Interaction of Closely Spaced Shallow Foundations on Sands and Clays: A review

Mohammed F. Alwalan
Graduate student, Department of Civil and Environmental Engineering, Western University, Canada.
Email: malwalan@uwo.ca

***Abstract*— *The evaluation of the static interaction of closely spaced footings and its influence in the overall bearing capacity and settlement on sand and clay soils is addressed in this review. The work is accomplished through a comprehensive look into all relevant literature regarding the interaction of sallow foundations, assessments are made, and conclusions are drawn which will ultimately be relevant to future endeavors associated with the design and the evaluation of closely spaced shallow foundations in terms of determining the optimal spacing between footings, enhancing bearing capacity, and controlling deformation. Furthermore, the work is divided to three major approaches: theoretical studies, experimental or field tests, and numerical analysis. Each have been discussed thoroughly in details, with indicating the shortcomings of previous studies and where each approach has reached. The result of this review has showed that nearly all previous research studies explored the effect of the interaction of closely spaced shallow foundations on the bearing capacity at the ultimate failure compared to the settlement behavior which is for some reason not addressed profoundly, even though it is more critical than bearing capacity. Additionally, current regulations and codes have not devoted a major effort toward addressing the influence of closely spaced shallow foundations appropriately, especially today, where the limitation of a site and the placing of footings close together in order to accommodate structural details are becoming a more common issue.*

Keywords*— *Ultimate bearing, Clay, Interference footing, Interaction, Multiple footings, Offshore, Sand, Settlement, Shallow foundations, Skirted foundations, Tilt.

I. INTRODUCTION

A shallow foundation is defined as a structure that is responsible for transmitting imposed loads into the ground, very near to the surface rather than the lower layers of the earth. Therefore, evaluating the capability of the soil to carry loads without a remarkable displacement in the structure and the ground nearby it, is an essential step in the design process. Several theories have been established to study the behavior of shallow foundations (bearing capacity, settlement, failure surface, etc.), which are used widely in practice, are valid provided that the shallow foundations in the close proximity are isolated and no such interference does exist between footings. However, foundations encountered in practice are often closely spaced and are not separated. Consequently, the characteristic behavior of individual footings in a group will differ compared to an isolated one. In many situations such as area restrictions, the geometry of the structure, or structures near to each other force engineers to construct footings that interfere with each other to accommodate requirements. This interference quantitatively leads to excessive settlement and severe damages to the structures if not probably controlled, especially, when the distance between the footings are reduced. It should be noted that due to the massive load and limitation of a site, the interaction of closely spaced shallow foundation in the term of stress and failure zone may lead to unequal distribution of stress within the soil which affect the determination of bearing capacity and settlement of footings resting on sand or clay, when compared to single footing behavior (Shahein & Hefdhallah, 2013).

Studies of the interference of neighboring shallow foundations are relatively limited. In fact, few methods are available in the literature that accounts for this phenomenon (Mesri, 1991 and Lee et al., 2010). This problem has been addressed in three different trajectories; theoretical approach, experimental work, and numerical analysis. All studies are based on vertical and horizontal loading conditions. Recently, a couple of papers were published that consider the interference of closely spaced foundations under general loading (vertical, horizontal, and moment) to emulate offshore environment loading conditions. However, this area is still widely undefined (Fisher, & Cathie, 2003).

The purpose of this literature review is to investigate how adjacent spaced shallow foundations interact with each other on sand and clay soils and to report the studies that have been developed recently. To achieve this, in this paper, the results of a series of experimental tests and the results of numerical investigation are compared, and conclusions are made.

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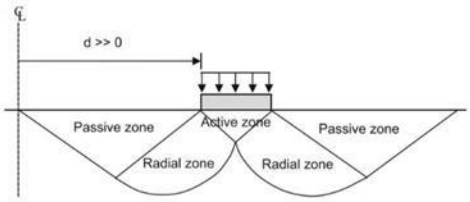
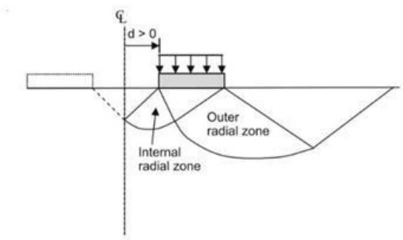
II. THEORETICAL STUDIES

The effect of closely continuously spaced foundations was theoretically examined by Stuart (1962) in cohesionless soil on the base of the limit equilibrium method. He assumed that the medium is homogeneous soil extending to great depth and the failure mechanism will have a similar geometry of that rupture assumed by Terzaghi. The rupture surface developed beneath the shallow foundation comprises of three zones; Rankine passive zone, radial zone, and triangular wedges (Fig. 1). Based on the center to center distance between the shallow foundations, Stuart (1962) concludes that as long as the rupture surfaces are only overlapping in Rankine passive zone, then there is no need to modify Terzaghi formula and should be applied directly. Nevertheless, the value settlement compared to individual footings will change at the ultimate loads. In the case if overlapping does exist in the radial zone, adjusting the bearing capacity is a necessity. For this case, Stuart introduces the use of efficiency factor (ξ) which is a function of spacing to width of the foundations and soil friction angle. Since the efficiency factor is greater than one, the ultimate bearing capacity increases as the center-to-center spacing between foundations decreases. However, settlement will be more significant than if compared to isolated foundations (Stuart, 1962). The effect of various parameters has not been considered in Stuart's assumptions; rigorous studies are required to include those parameters such as the variation of elastic modulus with depth.



