The Effect of Interference of Shallow Foundation on Settlement of Clay Soil

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Abstract. As a result of urban development, buildings were constructed adjacent to each other due to the limited construction area. As a result of this neighboring of buildings, there are often signs of damage to the structures that indicate a change in the soil’s behavior supporting the structure in terms of bearing capacity and settlement. This paper presents a numerical study using 3D Plaxis application finite element analysis to investigate the effect of the foundation interfering on the settlement of clay soils. This effect is investigated on two types of foundations, a strip foundation of 1 m wide and a square foundation of 1.5 m wide. Three cases of interference and their effect on the settlement are studied, the first case of two adjacent striped foundations, the second case of two adjacent square foundations, and the third case of two adjacent foundations, one of which is striped and the other is square. The study also adopts the imposition of a case study, in which a new building is constructed adjacent to an old building, where the effect of this juxtaposition on the settlement of the foundations of the old building is studied. The investigation results showed that the settlement in the case of adjacent strip foundations increased by 314% over the settlement of the isolated foundation, and the effect ratio decreased non-linearly with the increase in the distance between the two foundations until it fades at a distance of 7B. In the case of adjacent square foundations, the settlement increases by 194% compared to the settlement of the isolated foundation, and the effect ratio decreases non-linearly, with the distance between the two foundations increasing until it fades at a distance of 4B. In the case of a strip foundation adjacent to another square, the settlement of the strip foundation increases by 152% over the settlement of the insulated foundation, while the settlement of the square foundation increases by 164% over the settlement of the insulated foundation. The aforementioned results make the option of two adjacent foundations of different types less effective and more acceptable than the two adjacent foundations of the same type. The results of the investigation of a new building adjacent to an old building also show an increase in settlement of up to 177% over the settlement in the isolated building, and also show that when increasing the depth of the foundation of the new building from 1m to 4m that reduces the risks for the old building by 42%.

Keywords. Interference, Adjacent foundations, Settlement, Adjacent building, Tilt, Clay soil.

1. Introduction
In practice, civilian installations are often constructed adjacent to each other. This juxtaposition creates interference in the failure envelopes of the foundations of these installations, which explicitly affects the
soil bearing capacity and settlement of the foundations. Some researchers towards an analytical grant in investigating the problem of interfering with the adjacent foundations. Stuart provided the first attempt in 1962 to find the efficiency factor for soil bearing capacity using the limit equilibrium method. The same approach was followed by other researchers using other methods of analysis [1]. Graham et al. 1984 relied on the stress-characteristics method [2], Griffiths et al. 2006 leaned the probabilistic approach method [3], Kumar and Ghosh 2007 reckoned the upper bound limit analysis method [4], Ghosh and Sharma 2010 reposed the theory of elasticity method [5], Ghosh and Rukmini Kumar 2011 used the lower bound limit analysis method [6], and Ghosh et al. 2017 depended on the Pasternak model method [7]. However, laboratory work was presented in an aspect of research, as several researchers adopted the laboratory model to investigate the effect of interference of foundations on the bearing capacity and settlement, reference is made to Das and Larbi-Cherif 1983 [8], Selvadurai and Rabbaa 1983 [9], Kumar and Bhoi 2009 [10], Ghosh 2011[11], Reddy et al. 2012 [12], Pusadkar et al. 2013 [13], and Subhan 2017[14]. The numerical analyses were also taking part in this problem. Some of these studies had investigated the problem by adopting the finite element analysis of foundations under the influence of a vertical load in addition to a horizontal load. In this regard, reference is made to Gourvenec and Steinepreis 2007[15], Nainegali et al. 2013 [16], and Stergiou et al. 2015[17]. Other numerical studies have embraced finite difference analysis of foundations under the influence of a vertical load, referred to Mabrouki et al 2010 [18], Daud 2012 [19], Lavasan and Ghazavi 2014 [20], and Fuentes et al. 2018 [21]. In many cases, some signs of failure may appear in some foundations of buildings due to the construction of a new building adjacent to the existing building. Among these signs are the appearance of cracks in the walls of the building as a result of increased differential leveling, and even appear in some buildings that were taken precautions to prevent the collapse of the soil under the foundations before the excavation of the foundations of the new building had been started. These problems in existing buildings occurred as a result of the interference of the foundations of the new building with the foundations of the existing building, which did not take an interesting area in the available studies [22]. In this paper, the interaction of foundations resting on clay soil and their effect on the settlement is studied using 3D Plaxis application finite element analysis. The study adopts two types of foundations, the first type is a strip foundation of 1m width and the second type is a square foundation of 1.5m width. The effect of interfering of the foundations on the settlement is investigated, in the first case of a strip foundation adjacent to another strip foundation, in the second case of a square foundation adjacent to another square foundation, and the third case of a strip foundation adjacent to a square basis. A case study is assumed, which includes the construction of a new building adjacent to an old building, and studying the effect of this juxtaposition on the settlement of the foundations of the old building.

