The Effect of Group of Piles on Existing Tunnel

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Abstract. This work focuses on the effect of construction and loading of piles group on an existing tunnel. This was achieved by performing model tests on a sandy soil using two relative densities (50% and 70%). The experimental models include group of piles (2x1) with 3d spacing and (2x2) with 3d and 8d spacing. Three clear distances between the pile and the tunnel were chosen to be 0, 0.6 and 1.6d (d: pile diameter). The pile used is a reinforced concrete pile with 20 mm diameter and 400 mm in length, the spacing piles in pile group is chosen to be 2d and 3d. The tunnel used was a reinforced concrete tunnel with diameter of 84 mm and 780 mm length. A numerical modelling of experiments was carried out using PLAXIS-software in which the hardening soil model (HS small) has been used for modelling. The main conclusion drawn from this study is that, the stresses generated on the tunnel lining during loading are higher than during construction stages. The stresses generated on the tunnel decreases with the increase in relative density and the distance from the tip of the pile.

Key Words: Group of piles, Tunnel, Bearing capacity, Experimental, Finite elements

Introduction

Many researchers have summarized the pile-tunnel interaction problems, which can be categorized into two groups: effects of tunnelling on piles and effects of piling on tunnels, where the second group received less attention. There are some case studies which investigated the effect of piling on existing tunnels. Benton and Phillips, 1991 studied the behaviour of two existing tunnels; British Telecom hollow tunnel and deep tunnel during the construction and loading of large diameter undreamed bored piles. Chapman et al, 2001, and Schroeder 2002a, 2002b also conducted a set of FE analyses to investigate the interaction between pile foundations and existing tunnels Charoenpak et. Al 2006 investigated the effect of pile row under loading adjacent to an existing subway tunnel. Yao et al 2006 described a series of centrifuge tests designed to investigate the effect of bored pile excavation on existing tunnels. Yao et al, 2009 examined the influence of bored piles on adjacent tunnels; the analysis was accomplished by using a FLAC three-dimensional computational model. Arun kumar and Ayothiraman, 2010 investigated the effects of pile loading on existing tunnels embedded in cohesive soil using ABAQUS program. Lueprasert et.al, 2015 used three-dimensional finite element program ABAQUS to analyse the impacts of single pile and pile row under loading on the subway tunnel of the Mass Rapid Transit Authority of Thailand in Bangkok. The effect of pile foundations on existing tunnels can be categorized into two parts: pile installation and the post piling period. In this study, the main objective is focused on both of them.

Experimental Work
1.1. Soil Used
The soil used was obtained from Karbala city (100 km south-west of Baghdad). Physical properties were obtained using standard tests according ASTM specifications. These properties are listed in Table (1)

Table 1. Physical properties of the sand used in the tests.

| Index properties                  | Value       | Specification     |
|-----------------------------------|-------------|-------------------|
| Specific gravity, Gs              | 2.68        | ASTM D-854        |
| Effective size (mm), D_{10}       | 0.16        | ASTM D-2487, D-422|
| D_{50} (mm)                       | 0.23        |                   |
| D_{90} (mm)                       | 0.38        |                   |
| Coefficient of uniformity, C_U    | 2.38        |                   |
| Coefficient of curvature, C_c     | 0.87        |                   |
| Soil classification (USCS)*        | SP          |                   |
| Maximum dry unit weight \(\gamma_{\text{max}}\) (kN/m³) | 18.8        | ASTM D 4253-2000 |
| Minimum dry unit weight \(\gamma_{\text{min}}\) (kN/m³) | 15.3        | ASTM D 4254-2000 |
| Dry unit weight \(\gamma_d\) (kN/m³) at D_r=50% | 16.87       | ASTM D 4253-00   |
| Dry unit weight \(\gamma_d\) (kN/m³) at D_r=70% | 17.59       |                   |
| Angle of internal friction \(\varphi\) (at D_r = 50%) | 35.5°       | ASTM D 3080      |
| Angle of internal friction \(\varphi\) (at D_r = 70%) | 38.5°       |                   |
| Maximum void ratio, \(e_{\text{max}}\) | 0.71        |                   |
| Minimum void ratio, \(e_{\text{min}}\) | 0.39        |                   |

* USCS refers to Unified Soil Classification System

2.2 Model Overview
The soil tank used has dimensions of (800 x 800 x 800 mm) with a thickness of steel plate (6 mm). Dimensions of the tank were chosen to ensure that, there is no interference between the walls and the zone around the pile tunnel system. The steel loading frame was manufactured to support the piston of hydraulic jack of (10 ton) capacity and applied load by running the piston downward.