(a) Failure mechanism of isolated foundation.



(b) Failure mechanism of closely spaced footings.

Fig. 1, Failure mechanism of isolated foundation and of closely spaced multiple footings (Lee & Eun, 2009).

Later, West and Stuart (1965) applied the method of stress characteristics to establish a solution for the interference of a strip footing on sand soil. Their outcomes showed that the efficiency factor (ξ) values were smaller compared to those obtained by Stuart in 1962 (West & Stuart, 1965). The downside of their research is that they only configure a solution for a soil having friction angle of 35º (Ghosh & Sharma, 2010). Furthermore, Graham et al. (1984) investigated the interference of three closely spaced strip foundations on sand using the same method suggested by West and Stuart (1965). The results show that the method of stress characteristics is applied to designate the interference of the outer foundations on the bearing capacity of the central footing and it is not suitable theory for two closely spaced footings. This may justify why West and Stuart (1965) obtain lower efficiency factors (ξ). Kumar and Ghosh (2007) provide the failure mechanisms beneath two rigid continuous foundations coincided well with the assumption of Stuart (1965). Moreover, several types of research are reported on the bases of analytical approach, probabilistic approach, and upper bound limit analysis that the bearing capacity of neighbored foundation increases as the spacing between them is reduced (Ghosh et al. 2017).

2.1 Theory of Elasticity

Nearly all of the former research works mentioned above explored the effect of the interaction of closely spaced shallow foundation on the bearing capacity at ultimate failure. On the other hand, the settlement behavior under similar conditions was not adequately examined, yet it is anticipated to be more perilous. A case study done by Shahein and Hefdhallah (2010) showed that considering the propinquity of the surrounding shallow foundation in the determination of the settlement could change the foundation type from isolated to a raft. In the field, soil deposit can be non-homogeneous; therefore, Ghosh and Sharma (2010) conducted a theoretical study on two-layer soil by mathematically solving the equilibrium equations under the plane strain condition of two closely spaced rigid strip footings using the theory of elasticity approach. Unlike previous researchers, they took on considerations the variation of soil (sand and clay) parameters such as elastic modulus and depth of layers and pressure intensity on each footing to generalize the settlement behavior of closely spaced footings. The settlement increases at the center line of the footing as the spacing between two closely spaced foundation decreases. Fig. 2, depicts this phenomenon form a shallow strip foundation constructed at the top of two-layered soil that has the same depth at a various value of modulus of elasticity. The parameter (ξ_δ) represents the ratio of the settlement of an individual footing in the presence of another footing to the settlement of the single footing. The value of (ξ_δ) is equal to one only if the ratio of spacing between footing to the width is

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greater than 4.5, which mean no interference existing among the shallow foundations. Otherwise, the interaction of closely spaced foundation must be taken on considerations to avoid catastrophic failure to any structure. Nevertheless, the developed chart for the efficiency factor (ξ_δ) could not be compared to available work on the same topic due to the lack of consensus on the parameters that match the one considered on this research (Ghosh & Sharma, 2010). However, three issues found in their research; first, the poisson's ratio is assumed to be constant for both layers. Second, the soil is also assumed to behave linearly elastic with depth. Finally, the load is applied in way such that no plastic deformation is experienced by the soil.

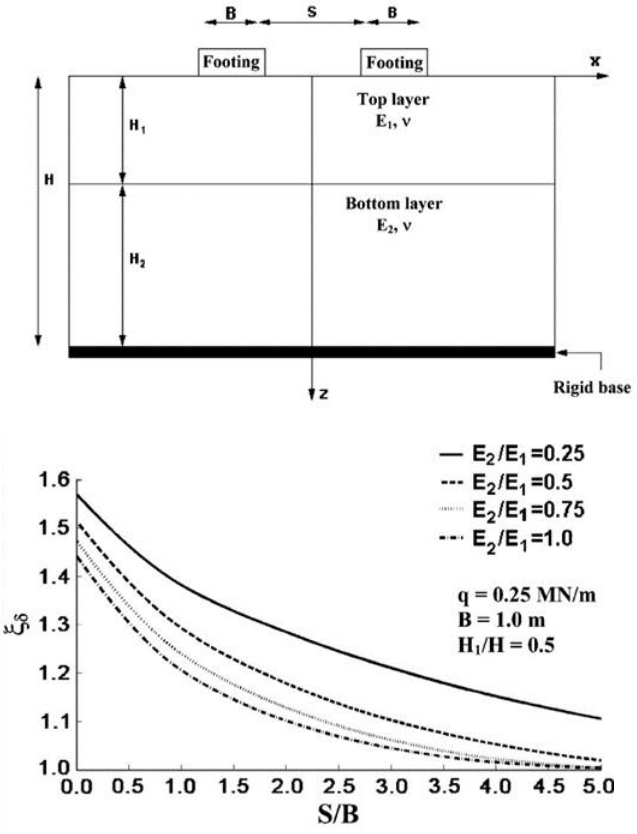

Fig. 2, Soil and footing configuration model studied by Ghosh, & Sharma (up) and Variation of ξ_δ with S/B for different E_2/E_1 (down), (Ghosh & Sharma, 2010).

