Use of Pile to Reduce Induced Settlement in Existing Adjacent Building following Construction of New Building (Case Study: Abadan)

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Abstract

Objectives: Estimating the impact of high-rise building on the adjacent building foundation of existing older building with few floors. Methods: Transfer of load from foundation to the earth not only spreads vertically but also transversely; thus, following increased tension, additional earth subsidence occurs in adjacent structures, which may damage them. Results: This is especially important when it comes to saturated fine grained soils due to high potential for consolidation subsidence. Failure to consider said mechanism has caused many old buildings with structural and masonry materials to undergo damage and cracking every year. A practical method to address this is to shift stress to lower layers using pile. Herein, a six-story building adjacent to a one-story one in Abadan was selected for case study. Using PLAXIS 3D Foundation, effect of pile and its role in reducing of adjacent building’s subsidence was studied. Conclusion: Numerical Results shows that when piles arrangement under the foundation of new building in such a way that place in the first row of piling and with axis-axis spacing of 3 m and length of 15 m next to the old building can rule out structure cracks Acceptably and reduce the interference between them. Also the results indicate that increasing the length and diameter of the piles can shift non-structural cracks to more distant areas.

Keywords: Adjacent Building, Pile, PLAXIS, Reaction, Subsidence, Settlement

1. Introduction

The basic objective of foundation is to transfer loads from building to the earth at a proper depth in such way that the stress caused by these loads does not adversely affect the adjacent building foundation and does not stress the soil not to an extent overbearing capacity and would not cause rupture (safety requirements). On the other hand, stresses in the soil must not create an unacceptable subsidence difference. That is, subsidence difference between two points of the building should not be as large as to disturb building (stable condition foundation). If the two conditions are met and if building is correctly designed and constructed, stability and strength of building will be ensured at the highest confidence.

Today, due to proliferation and diversity of large structures and the lack of suitable land and materials, engineers should build foundations of the buildings in close proximity. Therefore, building foundations generally are not spaced at all. Interaction between foundations has fundamental importance to both structural engineering and geotechnical engineering. To ensure proper and accurate design, information about the subsidence, deviation and capacity of the soil is required.

2. Literature

Several researchers have been done on the impact of the acceptable distance and effect on dimensions and depth of adjacent foundations on bearing capacity and subsidence. In studied bearing capacity of shallow close foundations and their effect on the load-bearing capacity. In verified results from analytical solution of two close rectangular structures placed on sand with hyperbolic behavior law against experimental results on the same soil. Research by showed average bearing
capacity in un-drained mode for two strip foundations placed on a random spatial soil increased compared to two separate soils. In this paper, it was assumed that load-bearing structure of each foundation was different from that of the other. In6 studied the allowable distance between the two buildings with different stories and concluded that if the difference between stories of old building and new building is higher, determinant factor of the minimum allowable distance between two adjacent buildings will be deformation caused by tilt. In7 provided an experimental model to show that the subsidence and bearing load capacity of a single foundation maximized in presence of another foundation when critical distance between them was maximized and thence, it decreased. In8 concluded that if a shallow foundation system used, in case of the impossibility of changing the superstructure system, subsidence of old building may be reduced by increasing the depth of new foundation. In9 showed in their studies that was conducted by finite element method on two adjacent foundations in which elasticity modulus of the soil changed with depth that predicting of the behavior of non-homogeneous soil is very similar to prediction of behavior of homogeneous soils. In10 showed in experimental study of adjacent foundations simultaneously and gradually loaded on sandy soil that the effect of interference was negligible foundations spaced by a distance 6 times as much as the width.

3. Allowable Subsidence of Foundations

Since new construction occurs next to existing building in urban areas, subsidence due to sudden rise of stress caused by new building is non-uniform. For this reason, it is recommended that in regions where internal stress in suddenly changes and restrictions on subsidence be considered.

Parameters of the subsidence include11:

- $\omega$: Tilt, total rotation which $\omega = \frac{\Delta ST_{(max)}}{L}$
- $\beta$: relative rotation $\beta = \frac{\Delta A}{AB}$

$\Delta ST_{(max)}$: Differential subsidence of two ends of foundation.

$ST_{(max)}$: Maximum subsidence.

$L$: Lateral dimension of building.

Figure 1 shows parameter related to subsidence that causes rotation of building. Canadian Geotechnical Society (2006) specified failure criteria and its limit.

4. Finite Element Modeling

In this paper, three-dimensional finite element method was applied using Plaxis 3D Foundation software. This software falls within finite element series of Plaxis software developed at the University of Delft, for use in analysis of

Table 1. Parameters of permissible subsidence limits based on type of building

| Type of building                        | Type of damage               | Criterion          | Permissible limit |
|----------------------------------------|------------------------------|--------------------|-------------------|
| Framed buildings and reinforced load-bearing wall | Structural damage | Relative rotation | 1/150-1/250        |
|                                        | Cracks in the walls and partitions | Relative rotation | 1/500              |
|                                        | Visual aspect               | Tilt               | 1/300              |
|                                        | Service                     | General settlement | (Sand) mm 50-75    |
raft-foundation, pile foundation, raft-pile foundation and coastal structures\textsuperscript{13,14}.