2. Methodology

Numerical investigations are carried out on saturated clay soils that are supposed to be homogeneous and isotropic with land area of 400 x 400m and depth of 20 m to avoid the effect of boundaries. The details of their properties are shown in Table 1, [23]. Where the primary focus is on settlement and tilt behaviors. The analysis is performed on the proposed types of foundations in reliance of the finite element method using 3D Plaxis program. The foundations are assumed to be a rigid reinforcement concrete with modulus of elasticity (E) equal to 23.5E6 kN/m² and Poisson's ratio (υ) equal to 0.2. The width of the strip foundation (B) is assumed to be 1 m, where for the square foundation is assumed to be 1.5 m and the thickness is assumed to be 0.7m for both types of foundations. The geometry of interfering foundations is shown in Figure 1, where B is the width of foundation and S is center to center spacing between foundations.
Table 1. Material properties of clay.

| Material model   | Material type   | $\gamma$ (kN/m$^3$) | $\gamma_{sat}$ (kN/m$^3$) | E (kN/m$^2$) | $\nu$ | C (kN/m$^2$) | $\phi$ (°) |
|------------------|-----------------|----------------------|--------------------------|------------|------|--------------|------------|
| Mohr-Coulomb     | Undrained       | 16.5                 | 18                       | 20000      | 0.4  | 35.5         | 0          |

Figure 1. The geometry of interfering footings.

The Mohr-Coulomb failure criterion, which is an elastic, perfectly plastic model, is selected for simplicity, practical importance, and the availability of the parameters needed. The investigation is departed into three cases; the first, two equal rigid strip foundations are spaced at spacing $S$, the second, two equal rigid square foundations are spaced at spacing $S$, and the third, a rigid strip foundation with a rigid square foundation are spaced at spacing $S$. In all analyses conducted, it is assumed that foundations are located on the ground surface of the soil. The plane strain condition with 15 triangular node elements is used in the modeling, while the foundations are modeled by plate elements.

In order to depend on the numerical investigation results, a laboratory model was manufactured to simulate the soil in the site to study the settlement characteristics of soil under the effect of interference of foundation. The load is applied using two hydraulic jacks, one for each foundation model; each jack's maximum capacity is 1 ton (10 kN). The foundation is represented by a miniature stiff steel plate model of 5 mm thickness supported vertically by a steel plate with a thickness of 5 mm from the load shed side. A 70 mm width model and 55 mm length is used for the strip foundation, while a 100 mm square model represented the square foundation. It should be noted that the foundations are placed freely on the surface of the soil to monitor the possibility of a tilt phenomenon. The apparatus consists of the following parts, as shown in Figure 2.