2.3 Measurement System
During all the experimental tests the applied load is measured using a “Sewha” load cell 2 ton capacity. A digital weighing indicator “Sewha” is used to read and display the load value. Furthermore, Earth-pressure cells were used in this study to measure the stresses generated on tunnel lining due to driving and loading of single pile.

2.4 Models of Piles and Tunnel
Concrete piles and tunnel were used to simulate the same friction and behaviour of concrete piles and tunnel in the field. A 20mm diameter and 400mm length was selected as the model pile and the dimension and configurations of piles cap are clarified in Table (2). The dimension of model tunnel used was 84mm, 780mm, 10 mm for diameter, length and thickness respectively. Figure (1) Shows pile configuration used in this study.
3. Physical Modeling

3.1. Sample Preparation
The sand deposit was prepared using a steel tamping hammer manufactured for this purpose. The steel container divided and singed into eight layers (each layer of 10 cm height and the same density). The volume and density for each layer were known, the weight of each layer was determined, then compacted by hammer to get the required height. Each soil layer was compacted to a predetermined depth and the concrete tunnel with the three pressure cells that attached on certain positions were placed in the container and then the soil deposit was completed to final layer. After completing the final layer, the top surface was scraped and leveled by a sharp edge ruler to get as near as possible a flat surface.

3.2. Insertion and Loading of Pile
The piles were inserted by means of a hydraulic jack. A vertical load was applied through a (2 ton) load cell which was mounted between the jack pin and the pile to control the applied load.

4. Numerical Model
10-node tetrahedral elements were used to model the soil and tunnel lining while piles are modeled using beams elements. Furthermore, interface elements were used to simulate the friction between piles, tunnel and the surrounding soils. Soil is modeled as Hardening-soil model with Small-strain (H Small-Model) while linear elastic model was used to model the concrete piles and piles cap, and
tunnel lining. Tables 3, 4, 5 and 6 clarify the properties of material used for pile cap, pile, tunnel and soil.

- Verification with Plaxis 3d was executed to the 32 experimental models for pile-tunnel same dry sandy soil, the piles and tunnel are made of concrete and the sand is modeled during utilizing the (HS small) model.

Table 3. Piles cap parameters adopted in the numerical analyses.

| Parameters | Value | units |
|------------|-------|-------|
| Thickness  | 0.025 | [m]   |
| E          | 30 856 000 | [kN/m²] |
| Γ          | 25    | [kN/m³] |
| V          | 0.3   | [-]   |

Table 4. Piles parameters adopted in the numerical analyses

| Parameters | value | units |
|------------|-------|-------|
| Diameter   | 0.02  | [m]   |
| E          | 30 856 000 | [kN/m²] |
| Γ          | 25    | [kN/m³] |
| V          | 0.3   | [-]   |

Table 5. Tunnel parameters adopted in the numerical analyses.

| Parameters | Value | units |
|------------|-------|-------|
| Thickness  | 0.01  | [m]   |
| E          | 30 856 000 | [kN/m²] |
| Γ          | 25    | [kN/m³] |
| V          | 0.3   | [-]   |

Table 6. Material properties of the sand adopted soil model is HS small.

| Properties                  | Medium Sand | Dense Sand |
|-----------------------------|-------------|------------|
| Dry unit weight (kN/m³)     | 16.87       | 17.59      |
| Drainage type               | Drained     | Drained    |
| Eₜₜ,ref (kPa)               | 40 900      | 47 150     |
| Eₜₜ,ref (kPa)               | 32 720      | 37 720     |
| Eₜₜ,ref (kPa)               | 98 100      | 113 100    |
| m                           | 0.55        | 0.53       |
| G₀,ref                      | 113 800     | 123 800    |
| γₜ₀.7                       | 0.00015     | 0.00019    |
| Cohesion c (kPa)            | 0.3         | 0.3        |
| Friction angle φ'           | 35.5        | 38.5       |
| Dilation angle ψ            | 6.5         | 10.5       |
| Tension cut-off (kPa)       | 0           | 0          |
| Kₑ(nc)                      | 0.371       | 0.318      |
5. Test Results and Discussion
- The Pile was installed at three different lateral tunnel-pile clear spacing: 0D, 0.6D and 1.6D.
- Two different relative densities were used: 50% for medium sand and 70% for dense sand.
- A single and three group of the pile (2*1) 3d spacing, (2*2) 3d spacing, (2*2) 8d spacing were tested.

Tables 7, 8, and 9 summarize the main results from this study.