2.2 Pasternak Soil Model

Mostly, the shallow foundations at different geotechnical work has dissimilar sizes and unequal loads. The interaction of two asymmetric closely spaced footings has not been attentively addressed in previous research papers. Because of this, two horizontal strip footing resting on a dry homogenous soil deposit was studied by Ghosh, Rajesh, & Chand in 2017 using Pasternak soil model. The reason to adapting this model is due to its strong implementation capability. In their study, the soil obeys both linear and nonlinear elasticity behavior. Fig. 3, shows the model used in by Ghosh et al. The objective of their study is to investigate the interaction of asymmetric strip footings, noted as left and right footing, positioned close to each other at spacing, S, on the surface of a homogeneous soil layer and report the finding in term of interaction factors ($\xi_L$and ξ_R) for the footings with respect to the settlement. $\xi_L$and ξ_R are defined as follow based on Ghosh et al;

$$\xi_L = \frac{\begin{array}{c}Average\ settlement\ of\ the\ left\ foundation\\ in\ existence\ of\ the\ right\ foundatiom\end{array}}{settlement\ of\ the\ \ isolated\ foundation\ (left)}$$

$$\xi_R = \frac{\begin{array}{c}Average\ settlement\ of\ the\ right\ foundation\\ in\ existence\ of\ the\ left\ foundation\end{array}}{settlement\ of\ the\ \ isolated\ foundation\ (Right)}$$

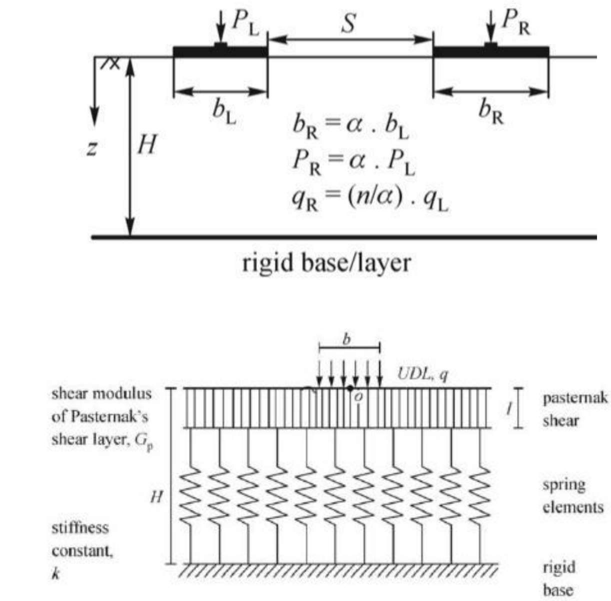

Fig. 3, Soil and footing configuration model studied by Ghosh, Rajesh, & Chand (up) and Pasternak soil model (down), (Ghosh et al., 2017).

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During their study, the left footing as seen in Fig. (3) is kept fixed in terms of load and width, while the right footing is changing in terms of load and width. The variation of interaction factors for symmetric condition, both has the same width (α= 1.0), in addition to asymmetric, both has dissimilar sizes (α = 2.0), are shown in Fig. 4.