Before the interfering investigation, both types of foundations, strip, and square are investigated as an isolated foundation. Terzaghi's theory is adopted to calculate the ultimate bearing capacity, so according to this calculation, the strip foundation is loaded of 202 kN/m$^2$ as a uniform load, and the square foundation is loaded of 590 kN as a point load. For interference cases which referred, in the first case, the two adjacent strip foundations are loaded to 202 kN/m$^2$ as a uniform load, where settlement under the center of foundation at point b and the edges at points a and c, as shown in Figure 1 are recorded for varies values of non-dimension $S/B$ until the effect of interfering vanishes. Also, in the second case, the same procedure used in the first case is applied to a pair of square foundations by shedding 590 kN as a point load for each one. While, in the third case, the strip foundation is loaded of 202 KN/m2, and the square foundation is loaded of 590 KN as a point load, so settlement for three points, a, b and c, under both foundations are recorded for varies values of non-dimension $S/B$ until the effect of interfering is vanished.
3. Results and discussion

In order to indicate the effect of interference of two closely spaced foundations, efficiency factors $\xi_\delta$ due to settlement is determined as expressed in the following equation:

$$\xi_\delta = \frac{\text{settlement of foundation under interference condition}}{\text{settlement of isolated foundation}} \quad (1)$$

For the first case, two closely spaced strip foundations, the numerical investigation results are summarized in Table 2 to 4. Whereas the numerical investigation’s results for the second case, two closely spaced square foundations, are included in while the numerical investigation results for the third case, two closely spaced strip and square foundations, are included in . The results of experimental investigation are included in Table 5. In additional, the variation of the efficiency factor $\xi_\delta$ with the non-dimension values of S/B for the three cases is shown in the Figure 3.

| Table 2. Numerical investigation of the interfering effect on strip foundations. |
|-----------------------------------------------|
| Type of foundation | Width of foundation (m) | Load on the foundation (KN/m²) | S/B | Settlement ($\times 10^{-3}$ m) | $\xi_\delta$ | Tilt (°) |
|---------------------|------------------------|-------------------------------|-----|---------------------------|-------------|--------|
| Isolated            |                        |                               |     |                          |             |        |
| 1                   | 14                     | 14                            | 14  | 1.0000                    | 0.0000      |        |
| 1.5                 | 60                     | 44                            | 28  | 3.1428                    | 1.8328      |        |
| 2                   | 29                     | 25                            | 22  | 1.7857                    | 0.4010      |        |
| 2.5                 | 23                     | 21                            | 19  | 1.5000                    | 0.2291      |        |
| 3                   | 20                     | 19                            | 18  | 1.3571                    | 0.1145      |        |
| 4                   | 18                     | 17                            | 17  | 1.2857                    | 0.0000      |        |
| 5                   | 16                     | 16                            | 16  | 1.1428                    | -           |        |
| 6                   | 15                     | 15                            | 15  | 1.0714                    | -           |        |
| 7                   | 14                     | 14                            | 14  | 1.0000                    | -           |        |
Table 3. Numerical investigation of the interfering effect on square foundations.

| Type of foundation | Width of foundation (m) | Load on the foundation (kN) | S/B | Settlement (×10⁻³ m) | ξδ | Tilt (°) |
|--------------------|-------------------------|-----------------------------|-----|----------------------|----|---------|
| Isolated           |                         |                             |     |                      |    |         |
| 1.5                | 590                     |                             | 1   | 1.0000               | 0.0000 |         |
| 2                  | 13.4                    | 13.4                        | 1.33 | 1.5000               | 0.2826 |         |
| 3                  | 15                      | 15                          | 2   | 16.4                 | 1.9402 | 0.2291 |
| 4                  | 13.4                    | 13.4                        | 3   | 15.1                 | 1.1194 |         |

Table 4. Numerical investigation of the interfering effect on strip- square foundations.

| Strip foundation 1m width, 202 kN/m² loaded | Square foundation 1.5m width, 590 kN loaded |
|---------------------------------------------|---------------------------------------------|
| S/B Settlement (×10⁻³ m) | ξδ | Tilt (°) | S/B Settlement (×10⁻³ m) | ξδ | Tilt (°) |
|-------------------------------------------|----|---------|-------------------------|----|---------|
| Isolated                                  |    |         |                         |    |         |
| 1                                         | 14 | 14     | 14                      | 1.0000 | 0.0000 |
| 1.25                                      | 23.2 | 21.7 | 20.2                   | 1.5285 | 0.1718 |
| 1.75                                      | 21.5 | 19.65 | 17.8                   | 1.4357 | 0.2119 |
| 2.75                                      | 17  | 16.5   | 16                     | 1.1785 | 0.0572 |
| 3.75                                      | 16.2 | 16     | 15.8                   | 1.1428 | 0.0229 |
| 4.75                                      | 14.7 | 14.65  | 14.4                   | 1.0392 | 0.0171 |
| 5.75                                      | 14.2 | 14.2   | 14.2                   | 1.0142 | 0.0000 |
| 6.75                                      | 14  | 14     | 14                     | 1.0000 | 0.0000 |
| 7.75                                      | 14  | 14     | 14                     | 1.0000 | 0.0000 |