**Table 7:** Maximum stresses generated at the crown and invert regions for group of pile (2×1) 3d spacing with relative density of (R.D=50% and 70%) for the three pile positions during construction and loading at piles ultimate load from numerical analysis.

|         | 0D       |            |            |            |
|---------|----------|------------|------------|------------|
| Group 2×1 3d spacing | insertion | crown | 50% | 70% |
|         |          | | | |
| Group 2×1 3d spacing | loading | crown | 50% | 70% |
| 0.6D    | crown    | 50% | 70% |
| Group 2×1 3d spacing | insertion | crown | 50% | 70% |
|         | loading | crown | 50% | 70% |
| 1.6D    | crown    | 50% | 70% |

| Group 2×1 3d spacing | insertion | crown | 50% | 70% |
| 0.6D    | crown    | 50% | 70% |
| Group 2×1 3d spacing | insertion | crown | 50% | 70% |
|         | loading | crown | 50% | 70% |
| 1.6D    | crown    | 50% | 70% |

Table 8: Maximum stresses generated at crown and invert regions for group of pile (2×2) 3d spacing with relative density of (R.D=50% and 70%) for the three pile positions during construction and loading at piles ultimate load from numerical analysis.

|         | 0D       |            |            |            |
|---------|----------|------------|------------|------------|
| Group 2×2 3d spacing | insertion | crown | 50% | 70% |
|         |          | | | |
| Group 2×2 3d spacing | loading | crown | 50% | 70% |
| 0.6D    | crown    | 50% | 70% |
| Group 2×2 3d spacing | insertion | crown | 50% | 70% |
|         | loading | crown | 50% | 70% |
| 1.6D    | crown    | 50% | 70% |
| Group 2×2 3d spacing | insertion | crown | 50% | 70% |
|         | loading | crown | 50% | 70% |
Table 9: Maximum stresses generated at crown and invert regions for group of pile (2×2) 8d spacing with relative density of (R.D=50% and 70%) for the three pile positions during construction and loading at pile’s ultimate load from numerical analysis.

| Distance | Crown | Invert |
|----------|-------|--------|
|          | 50%   | 70%    | 50%   | 70%    |
| 0D       |       |        |       |        |
| Group 2×2| insertion | 22.55kPa | 44.5kPa | 31.48kPa | 54.28kPa |
| 8d spacing | loading  | 17.01kPa | 34.7kPa | 33.75kPa | 57.12kPa |
| 0.6D     | crown  | 50%    | 70%    | 50%    | 70%    |
| Group 2×2| insertion | 40.24kPa | 64.4kPa | 34.86kPa | 59.4kPa |
| 8d spacing | loading  | 39.16kPa | 63.33kPa | 35.76kPa | 62.01kPa |
| 1.6D     | crown  | 50%    | 70%    | 50%    | 70%    |
| Group 2×2| insertion | 14.3kPa  | 22.5kPa | 3.98kPa  | 17.4kPa |
| 8d spacing | loading  | 11.4kPa  | 18kPa  | 4.12kPa  | 15.81kPa |

5.1 Effect of Relative Density

Tables 7 to 9 show that, the stress values increased with the increasing of relative density, this increment varies from 20% to 124% for maximum value for all pile positions and pile configurations through insertion and loading period, the maximum stresses generated at the crown and invert for (R.D=50% and 70%) for the three piles positions during construction and loading at pile’s ultimate load. The stresses generated for these two relative densities increased with the increasing of relative density, this increment was because of heavier weight of the sand having higher relative density soil. Furthermore, the applied stress would be higher, and the height of the tunnel pressure arch becomes bigger as the coefficient of lateral earth pressure increases.

5.2 Effect of the Position of Piles with Respect to Tunnel

Tables 7 to 9 give the maximum stresses generated in tunnel lining for different lateral horizontal distances, the results show that the maximum value of stress is at a distance 0D for all cases then the stress values tend to decrease with the increasing of lateral distance value, the percent of reduction at 0.6D would be (18-44%). For 1.6D, the effect becomes less in value and appears at the right shoulder for some cases, and the reduction would increase to (85-99%). That is for both stress ratio and stress values through insertion and loading of piles. Unlike other groups of piles, for the group of pile (2×2) 8d spacing the maximum stress value was at lateral distance of 1D. The similar trend was found in the stress values for both relative densities of 50% and 70%.