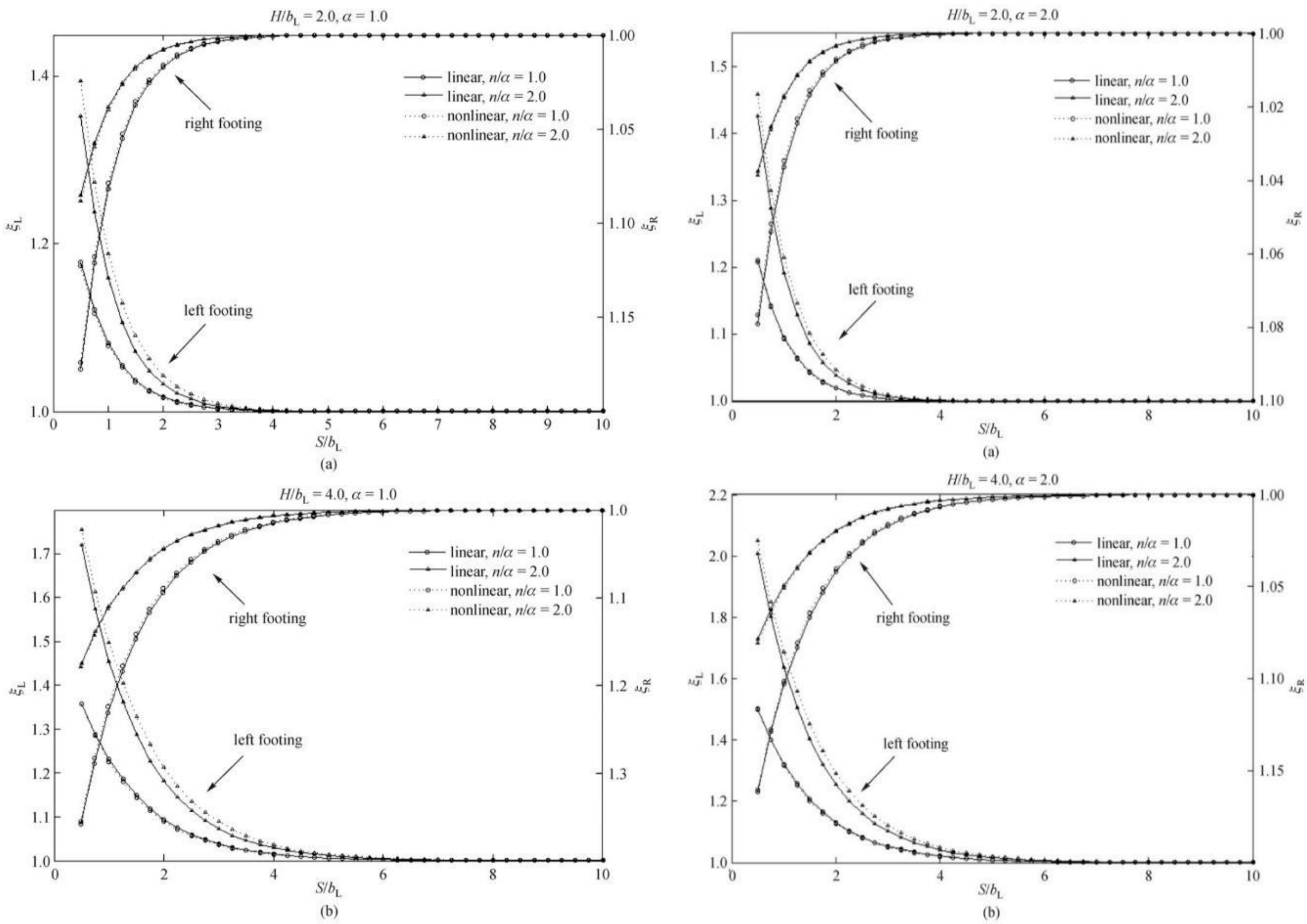


Fig 4, Comparison of interaction factors obtained from linear and nonlinear elastic analysis for symmetric (α= 1.0), and asymmetric (α= 2.0), footings with (a) H/b_L = 2 and (b) H/b_L =4 (Ghosh et al., 2017).

Where, n/α represent loading to dimension ratio with left footing is considered to be as a reference. The depth of the rigid base is taken to be two and four times the width of the left footing (H/b_L = 2 & 4). When n/α = 2, for instance, it means the load on the right footing is twice the load on the left footing (Ghosh et al. 2017). It can be observed for the above figures that $\xi_L$and ξ_R decreased to become one as the spacing increased. For linearly and non-linearly analysis the interaction becomes neglectable when the foundations are approximately positioned apart at a distance equal to 5 times the smaller width of the foundations for H/b_L = 2, similar to the result found of the theory of elasticity. For H/b_L = 4, the interaction becomes neglectable when the spacing between footings equal to 7.5 and 8 times the smaller width of the foundations. Hence, whenever the rigid base (H) increases, the interference effect is increased. In conclusion, the finding of Ghosh, Rajesh, & Chand research can be summarized as follow;

I. The outcomes found from the linear elastic analysis are larger than those determined from the nonlinear elastic analysis.
II. The depth of the bearing layer affects the interaction of closely spaced foundation.
III. In case of different footing size, the failure surface tends to be significant below the smaller footing and in case of asymmetric loading, the interference effect is more for the footing with smaller load.
IV. $\xi_L$and ξ_R values get larger as the load increases in any footing that is located close to each other in the nonlinear elastic analysis.

III. EXPERIMENTAL TESTS

3.1 Sand

Besides these theoretical analyses mentioned above, a number of small-scale model test have been performed by different researchers. Das & Larbi-Cherif (1983) conducted laboratory study on two rough strip closely spaced foundation placed on the top of sand soil with a relative density of 54%. The interaction started to take place when the ratio of spacing to width of footing is equal or less than 4.5. The result was found to be similar to the theoretical result proposed by Stuart (1962). The bearing capacity and the settlement becomes larger as the footing spacing is reduced. However, the interaction factor (ξ) was smaller than what Stuart (1962) suggested (Das & Larbi-Cherif, 1983). The inconsistency between the theoretical and experimental interaction factor (ξ) are may be due to the assumption of ideal behavior of soil or due to the self-weight of the soil which have been discarded in the theoretical approach. Furthermore, table 1, summarizes various researchers that investigate the load-deformation interference of two footings resting on cohesionless soil medium.

