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ORIGINAL RESEARCH

# Numerical investigation of settlement effect caused by tunneling on surface structures based on pile group

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**Abstract:**

In this study, an attempt has been made to investigate the effect of various factors on the super structures by modeling the structures based on the pile group and its interaction with urban tunnels. The effect of various parameters such as the presence of pile group, the horizontal distance of the center of the tunnel from the center of the foundation, the vertical distance of the tunnel to the tip of the piles, the length of the piles and the height of the super structure on the tunnel-soil-structure interaction has been investigated. Based on the analysis, it was observed that the placement of the pile group in the substructure will lead to the reduction of settlement caused by tunneling in the superstructure. From the point of view of the horizontal distance of the tunnel from the center of the superstructure.The location of the structure in the critical range of the tunnel, which includes two lines with the internal friction angle of the soil relative to the vertical, the structure has the greatest impact from tunneling The increase in the length of the piles due to the change in the axial force of the piles increases the period of the foundation and vice versa reduces the settlement of the structure. In general, the side piles in the pile group are less affected by tunneling, but the central pile suffers a significant decrease in axial force. The smaller the distance of the tunnel from the pile group or the more stiffness increase of the pile group, the reduction of the axial force and the impact of the pile from tunneling is greater.

**Keywords:**
Soil-Pile-Structure Interaction, Pile Group, Superstructure, Tunnel, Concrete Structure.

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## 1. Introduction

Considering the expansion of civil infrastructure, especially underground public transportation, and the intersection of these areas with nearby structures and especially deep foundations, it has led researchers to conduct extensive studies on the effect of drilling on the behavior of the pile group adjacent to the drilling area. In order to design and achieve its parameters, three main methods have been presented: (1) simple calculation methods, (2) estimation methods based on simple computer software, (3) advanced numerical methods. Simple methods are used only to achieve the possibility of using a mat foundation based on the pile group. With these methods, the number, position, diameter and length of the piles needed to meet the design requirements can be determined. These methods are mainly based on determining the behavior of a pile and extending it to the pile group by applying the pile group coefficient. An example of these methods is provided by Poulos and Davis [1], Randolph [2] and Berland [3]. But by using advanced estimation and numerical methods, it is possible to obtain parameters such as stress distribution, displacement, structural efforts of members, etc. [4,5] When a structure is built on the ground, an area of the soil is affected by the weight and stiffness of the structure. When these two zones interfere with each other, tunnel-soil-structure interaction will occur. The behavior of this system is different from when only the tunnel or structure is built in the soil [6]. Different researchers showed that considering the hardness of the super structure leads to the reduction of surface deformations caused by tunnel excavation compared to free field condition. Potz and Edenbrook in 1997 made the first attempt to analyze the tunnel-structure interaction [7]. Using 2D finite element analysis, they investigated the effect of structure stiffness in reducing ground settlement caused by tunneling in London clay. Byrd et al. in 2000, using three-dimensional finite element analysis, investigated the interaction of a masonry structure with a tunnel [8]. Their analysis showed that the stiffness of the structure in the depressed section of the deformed soil is higher than the stiffness of the structure in the raised section of the deformed soil. Liu et al. also obtained similar results in 2000 [9]. They stated that the reason for the more critical placement of the superstructure in the bulge section is the greater rotation of the superstructure or its Asymmetric settlement. A similar result was obtained by Marouye and Shahrour in 2003 with 3D modeling of reinforced concrete structures [10]. They showed that not considering the weight of the structure leads to an underestimation of the surface settlement caused by tunneling. In 2006, Franzius et al. extended the study of Patz et al. to a three-dimensional mode and considered the effect of structure width and tunnel depth in the previous relationships [11]. Taking these assumptions into account led to an improvement in the relationship prediction of Patz et al. In 2010, Pichavoro and his colleagues investigated the behavior of masonry structures under the influence of tunneling with the equivalent beam method [12]. They used Timoshenko beam theory with equivalent in-plane bending and shear stiffness. The results of their modeling for the structures located in the depression area of the soil deformation zone were in agreement with the measured values; But for the structures located in the bulging area, the used method obtains a higher stiffness for the structure. Such a result was also obtained by Gah and Mayer in 2011 [13]. The interaction of tunnel-soil and masonry structure has also been investigated by laboratory tests. An example of these studies was conducted by Giardina et al. in 2012 [14]. They investigated this phenomenon using a scaled model. The studies showed that the foundation bed materials have a significant effect on the tunnel-soil-structure interaction behavior. In another research, the behavior of various concrete and masonry structures was investigated using centrifuge tests by Faralel and Mayer in 2012 and Faralel et al. in 2014 [15,16]. They showed that ground subsidence occurs in rigid structures unlike flexible structures Also, the horizontal strains created in the structures can be ignored. In 2013, Mirhabbii and Soroush investigated this issue using two-dimensional and three-dimensional finite element analysis [17]. They showed that unlike masonry structures, the stiffness of concrete structures will not have much effect on ground surface settlement. Especially when the structural frames are open frames. Zeng et al have reached a similar conclusion. They have shown increased settlement around concrete frames in their analysis [18]. To investigate the behavior of concrete frames, Giardina and colleagues performed the numerical modeling of the centrifuge tests performed by Faralel and Mayer in 2012. Their conclusion showed that the increase in the weight of the structure leads to a decrease in the soil structure separation during the deformation caused by tunneling, and on the other hand, it leads to an increase in the deformation of the surface of the earth and it is closer to the state without the structure. The effect of the stiffness of the superstructure is also dependent on the weight, and with the increase of the weight, the effect of the stiffness of the structure on the superstructure-soil-tunnel interaction decreases [19,20]. The effect of the existence of the basement in the structure has also been investigated by Fargnoli et al. in 2015 [21]. Using two and three dimensional analysis, they investigated the structure behavior during the excavation of Milan subway tunnels. Their investigation showed that the stiffness of the structure in the basement has an effect on the surface settlement. This issue was clarified by examining the results of the complete structure models with the models that only modeled the basement of the structure; In 2017, Biloutetta et al also investigated various parameters such as the tunnel excavation step, tunneling method and the horizontal distance between the superstructure axis and the tunnel axis and came to the conclusion that the most critical parameter in the tunnel-soil-superstructure interaction is the horizontal distance between the superstructure axis and the axis tunnel. In 2018, Darvishpour et al., investigated The Effect of Soil Reinforcement on the Stress and Strain Field Around Underground Square-Shaped Areas and its Internal Lining Efforts in Urban Areas by using abaqus software [23]. Mechanized excavation of tunnels is done using a full-section drilling machine, and soil behavior modeling is done with Mohr-Columb model and full plastic nonlinear model. In 2019, al-Omari et al investigated the behavior of the pile group under the influence of tunneling with 3D finite element analysis [24]. Their main goal was to check the distance of the pile group from the tunnel axis. Soomro et al, used three-dimensional centrifuge experiments to investigate the effects of different construction sequence of twin tunnels construction on an axially loaded $2 \times 2$ pile group in dry sand. Moreover, the centrifuge tests were back-analysed by three-dimensional finite element analyses, in which an advanced hypoplastic constitutive soil model was employed [25].