Table 5. Experimental investigation of the interfering effect on the strip and square foundations.

| Strip foundation | Width of foundation (mm) | Load on foundation (kg) | ξδ |
|------------------|--------------------------|-------------------------|----|
| Iso.             |                         |                         | 1  |
| 1                | 3.07                     | 3.07                    |
| 1.5              | 1.81                     | 1.81                    |
| 2                | 1.37                     | 1.37                    |
| 2.5              | 1.25                     | 1.25                    |
| 3                | 1.23                     | 1.23                    |
| 4                | 1.2                      | 1.2                     |
| 5                | 1.1                      | 1.1                     |
| 6                | 1.05                     | 1.05                    |
| 7                | 1                        | 1                       |

| Square foundation | Width of foundation (mm) | Load on foundation (kg) | ξδ |
|-------------------|--------------------------|-------------------------|----|
| Iso.              |                         |                         | 1  |
| 100               | 268                      | 4                       | 1  |

The coefficient of determination (R²) was used to check the acceptability of numerical analysis relative to laboratory experiments. The value of R² gave a good percentage of acceptability, where it was 97% and 94% for strip and square foundations, respectively. When looking closely at Figure 3, it is evident there is an increase in the value of the settlement efficiency factor ξδ with decreasing the value of S/B for all cases of interference which is presented. For the first case, two closely spaced strip foundations, the curve which represents the relationship between the settlement efficiency factor ξδ and non-dimension value of S/B take a linear shape when the value of S/B decreases from 7 to 3, where the value of ξδ recorded to be 1.2857.
Figure 3. Variation of efficiency factor ($\xi_\delta$) with S/B.

After this point, the curve begins to shift to a non-linear shape, where it records an accelerated increase in values of $\xi_\delta$ to be 3.1428 as the highest value when the value of S/B is equal to one, where the two foundations are closely related to each other. As a second case, two closely spaced square foundations, from the view of the efficiency coefficient curve, it can be observed that the behavior of the soil under the adjacent square foundations is not very different from that in the case of adjacent strip foundations, only that the values of the efficiency factor $\xi_\delta$ which recorded in the second case are less than the first case, and the impact distance is shorter than in the first case where the maximum value of efficiency coefficient is recorded as 1.9402 at the value of S/B equal to one, since it is less than the first case by 38.26%, while the effect of interference fades at a value of S/B equal to 4, which is less than the first case by 42.85%. While the third case, two closely spaced strip and square foundations, shows some differences from one foundation to another. However, when studying the interference effect on the settlement of a strip foundation adjacent to a square foundation at different distances, the curve shows that the interference effect records its maximum value of 1.5285 at an S/B value equal to 1.25. The interference effect fades at a value S/B equal to 6.75. In contrast, if the case is reversed where the square foundation is adjacent to the strip foundation, the curve shows that the interference effect records its maximum value of 1.6492 at the value of S/B equal to 0.833 and the interference effect fades at the value of S/B is equal to 5.167. Also, the effect on the tilt can be observed. In the case of the strip foundation, the degree of tilt is reached to 1.83°, while in the case of the square foundation, it records 0.23°. When the values of tilt in Tables (2&3) is compared with damage limits of $\delta/l$ equal to 0.19° by Skempton and Macdonald 1956 [24], that gives the distance between two foundations must not decreases less than 2.5m for strip foundations and 2m for the square foundation to be safe.