Table 1, A summary of the experimental work done on investigating the interaction of shallow adjacent footings on cohesionless soil.

No.	Names of the researchers	Type of the soil	Results
1	Selvadurai and Rabbaa (1983)	Ottawa sand	Interference initiated when spacing to ratio S/B < 3.
2	Graham (1984)	Ottawa and silica sand	The interaction depends on soil friction angle and efficiency factors for versus spacing are given.
3	Lee and Eun (2009)	Sand	Conducted field circular plate test. Failure stress of the soil beneath neighbored footing is higher than isolated footing; however, larger settlements occurs beneath neighbored footing.
4	Srinivasan and Ghosh (2011)	Dry dense homogeneous sand	They performed several laboratories scaled model tests of circular footings. Efficiency factors (ξ) are found to be maximum at S/B = 0.5.
5	Reddy, Borzooei, and Reddy (2012).	Medium dense sand	Square and circular footing model were conducted. On sand, the closeness of footings found to improves the responses of foundations both in terms of settlement and ultimate bearing capacity; nevertheless, increasing in settlements are being observed at between $B \leq S \leq 6B$.
6	Srinivasan and Ghosh (2013)	Two layers sand (weak layer underline by strong layer)	The bearing capacity and the developed settlement at failure declined with an increase in the depth of the upper weak layer. Efficiency factors (ξ) are found to be maximum at S/B = 0.5.

3.2 Clay

The interaction of closely positioned shallow foundations on clay is different than sand. The issue becomes more critical due to the tilting action of the footings which is significant as the spacing between footing decreases. The bearing capacity on clay is barely affected by the interference; in fact, for undrained condition, it can be ignored (Saran & Varma,1988). Therefore, during the design process the shear failure, settlement, and tilt failure analysis is a necessity when designing closely spaced structures on clay. Saran and Varma were the first to conclude the tilting behavior of footings on clay; however, they did not show how failure surface is developed, and when the tilting is at its most value. Several years later, Amir (1992) conducted in his thesis a full laboratory study to predict the load-displacement and load-tilt characteristic of neighbored footings on clay. He noticed that the interaction started to occur at a spacing to width ratio of 4, reaching to a maximum interference when spacing to width ratio of 1.5. Any further reduction in spacing the footing started to act as one block with a width equal to 2B.

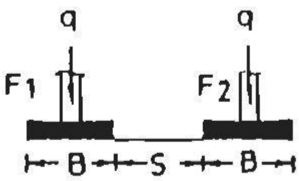


Fig. 5, Foundations model studied by Amir (1992).

The load-displacement and load-tilt curves have been obtained for the model shown in Fig. (5). The resultant curves are depicted in Fig (6). It can be observed that there is no significant change in bearing capacity for a closely spaced isolated footings. This is similar to what Saran and Varma concluded; however, the tilting does happen significantly when the footings are located close to each other as seen in Fig. (6). The rupture surface will be similar to the one shown in Fig. 7 (A) as long as spacing to width is less than 3; if more than three the rupture surfaces will be identical to the one shown in Fig. 7 (B) (Amir, 1992). Amir's work can be summarized in three points:

I. At a given load intensity, as the spacing to width ratio decrease, settlement and tilt increases.
II. The tilting mechanism of the footing take place toward the center of the system; in other meaning tilt toward each other.
III. The magnitude of tilting depends on imposed pressure, spacing, and the width of the foundations.

To be noted that no further experimental test explored in clay is found after 1992.

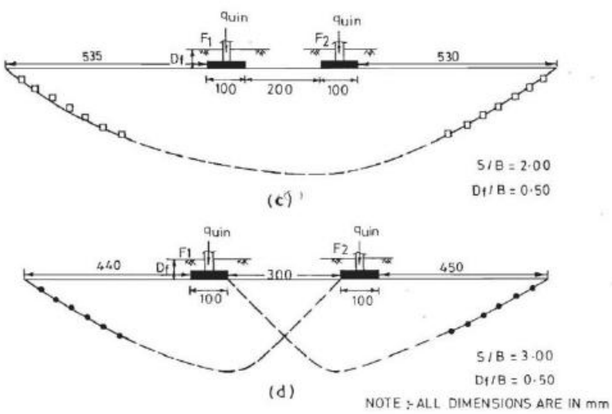
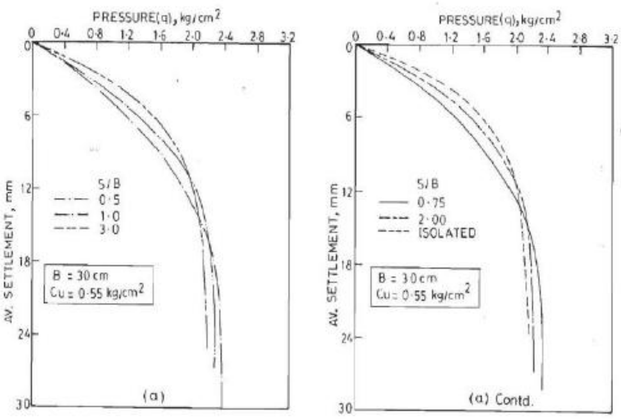
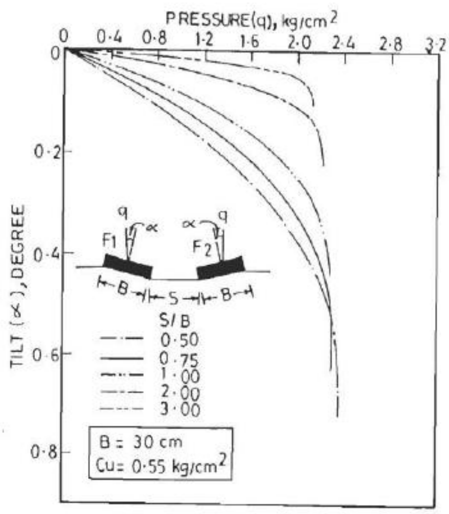