In Zheng gang et al. [26] research a shield tunnel project is presented first, including line alignment, hydrogeology, and the tunnel position with respect to the piled building. The building response to adjacent shield tunnelling is monitored. Then, a three-dimensional soil-fluid coupled numerical model is established, which carefully reproduces tunnel construction in practice. The computed and measured data are compared to validate the reliability of the numerical model.

In this research, by using Plaxis finite element software, the effect of passing the tunnel through the superstructure placed on the pile group on the behavior of the pile group has been investigated.

In this research, unlike the previous studies in which the structure on the pile group was modeled as a distributed load, it was fully modeled to consider the effect of the frame stiffness of the structure in the interaction between the structure, the pile group and the tunnel. The effect of various parameters, including the distance of the tunnel from the pile group, the height of the structure and the height of the piles, etc., on the forces created in the pile group have been investigated.

**2. Software selection and verification**

With computers developing, the use of advanced software for stress-strain analyzes of various projects in geotechnical engineering has been developed. Each of these software has advantages and disadvantages. In this research, five criteria have been considered for choosing the right software, which are ease of learning, speed of analysis, ease of modeling, availability of suitable behavioral models and application in technical environments. It can be seen that considering the introduced criteria, Plaxis software is suitable for performing the analysis of this research. Triangular elements are used for meshing the soil environment in the software. This element can be used as 6 or 15 nodes in the model. Although the use of these elements requires more memory than the six-node elements and increases the analysis time, but due to the higher accuracy in determining stresses and displacements, it has been suggested for use in various problems. For this reason, 15-node elements are used in this research [27]. In tunneling issues, it is very important to choose a soil behavior model that can take into account different stiffness during loading (for example, surface structure) and unloading (for example, tunnel excavation). For this purpose, the behavioral model of hardening soil (HS model) has been used in the software. The main feature of this behavioral model is considering different stiffnesses during loading and unloading and stiffness depending on the stress level. The behavior of soil strain stress in this model is considered as a hyperbolic function [28]. For validating the present research, the Oras study in 2021 was used [29]. In his study, he investigated the effect of the ratio of tunnel center (X) to tunnel diameter (D) in the surface settlement of the superstructure based on the pile group. In the mentioned research, the superstructure is simply modeled as an overhead and the geometry modeling of the superstructure is omitted. The width of the footing is 6 meters, the amount of superstructure overhead is 150 kilopascals, the length and diameter of the pile is equal to 15 meters 80 cm respectively, which is placed in a three by three arrangement. The diameter of the tunnel is 10 meters, the thickness of the cover is 50 cm, and the value (X/D) is considered in different values from zero (the center of the tunnel corresponds to the center of the foundation) to 2. The distance between the tip of the pile and the crown of the tunnel (Z/D) is equal to 0.25, (2.5 meters). The soil layer is also assumed to be sandy soil with a hardening soil behavior model, whose parameters are presented in table (1). The geometry modeled in the software is presented in figure (1)