4.1 Network of Finite Element and Boundary Conditions
Figure 2 shows an example of the network of finite elements used in this paper. Parametric study was conducted for different dimensions of pile and different arrangements. Soil material properties, piles and raft are listed in the table below. Studied soil was clay soil of Abadan. In this study, a new building with dimensions of $20 \times 20$ m with raft foundation with a thickness of 80 cm and old building, with dimensions of $10 \times 20$ meters with a foundation with negligible thickness of 20 cm were modeled in the distance of 30 cm from each other. The dimensions of model were extended on each side by 5 times the width. Simulation environment was 240 meters long and 100 meters deep. Figure 3 shows the location plan for the two foundations.

![2D meshing](image)

**Figure 2.** 2D meshing.

![Location plan and location of foundations](image)

**Figure 3.** Location plan and location of foundations.

4.2 Property of Materials in Model
The groundwater level in the city of Abadan is at one meter above the ground, so the soil is saturated. This study soil profile is modeled by Mohr-Coulomb model. Given effect of the final subsidence of building on adjacent structures was to be studied, the parameters of drained soil was used. In the following tables properties of foundation and soil and piles used are provided according to test results of soil mechanics and foundation in the site.

4.2.1 Profile of Foundation
4.2.2 Specifications of Soil Layers
4.2.3 Specifications of Piles
Specifications of piles were modeled in Plaxis 3D foundation software in non-porous environment and with linear elastic behavior. Specifications of piles in the

| Layer Number | Type of layer | Layer Descriptor | Layer depth | C' (kn/m$^2$) | q' | Y' (kn/m$^2$) | $E_s$ (kn/m$^2$) | $\nu$ | $R_{int}$ |
|--------------|---------------|------------------|-------------|--------------|---|--------------|--------------|---|----------|
| 1            | Cl            | Clay Brown       | 6           | 23           | 22 | 19           | 6000         | 0.35 | 1        |
| 2            | Cl            | Gray clay        | 6           | 24           | 19 | 18           | 8000         | 0.4  | 1        |
| 3            | Ml            | Sandy silt       | 3           | 14           | 30 | 19           | 10000        | 0.3  | 1        |
| 4            | SM            | Fine sand        | 5           | 10           | 36 | 20           | 18000        | 0.25 | 1        |
| 5            | SM            | Fine sand        | 10          | 7            | 41 | 20           | 15000        | 0.25 | 1        |
| 6            | CL            | Brown Clay       | 5           | 26           | 21 | 20           | 16000        | 0.35 | 1        |
| 7            | CL            | Dense marl       | 65          | 29           | 20 | 21           | 35000        | 0.35 | 1        |

| Foundation type | Thickness (m) | Foundation modulus of elasticity (KPa) | Poisson's ratio | Unit Weight (KN/m$^3$) |
|-----------------|---------------|----------------------------------------|-----------------|------------------------|
| New building    | 0.8           | 2.686e7                                | 0.15            | 24                     |
| Old building    | 0.2           | 2.686e7                                | 0.15            | 24                     |
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The behavior of soil materials was modeled using Mohr-Coulomb model that is a simple and fast model used simulation of soil’s behavior. Because the elastic modulus of elasticity of piles and raft was much higher compared to soil, raft and piles remained in elastic range and therefore, linear elastic model was used to simulate their behavior.

5. Verification of Software Model

In order to verify software performance and validation of model, lab tests data including centrifuge test developed by Hoorikshi and Randolph were used. In this experiment, pile groups of 9 each with a length of 15 meters and a diameter of 0.32 m were simulated and raft foundation of a diameter of 14 meters and a thickness of 0.05 mm and soil range of up to 25 m were considered. The average subsidence of raft-pile foundation was given by following equation as developed by Davis and Taylor (1962). Figure 4

\[ S_{avg} = \frac{1}{3} \times (2 \times S_{center} + S_{corner}) \]

Where \( S_{avg} \) denotes average subsidence, \( S_{center} \) and \( S_{corner} \) denote subsidence values at the center and corners of raft-pile foundation. In Table 5, the numerical values of average subsidence obtained from the experimental and theoretical studies by Hoorikshi, which a load of 12 mega Newton on pile caps, are provided, and values were compared with software Plexis values.