Fig. 6, Rupture surface patterns for closely spaced foundations in clay after Amir (1992).



(A)



(B)

Fig. 7, (A) pressure versus settlement curves and (B) pressure versus tilting for clay (Amir,1992).

IV. NUMERICAL ANALYSIS

Due to the advancement of computer coding, several studies have emerged in the same topic using finite element method (FEM) programs. Generally speaking, these programs have allowed performing geotechnical analyses on a variety of soil parameters and sources of variabilities on the performance estimation of structures.

4.1 Sand

The numerical results in the case of sand correlate well with the theoretical and experimental data mentioned above. The interference of shallow foundations gives bearing capacity noticeably greater than separate foundations that have the same dimensions. The interference is substantially important when spacing to width ratio is in the range of 0.1 to 0.5 for sand in which the friction angle is between 25° to 40°. The failure zone is comparable to the failure mechanism found by Terzaghi and suggested by Stuart (1962). Furthermore, a triangular elastic wedge zone immediately forms between the foundations due to blocking effect behavior, also called "jamming soil". This differs from isolated foundations were a triangular elastic wedge immediately underneath the footing is formed (Mabrouki et al., 2010). Morover, The settlement due to the interference continuously decreases as the spacing to width increases and attains a value equivalent to that of the individual footing. The settlement interference reduces as the stiffness of the soil increases with depth (Nainegali et al., 2013a). However, the interference factor (ξ) is found to be similar to the values represented by Ghosh and Sharma (2010). Many researchers (Nainegali et al. 2013b, Eltohamy and Zidan 2013, Kumar and Bhattacharya 2013) have reported similar findings which are discussed in this section.

4.2 Clay

The interference of two symmetrical footing with a gap equal to B, resting on undrained clay soil was studied by the finite element method using a viscus-plastic algorithm with variable undrained shear strength values by Griffiths et al. (2006). The study indicated that if the two footings supported two separated structures then the interference generally increases the mean bearing capacity over isolated footing values; the failure surface will be similar to Fig. 8, (A). On the other hand, if the footings are supporting the same structure where the failure of one isolated footing is a failure to the whole system, the value of the mean bearing capacity owing to the interference was lower than that of an isolated footing; the failure surface will be similar to Fig. 8, (B).

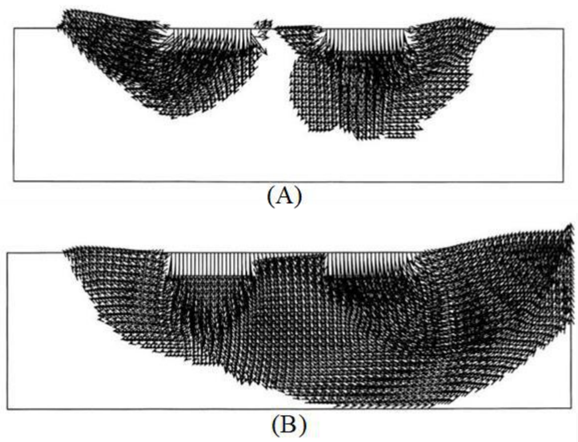


Fig. 8, Failure surface of closely spaced footing: (A) separated footings, (B) connected footings (Griffiths et al., 2006)

In both cases, the undrained capacity was no more than 10% difference (Griffiths et al. 2006). This work confirms the results of Amir (1992) in two sides; for fine grained undrained soil (φ=0) the increases on bearing capacity is insignificant, and tilting is critical on clay soil as seen in Fig. (8) where the failure mechanism is shifted to the right. Therefore, the bearing capacity will reduce in contrast to the settlement which will augment as the spacing decreases in the close proximity of foundations. A need to determine the minimum distance where the footings should be placed for optimum performance is essential. In this regard, Nainegali and Ekbote (2016) published research where they studied the interaction of foundations on clay medium using a program called Plaxis 2D. The results are quite different than what Griffiths et al. reported in 2006. The bearing capacity is, in fact, reduces as the footings spacing decreases in order to maintain the allowable settlement at a tolerable value. Fig. (9), shows that the bearing capacity ratio and variation of the settlement obtained by Nainegali and Ekbote (2016)

