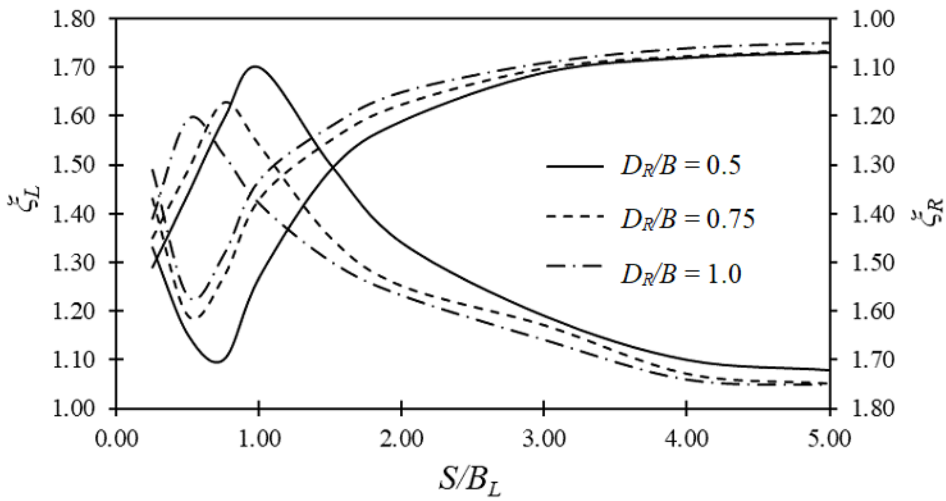
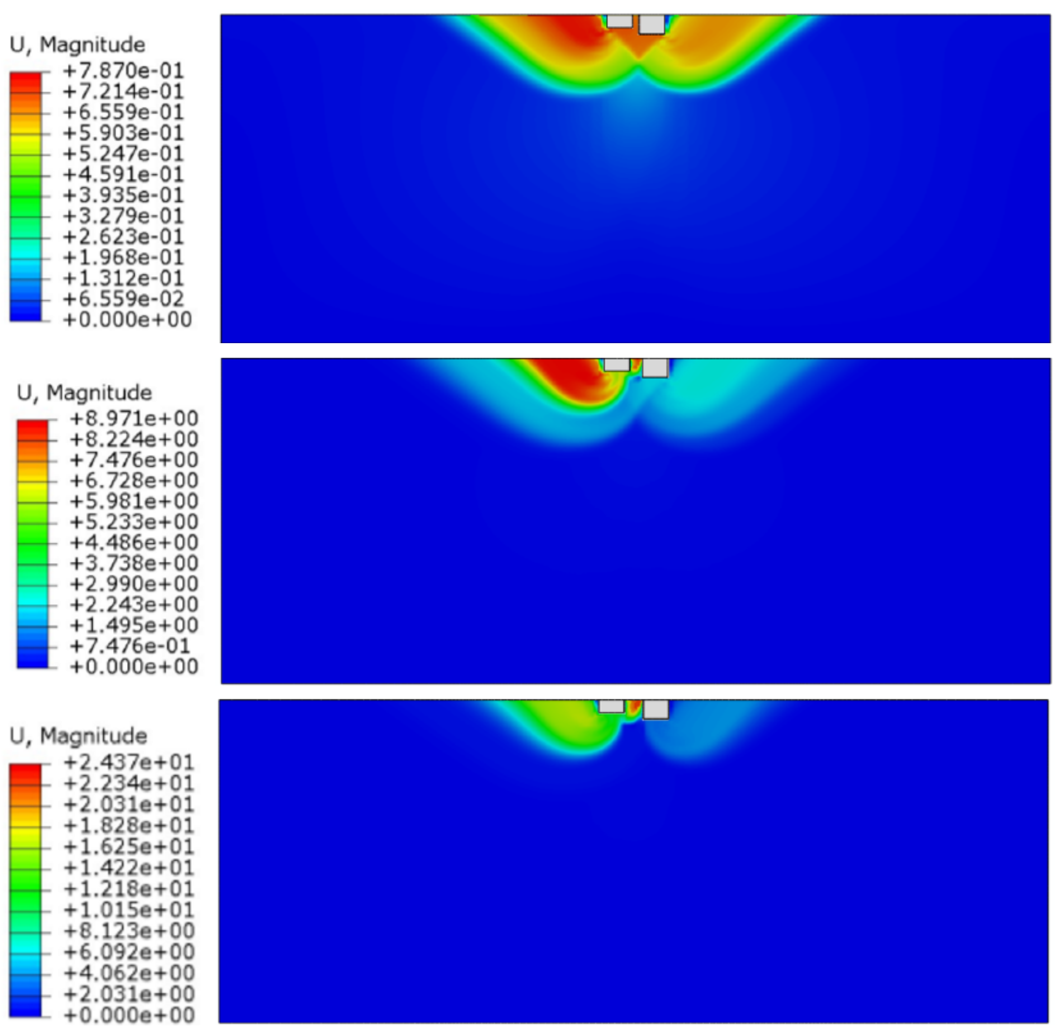


Figure 11.
Variation of ξ_L and ξ_R with S/B for $D_L/B = 1.0$ and $D_R/B = 0.5$, 0.75 and 1.0.