4. Numerical case study
The effect of interference of foundations is clearly apparent in practice on constructions when constructing a new facility adjacent to an existing one. For this purpose, in this section, the effect of interference on an existing building's settlement as a result of constructing a new building adjacent to it is studied.

4.1. Soil properties
The investigations of the case are carried out on saturated clay soils, the details of which are shown in Table 1, which supposes to be homogeneous and isotropic with a land area of 200 x 200m and depth of 20 m to avoid the effect of boundaries.
4.2. The existing building

The existing building has been assumed as a multi-story building, built on an area of 20 x 30 m, supported by a reinforced concrete strip foundation, with a width of 1 m, a depth of 1 m, and a thickness of 40 cm, as shown in Figure 4. Table 6 show the properties of reinforced concrete. The external foundations are loaded by 55 kN/m line load, and the internal foundations are loaded by 67 kN/m line load [25].

![Figure 4. Existing and new buildings, top view, foundations plan.](image)

Table 6. Material properties of reinforced concrete.

| Material       | $\gamma$ (kN/m$^3$) | $E$ (kN/m$^2$) | $\nu$ |
|----------------|----------------------|----------------|------|
| Reinforced concrete | 24                   | 23.5 E6        | 0.2  |

4.3. Assumption

In order to study the effect of interference on the settlement by a newly constructed building adjacent to an existing building, it is assumed that the new building is also a multi-story building with dimensions of 20 x 30 m supported by a reinforcement concrete raft foundation of 50 cm thickness, where the settlement values for points a, b, c, d, e and f, which are shown in Figure 4, are recorded before constructing the new building and comparing it with the following hypotheses:

- Excavations of foundations of the new building: where the interfering effect on the settlement of the existing building is studied due to excavation work for the foundations of the new building and for different depths starting from 1 m until 4 m, as shown in Figure 5.
- Construction works for the new building: where the final load of the new building is divided into four sections. Each section represents a construction stage until the final load is reached, considering the loads within the cases mentioned in paragraph (1) above, as shown in Figure 6.

4.4. Results and discussion of numerical case study

The results of investigating the effect of constructing a new building adjacent to an old building on the settlement of the old building are shown in, Figure 7, and Figure 8 and Table 7.
Figure 5. The effect of nearby excavation of new building on the old building.

Figure 6. The effect of the nearby new building on the old building.
Table 7. Settlement effect of the new building on the closely spaced old building.

| Case                                      | Settlement mm |
|-------------------------------------------|---------------|
|                                           | f  | e  | d  | c  | b  | a  |
| Isolated building                         | -3.5| -5.2| -7 | -7.3| -6.4| -3.58|
| 1 m excavation of new building            | -7.8| -11.8| -13.6| -14.1| -11.6| -6 |
| 1 m depth of the new building             | -11 | -17.4| -20.1| -21 | -17.9| -9.8 |
| 20 kN/m²                                  | -11 | -17.4| -20.1| -21 | -18.7| -14 |
| 40 kN/m²                                  | -11 | -17.4| -20.1| -21 | -19.6| -18 |
| 60 kN/m²                                  | -11 | -17.4| -20.1| -21 | -20.1| -18 |
| 75 kN/m²                                  | -11 | -17.4| -20.1| -21 | -20.1| -21 |
| 2 m excavation of the new building        | -8.5 | -11.2| -12.5| -12.7| -10.6| -4.5 |
| 2 m depth of the new building             | -12.1 | -17 | -18.6| -19.7| -16.2| -6.7 |
| 20 kN/m²                                  | -12.1 | -17 | -18.6| -19.7| -4.3 | -9.6 |
| 40 kN/m²                                  | -12.1 | -17 | -18.6| -19.7| -12.5|
| 60 kN/m²                                  | -12.1 | -17 | -18.6| -19.7| -18 | -15.5 |
| 75 kN/m²                                  | -12.1 | -17 | -18.6| -19.7| -20.1|
| 3 m excavation of new building            | -8.4 | -13 | -13 | -13.3| -10.3| -4.4 |
| 3 m depth of the new building             | -12.3 | -19.6| -19.8| -20 | -15.5| -5.9 |
| 20 kN/m²                                  | -12.3 | -19.6| -19.8| -20 | -15.8| -8 |
| 40 kN/m²                                  | -12.3 | -19.6| -19.8| -20 | -16.1| -10 |
| 60 kN/m²                                  | -12.3 | -19.6| -19.8| -20 | -16.3| -11.6 |
| 75 kN/m²                                  | -12.3 | -19.6| -19.8| -20 | -18 | -15.5 |
| 4 m excavation of new building            | -7.6 | -12.6| -14.5| -14.2| -11.6| -4.3 |
| 4 m depth of the new building             | -11.4 | -18.9| -22.1| -22.2| -17.2| -4.5 |
| 20 kN/m²                                  | -11.4 | -18.9| -22.1| -22.2| -17.6| -7.1 |
| 40 kN/m²                                  | -11.4 | -18.9| -22.1| -22.2| -18 | -9.8 |
| 60 kN/m²                                  | -11.4 | -18.9| -22.1| -22.2| -18.2| -11.8 |