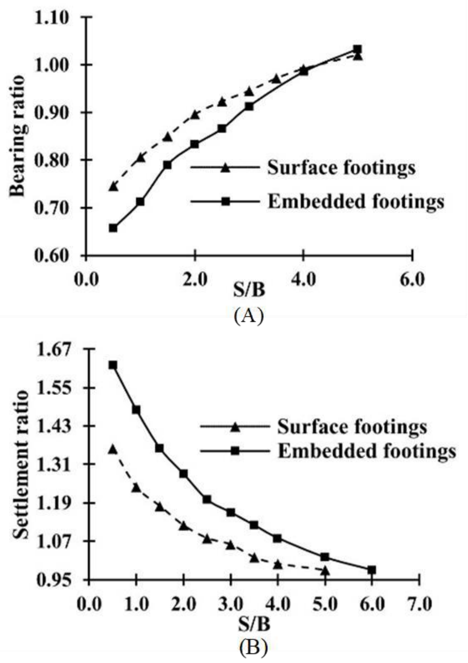


Fig. 9, variation of bearing ratio with S/B ratio (A), and settlement ratio with S/B ratio (Nainegali, & Ekbote, 2016).

It can be seen that the bearing capacity does change unlike what other previous research indicated. The reduction expected to be 25% compared to isolated foundation. Moreover, the most severe condition is when the spacing to width ratio is equal 0.5 where the settlement increase by 70% at the mid center of the two footings. The zone where there is no interaction is when spacing to width ratio is

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equal five as seen in the figures above (Nainegali, & Ekbote 2016). The problem is there are not enough researchers done in cohesive soil compared to cohesionless soil which is well studied and categorized. A rigorous study is required to justify this diversity on the results reached by previous studies and outweigh one of them in regard to the interaction of closely spaced shallow foundation on clays.

V. CLOSELY SPACED SHALLOW FOUNDATION IN OFFSHORE STRUCTURES

Typically, conjoint offshore shallow foundations are assumed to be separated, and the bearing capacity is just the sum of the individual footings; ignoring any interference of the foundations which may add additional capacity or reduce the capacity due the severe stress develop because of such interaction. Currently, multi-footing foundation system is emerging as a support for offshore wind turbine structures. It considered as an alternative to the conventional monopiles. The interaction between tripod or quadruped shallow foundation systems under general loading is less clear. Only couple of studies exists in the literature which will be discussed here. A finite element investigation was carried out by Gourvenec and Steinepreis (2007) to determine the undrained capacity of conjoint rigid two foundation system resting on uniform elastic-perfectly plastic deposit under four loading conditions; pure Vertical (V), horizontal (H), and moment (M) loading plus a general combined loading (VHM). For a pour vertical loading condition, an increase on the bearing capacity (V_{ult}) was observed when S/B ≤ 1, reaching to a maximum value at S/B= 0.25; the rise in capacity is around 5% (where S/B is spacing to width ratio). If the distance is S/B > 1, the footings will act independently, hence, no additional capacity is developed ($V_{ult} = V_{ult}$(single)). In the case of pure horizontal loading, the multi-footing foundation system has horizontal capacity equal to the sum of the single foundation. It is not affected by the interaction (Gourvenec & Steinepreis, 2007).

on the contrary to onshore, shallow foundations on offshore are subject to harsh environmental loading, especially extreme moments. The moment capacity of two-footing system tends to have three different behaviors. First, when the footing is positioned such as the S/B is less than 3, the moment capacity on this case contract proportional to B^2 as the S/B reduces. The failure surface encompasses of circular slip plain concurring at the edges of the footings, creating scoop mechanism failure. The upper limit moment capacity is presumed to be as the ultimate moment capacity of a single footing. The second behavior is when the footings are widely separated (S/B> 5), the moment capacity improved linearly as the S/B ratio increases. Typical shear failure mechanism arises underneath both footings. Third, is when the footings are located at approximately 3B and 5B apart. The failure surface comprises of both scoop and shear mechanism as shown in Fig. (10). However, a complex solution is needed to describe such case (Gourvenec & Steinepreis, 2007)