In order to ensure the accuracy of the analysis software, the model built by software were loaded under loads of 5, 10, 12, 15 and 20 Mega-Newton and the accuracy of the answers was investigated by comparing them according to the article Horikoshi and Randolph. Figure 4.

| Table 5. Compares the experimental results with the numerical model used in this article |
|---------------------------------|-----------------|-----------------|-----------------|
| Average settlement of laboratory study | 22              | Average settlement of the theoretical study | 23             |
| Average settlement of software analysis | 21              |                                              |                |

As we can see, there is a good accommodation between analysis software and laboratory.

6. Calculation Procedure

Angular rotation is given by dividing width of the old building to 9 points, by calculating the difference between every two consecutive points and dividing them by the
distance between them (1.25 m). To calculate rotation, subsidence difference between two ends of foundation is divided by the distance between them (10 m). According to the Canadian regulation, limit of rotation $\beta$ for structural and non-structural cracks are 0.004 and 0.002, respectively. Therefore, permissible subsidence difference between the two points spaced by 1.25 is:

$$\beta = 180 \times \pi/0.004 = \tan^{-1} \frac{x}{25/1} \rightarrow x = 5 \text{ Mm}$$

That is known as Structural cracks limit.

$$\beta = 180 \times \pi/0.002 = \tan^{-1} \frac{x}{25/1} \rightarrow x = 5 \text{ mm}$$

That is known as Architectural cracks limit.

The allowed rotation according to the said regulation is 1.300 side of the building. Given that the critical side length of 10 meters, allowed difference value between the two ends of the old building is equal to $10 \times 1.300 = 33 \text{ mm}$. To further investigate the impact of the adjacent building, due to geometric symmetry, half of the old building was denoted by the letters A, B, C, D and numbered sequentially and the subsidence at the four sides of the old building foundations under the influence of 60 kN/m$^2$ load in the new building was drawn. Figure 5 shows subsidence of old building and at marked points.

As seen from Figure 6, the maximum angular rotation in the old building occurs at side C that is in the middle of the building. Also, it is seen from the figure that difference between subsidence at two consecutive points is greater than 5 mm in all these sides. Therefore, structural cracks were found across this side. On the other hand, following the biggest difference between the two ends is $92 - 28 = 64$ millimeters and since that permissible limit is 33 mm for rotation, this side was chosen as the critical side and the effect of pile on its subsidence was studied.

Figure 5. Show marking the foundations old.

Figure 6. Curved sides subsidence in the vicinity of the old building and new building.
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7. Results of Numerical Analysis and Discussion

7.1 Minimum Acceptable Length of the Pile
In order to select the minimum length required to avoid structural cracks in the old building in the first row of piles, piles with a fixed diameter of 60 cm with axis to axis distance of 1.5, 2, 2.5, 3 and 3.5 meters were placed under the foundation of the new building, 30 cm off the foundations of the old building.

These are the results of the software analysis.

According to Figure 7 and the rotation criterion, piles each with a length of 10 meters, with axis to axis distance don’t exactly resolve structural cracks. Table 6 shows the values of subsidence of the two ends of side C for with axis to axis distances of 1.5, 2, 2.5, 3 and 3.5 meters. Accordingly, based on the maximum rotation criterion, maximum permissible difference between the two ends of the foundations was obtained to be 33 mm. For this reason, the least selected length for the piles was 15 meters. Further, for piles with axis to axis distance of over 3.5 meters and a length of 15 meters, rotation criterion doesn’t resolve the problem (Figures 8 and 9).
Table 6. Values of the subsidence at two ends of side C

| The distance of the pile axis (S) | Pile length L | First point settlement of the old foundation | End point settlement of the old foundation |
|----------------------------------|--------------|---------------------------------------------|---------------------------------------------|
| 1.5                              | 10           | -72                                         | -29                                         |
| 1.5                              | 15           | -56                                         | -29                                         |
| 2                                | 10           | -73                                         | -29                                         |
| 2                                | 15           | -58                                         | -29                                         |
| 2.5                              | 10           | -75                                         | -29                                         |
| 2.5                              | 15           | -60                                         | -29                                         |
| 3                                | 10           | -81                                         | -29                                         |
| 3                                | 15           | -61                                         | -29                                         |
| 3.5                              | 10           | -63                                         | -29                                         |
| 3.5                              | 15           | -54                                         | -28                                         |

7.2 Choice of Optimum Center-to-Center Distance of Pile

To choose the optimal distance, the Average Efficiency of Pile Row (AEPR) was used. By definition, if AEPR is defined as contribution of each pile to reduced settlement, for 15 meter piles length, we will have:

\[
AEPR = \frac{\text{Subsidence difference in presence vs. in absence of pile}}{\text{number of piles}}
\]

If acceptable arrangement of pile is assumed to be pile that have no structural crack and if efficiency 19 points is deemed as the most critical point based on subsidence in the old building, Table 7 will result. It is noteworthy that in no-pile mode, subsidence at point 19 is equal to 92 mm.