Figure 7. Settlement effect of the excavation of new building on the closely spaced old building.
It is noted from the results that the effect of the new building begins at the foundation excavation stage, where the increase in settlement appears for all points on the foundations of the old building. It is worth noting that the soil's behavior almost shows a homogeneous and equal settlement for all points as a result of the various depths of the excavation, as shown in Figure 7. Also, it can be observed the relative difference in the settlement between points a and b on both ends of the foundation of the old building, where the value of the settlement in the point b (far from the excavation) is higher than point a (near the excavation). This difference is due to the soil's behavior under the building in an attempt to offset the value of the lost stress as a result of excavation works to the foundations of the new building.

When increasing the load on the foundations of the new building, the settlement of foundations of the old building increases at all points. It is also noted that the settlement in the points starting from c to f reaches its peak in the initial stages of loading on the foundations of the new building, while the increase continues to settlement in points a and b until the loading reaches the allowable limit. It is also noted that the construction of adjacent buildings on shallow foundations has a more significant impact on the old building, as the heterogeneous increase in the settlement causes the creation of additional stresses, usually not taken into account in the structural design of the foundation, may lead to the failure of the foundation and the appearance of cracks in the building. While the investigation shows a somewhat homogeneous increase in settlement of all points on the foundations of the old building when constructing the adjacent new building on deeper foundations, as shown in Figure 8. This means that the old building will maintain its stability despite the increase in the settlement, and thus a potential failure will appear in the floor finishing, so it is considered easy to repair.

5. Conclusion

- The numerical analysis of the adjacent shallow foundations shows a significant effect of interference on the settlement in two strip-type foundations, where the efficiency factor value reaches 3.14, and the interference effect extends to a distance of 7B. In the case of the interference of two square foundations, the value of the efficiency coefficient reaches 1.94, which is much less than the case of the strip foundation, and the effect of interference fades at a distance of 4B, so it is considered an optimal option in the case of closely spaced of the same type of foundations.
The effect of interference on settlement also appears on foundations of a different type. The effect of settlement is achieved on the square foundation adjacent to a striped foundation. The effect of the striped foundation on the square foundation is 8% higher than the effect of the square foundation on the striped foundation. However, it is also noticed from the investigation, the effect of interference on the settlement in the case of foundations of a different type is less than in the case of foundations of the same type, where the effect on the strip foundation is 51% less, while the ratio for the square foundation is 15%. From these ratios, the choice of foundations of a different type can be considered better than the foundations of a similar type when interference occurs.

In addition to the effect of interference on the settlement, its effect on the tilt can also be observed. In the case of the strip foundation, the degree of tilt is reached to 1.83°, while in the case of the square foundation, it records 0.23°. The state of tilt occurrence must be taken into account when designing the foundations, as they produce additional stresses due to the deflection of the applied load axis.

The numerical analysis carried out on a neighboring new building to an old building shows an effect on the settlement of the old building with an average increasing rate of 177%. The analysis also showed that the risk of interference on points near the new building decreased by 42% when the depth of the new building's foundation increases from 1m to 4m.

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