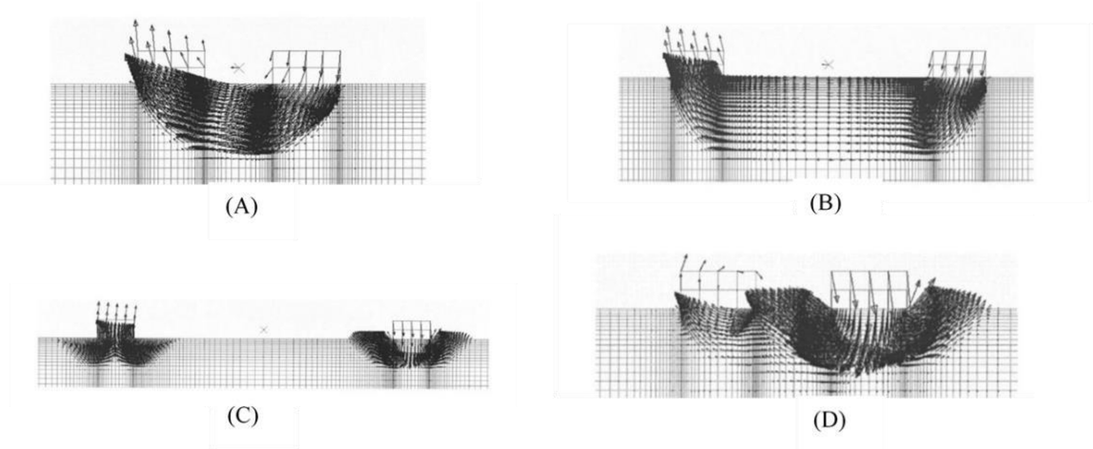

Fig. 10, failure mechanisms for closely spaced footings: (A) Two-footing scoop mechanism under pure moment, (B) Transitional mechanism under pure moment, (C) Independent push–pull mechanism under pure moment, (D) Failure mechanism at $V=0.5V_{ult}$ and S/B=1. (Gourvenec & Steinepreis, 2007).

If (VHM) loading conditions experienced by the conjoined shallow foundations, the failure surface and the interference will depend on the level of vertical loads as well as S/B ratio. In general, the horizontal and the moment capacity of the system reduces with the rise of vertical loads and increases with footing spacing. At vertical load equal or less than 25% of the ultimate vertical capacity (S/B = 0,1,2, and 3) with large horizontal and moment loads, the surface failure underneath the conjoined footings are a combination of scoop-wedge mechanisms which leads to a reduction on VHM system capacity (Gourvenec & Steinepreis, 2007). However, the reduction is small (Gourvenec & Jensen, 2009). Under high vertical load situations, the interactions mechanism is observed to be as those shown in Fig. (10) (Gourvenec & Steinepreis, 2007). Furthermore, the VHM capacity can be enhanced as the embedment depth of the closely spaced footings increases compared to surface footings. Though, the relative enhancement is basically unrelated to footing spacing (Gourvenec & Jensen, 2009).

5.1 Skirted foundations

A group of three rigidly coupled skirted foundations to support offshore wind turbines are currently grabbing attention due to the ease of installation and cost efficiency. Wind turbine is subject to high moment to vertical loading ratio (M/V), therefore, the compound effect of a moment and a vertical loading on closely spaced connected skirted foundations was investigated numerically by Stergiou et al. (2015) in order to establish comprehensive load interaction diagrams. They were able to produce a general equation that is applicable to any spacing and loading direction provided that the failure loads and the failure surfaces are suitably normalized. The equation is as follow:

$$\frac{M}{M_{ult}} = \min\left[\left(1 + 1.8\frac{V}{V_{ult}} - \left(\frac{V}{V_{ult}}\right)^2\right), 2.1\left(1 - \frac{V}{V_{ult}}\right)\right]$$

The critical spacing beyond which there is no interaction and the multi-footings have no effect on each other is 4 times the skirted dimeter. In the opposite, the group will experience a reduction on the gross undrained capacity when the skirted foundations are positioned at a smaller distance than 4 times the skirted diameter. The optimum reduction is approximately 12% (Stergiou et al.,2015).

VI. CONCLUSION

The following could be concluded based on in the information discussed above;

- The existing experimental and theoretical investigations invariably reveal that the magnitude of the ultimate bearing pressure, increases substantially in the presence of another footing.
- Ultimate bearing capacity for interference footing is almost same as of isolated footing in case of clay while its higher in sand.
- In sands, the interference of the surrounding foundation on each other increases as the center to center spacing decreased, and the settlement value increases as the number of the around footing increases by 4 to 5 times the settlement of individual footing considering the spacing between footings.
- The settlement interference reduces as the stiffness of the soil increases with depth.
- In clay soil, the interaction will start to occur at a spacing to width ration of 4, reaching to a maximum interference when spacing to width ration of 1.5. Moreover, the tilting mechanism of the footings is more critical than settlement.
- Further studies are needed to investigate the interaction of adjacent shallow foundations based on the ultimate limit state especially for clay soils.
- A rigorous study is required to justify the diversity on the results reached by previous studies in regards of the interaction of closely spaced shallow foundation on clays.
- For a series of connected skirted foundation, the critical spacing beyond which there is no interaction is four times the diameter.
- Offshore closely spaced shallow footings will experience a minimum reduction in horizontal and moment capacity at relatively small vertical loads. In the contrary, the horizontal and the moment capacity of the system reduces substantially with the increase of vertical loads.
- The VHM capacity can be enhanced as the embedment depth of the closely spaced footings increases. Additional moment capacity is available for structurally connected footings.
- It is recommended to develop a standard code that clearly indicates the smallest distance after which engineers should consider the possibility of overlapping between potential failure surfaces of adjacent foundations in their design process because this could result in changing the foundation system from an isolated to a raft or even in some circumstances to pile foundation. This is significantly important today due to the limitation of space and the fast growth of cities.

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