Table 7. Average efficiency of pile row

| Distance between piles (m) | Number of pile in a row | Settlement in the point 19(mm) | Settlement difference | Efficiency |
|---------------------------|-------------------------|---------------------------------|-----------------------|------------|
| 1.5                       | 13                      | -56                             | -36                   | 2.76       |
| 2                         | 10                      | -58                             | -34                   | 3.4        |
| 2.5                       | 8                       | -60                             | -32                   | 4          |
| 3                         | 7                       | -61                             | -31                   | 4.43       |

Given Table 7, maxim contribution of each pile's load bearing to reduced subsidence was piles spaced by distance of 3 meters.

7.3 Investigation of Increase of Number of Rows and Distance of Piles

To increase number of rows piles, 4 rows spaced by 2 meters were considered as shown in Figure 10. And its effects were studied once in rows 1, 2, 3 and 4 independently and then in groups in rows 1 and 2; 1 and 2 and 3 and 1, 2, 3 and 4. Subsidence graph was shown in Figure 11, old building's angular rotation in Figure 12 and rotation graph in Figure 13.

Figure 10. Location plan of plan piles.

Figure 11. Curve of subsidence of pile arrangement 2-3.
In Figure 11, pile x-y R_i, in the meaning of the piles with x meter axis to axis in Y direction and with y meter axis to axis in X direction as well as R_i in the meaning of the piles in i row. According to Figure 11, group arrangement of piles in form of four rows of piles had no significant effect on subsidence. In addition, as expected, with increased distance of axis of piles from the widths of building, pile’s impact on subsidence reduced by 19 points. Effective depth of piles with respect to reduction of subsidence was up to point 25 (5 to 6 meters from the width of old building). According to Figure 12, when there is no pile, structural cracks will be seen throughout the building. Among arrangements of piles, rows 4 and 3 caused structural cracks, which means that the effect range of pile row was up to the distance of 2.8 m from the width of old building. In all arrangement of pile, cracks occurred in the old building. According to Figure 13, piles rows 2,
3 and 4 do not satisfy rotation criterion. Therefore, the threshold was 2.8 m for permitted place of pile row. Also it is seen from Figure 14 that the efficiency was calculated on the basis of subsidence at 19 points. According to the results, maximum efficiency related to arrangement of pile 2-3 of pile row 1 (the distance between the two piles is 5 times the diameter).

7.4 Parametric Study of Simultaneous Effect of Length and Diameter of Pile

To study the simultaneous effect of length and diameter of piles with diameter of 60, 80 and 100 cm and lengths of 15, 20, 25, 30 and 35 meters placed in the first row and spaced by 3 meters distances were analyzed and the results were evaluated. To ensure better comparison of the results from the software, with results were measured using L/d ratio. The starting point of cracking at the length of side C are given for different L/d ratios (Figure 15).

Figure 15 gives the following results:

- In ratio of L/d = 35, the farthest non-structural cracking point lies.
- Ratio of L/d = 35 related to piles with a diameter of 100 cm and a length of 35 meters means that with increase of the diameter of piles and therefore, increased proximity of piles, piles act somewhat as wall and induce less stresses on adjacent building, so fewer cracks are caused.
- As expected, with increasing length of the pile due to transfer of load to the lower layers, less induced subsidence happened.
- As length of pile increased, crack area shifted farther away from the border of adjacent building.

8. Conclusion

We present a case study based on numerical analysis by Praxis software and soil lab results of Abadan and aimed to examine the effect of pile placed under foundations new 6-floors buildings adjacent to old one-story building with dimensions of 20 × 20 and following results were obtained:

- The highest subsidence in the old building occurred at the middle of 20-meter side of the new building (side C in the old building and point 19) (measuring 92 mm), because stress in this part of the new structure was more than stress in other points.
- The minimum acceptable pile length to avoid structural subsidence of old building was obtained to be 15 meters. Because of transfer of load of new structure to lower layers, less stress is induced on adjacent structures and therefore there will be less subsidence. The higher the load of the new structure, the longer the pile should be.
- The effective depth of piles of length of 15 meters was 5 to 6 meters of the width of the old building. The difference between use of pile and nonuse of pile became negligible at higher depths -Figure 11.
- Using the criteria of the rotation and efficiency parameter, piles with axis-to-axis spacing of 3 meters were used to reduce subsidence in old building (the distance between the two piles was 5 times the diameter).
- Authorized threshold of row of piles with a distance of 3 meters reached 2.8 m of building's width given rotation criterion.
• Ratio of $L/d = 35$ related to piles with a diameter of 100 cm and a length of 35 meters means that with increase of the diameter of piles and therefore, increased proximity of piles, piles act somewhat as wall and induce less stresses on adjacent building, so fewer cracks are caused.

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