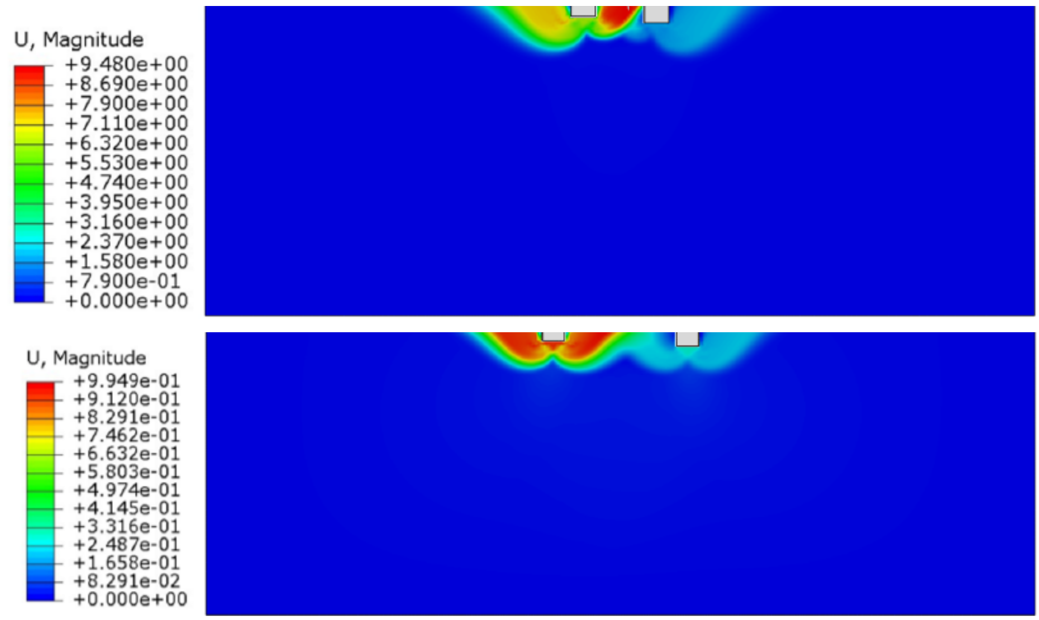


Figure 12.
VTotal displacement contour for D_L/B = 0.5 and D_R/B = 0.75

The failure envelope for adjacent strip footings embedded at different levels is comprehended through the total displacement contours. The total displacement plots for various spacing between the footings for $D_L/B = 0.5$ and $D_R/B = 0.75$ is illustrated in Figure 12 for S/B = 0.25, 0.50, 0.75, 1.0, 2.0 and 5.0. Figure 12(a) reveals the occurrence of significant interference between the footings and the existence of triangular trapped wedge, signifying that two footings behave as a single footing twice the width of isolated footing. Further, the spacing between the footings, the passive zones seemingly start separating, and a clear influence of footing with higher embedment level over the footing with lower embedment level is observed; the same is presented in Figure 12(b). The maximum influence for the left footing is observed at $S/B = 0.5$ and at the right footing at $S/B = 0.75$. However, from Figure 12(c) for $S/B = 0.75$, the UBC increases due to the confinement effect. Further, increase in the spacing between the footings, the interference effect starts diminishing, and the footings start behaving as isolated footings as evidenced in Figure 12(d) and Figure 12(e) for $S/B = 2.0$ and $S/B = 5.0$, respectively.

5. CONCLUSION

The present study is carried out using ABAQUS, a commercially available finite element analysis program. The analysis is carried out to assess the influence of embedment level on two adjacently placed strip footings. The load-settlement (p-δ) curves are obtained for each footing placed at different clear spacing and embedment depths considered for the analysis. Subsequently, the UBC of the left and the right footings are obtained and represented in terms of interference factors. The analysis reveals the following conclusions:

- A substantial effect of different embedment levels on the interference of two strip footings is observed. The variation of estimated interference factors with spacing between the footings reveals that UBC attains a maximum at specific spacing. It perpetually decreases with an increase in spacing between the footings.
- The load-settlement behaviour for adjacently placed footings is found to deviate relative to the isolated footing of the same width and embedment depth. It is increased when the embedment depth of the adjacent footing is higher.
- For a given value of embedment depth of the right footing (D_L/B), the interference factor for left footing increases with an increase in the embedment depth of the right footing (D_R/B). Nevertheless, the interference factor for right footing decreases with an increase in the embedment depth of the right footing (D_R/B).

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