5.3 Effect of the Pile Configurations

It was observed from Figure (2) the generated stresses increased with increasing number of the pile in group from 33% for the group (2×1) to 140% for a group of (2×2) (3d spacing). This behavior is different for a group of (8d spacing) that the stresses values would be less as compared to other groups due to the effect of spacing between piles. The effect of spacing of pile is very noticeable when the spacing is increased; a reduction in value of stresses 61% to 80% for all positions as compared to group of pile of (spacing 3d).
5.4 Effect of Tunnel on the Load Carrying Capacity of Single pile and Group of Piles

Figures (3) to (6) show that, the load carrying capacity increases with increase in the relative density, spacing between pile and the number of piles in the group (this is due to the better distribution of loads on the pile group for the increased number of piles and the width containing them). From these figures, the load carrying capacity decreases as moved for lateral distances but still higher than the ultimate load without existing of tunnel, unlike group of 8d spacing that maximum ultimate reach when group is at (0.6D) from tunnel that the edge of group would be close to tunnel. This is due to the decreased stiffness of the soil tunnel interaction. Some of the applied load is carried by tunnel.

**Figure 2.** Invert region for different configuration of piles during insertion stage for pile positions (0D), (R.D=70%)

**Figure 3.** a group of pile (2×1) (3d spacing) (R.D=50%) with and without existing of tunnel.

**Figure 4.** a group of pile (2×2) (3d spacing) (R.D=70%) with and without existing of tunnel.
Figure 5. a group of pile (2×2) (8d spacing) (R.D=50%) with and without existing of tunnel

Figure 6. a group of pile (2×2) (8d spacing) (R.D=70%) with and without existing of tunnel

5.5 Validation of pile-tunnel problem

Finite element analysis was carried out by PLAXIS 3D program. By plotting a load-settlement curve and load-stress for the results, it can be realized that there is a good agreement between the finite element and experimental results. Figures (7 to 11) clarify the comparison between the experimental and finite element analysis result of the stresses generated at crown, invert region for different lateral distances, furthermore, the results of the ultimate bearing capacity of piles.

Figure 7. Stress for crown region for group of pile (2×1) (R.D=70%) (0D) (experimental and finite element analysis)

Figure 8. Stress for crown region for group (2×1) (R.D=70%) (0D), (0.6D), (1.6D) (experimental and finite element analysis)

Figure 9. Crown Stress region for group 2×2 8d spacing(R.D=50%) (0D), (0.6D), (1.6D) (experimental and finite element analysis).
Figure 10. Load-settlement curve for group of piles (2×1) when piles are at (0D) (R.D=50%) (experimental and finite element analysis).

Figure 11. Load-settlement curve for group of piles (2×2) (R.D=70%) when piles are at (0D)

6. Conclusions
The following observations were made from this study:-
1- Crown and invert regions experienced maximum values of stress which made them most important points as compared to the shoulder where values vary between negative and positive.
2- Through the insertion of the pile, the stresses increased with increasing of the insertion depth for cases when tunnel was located at distances (0D, 0.6D) while at (1.6D) the stresses would increase to a certain depth then significant reduction would occur. That is right also for loading stage when piles reach their ultimate load.
3- Positive stresses centralized in the crown region where the maximum value was at the highest point of the crown for all cases, but they are different in values, which increased by increasing of relative density, number of pile in group. The stresses generated for group of pile (2×2) (3d spacing) were highest in value than for the single and other groups of pile in this region of the tunnel for the same test conditions.
4- Stress ratio generated within the tunnel decreased with the increase of relative density. This is because of an arching phenomenon which occurs by transformation part of vertical load laterally within adjacent sand grains.
5- Load carrying capacity of single and group of pile increased with the presence of the tunnel using single pile with existing of tunnel and at 70% relative density the maximum increment approaches 52%.
6- The F.E.M. analysis demonstrated close results in term of stress and bearing capacity as compared with the corresponding results from model tests.

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**Nomenclatures**

| Symbol | Description |
|--------|-------------|
| $E_{50,\text{ref}}$ | Secant stiffness from triaxial test at reference pressure (kN/m$^2$) |
| $E_{oed,\text{ref}}$ | Tangent stiffness from oedometer test at p pressure (kN/m$^2$) |
| $E_{\text{ur}, \text{ref}}$ | Reference stiffness in unloading / reloading (kN/m$^2$) |
| $G_{\theta, \text{ref}}$ | Reference shear stiffness at small strains (HS small only) (kN/m$^2$) |
| $\gamma_{0.7}$ | Shear strain at which G has reduced to 70% (HS small) (kN/m$^2$) |
| $m$ | Rate of stress dependency in stiffness behavior |
| $c'$ | Cohesion (kN/m$^2$) |
| $\phi'$ | Friction angle (degree) |
| $\psi$ | Dilatancy angle (degree) |
| $R_f$ | Failure ratio $q_f / q_a$ like in Duncan-Chang model (0.9) |
| $K_{0,mc}$ | Stress ratio $\sigma'_{xx}/\sigma'_{yy}$ in 1D primary compression |