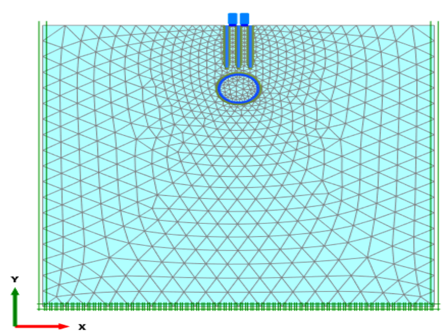



**Fig 1. Geometry and mesh created for validation for X/D=0**

**Table 1. soil parameters used by Oras [28]**

| Soil Type/Parameters | Sand |
|---|---|
| Dry Unit Weight, $\gamma_{unsat}$ | 18.50 (KN/m$^3$) |
| Saturated Unit Weight, $\gamma_{sat}$ | 19.00 (KN/m$^3$) |
| $E_{50}^{ref}$ | 9650 (KPa) |

| | |
|---|---|
| $E_{oed}^{ref}$ | 9650 (KPa) |
| $E_{ur}^{ref\ (1)}$ | 28950 (KPa) |
| $C^{(2)}$ | 5 (KPa) |
| $\emptyset^{(3)}$ | 25 (Deg) |

Figure (2) shows the results of ground settlement for different (X/D) values from 0 to 2 in Uras research and the present research. It can be seen that the surface settlement values obtained in both researches are very close to each other, which indicates the correctness of the process followed for modeling the analysis of tunnel-soil interaction and pile group.

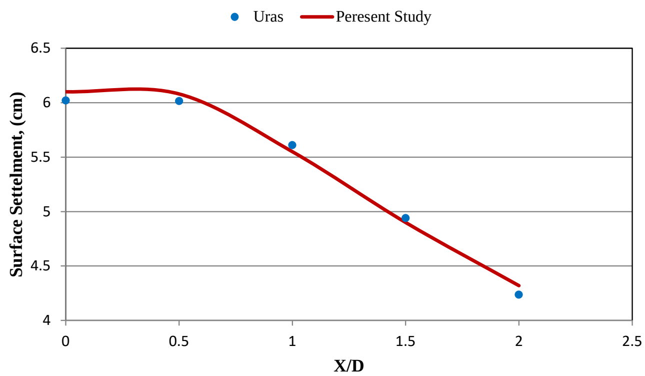
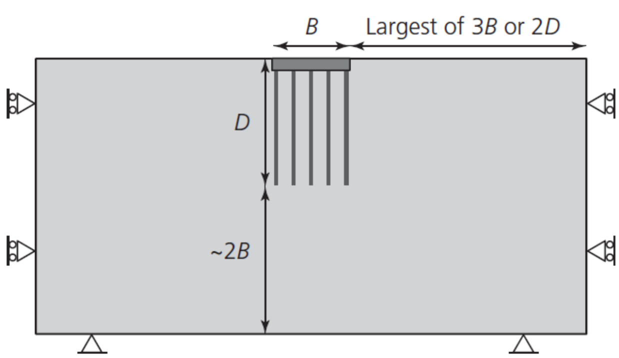



**Fig 2. The surface settlement created in the Uras study [29] and the present research**

## 3. Modeling and specification of materials

The dimensions of the numerical model should be chosen in such a way that they have no effect on the obtained results. In technical texts, according to the type of structure, different values are presented. For example, for the pile and tunnel group, the dimensions of the numerical model of the current research have been selected as Figure (3) [30].



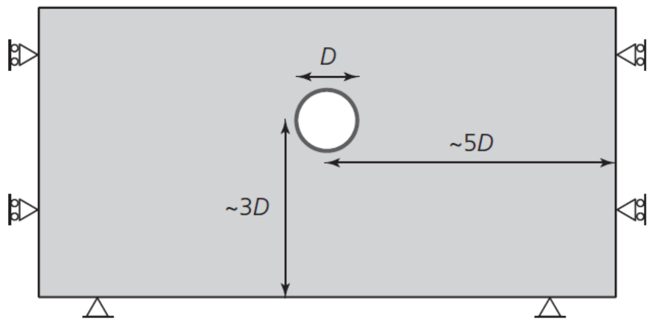



**Fig 3. Suggested dimensions of the numerical model in the pile and tunnel group [30]**

In this research, three concrete structures with bending frames of four, eight and twelve floors are considered. All structures have five openings in the x direction, 5 meters long, and three openings in the y direction, 6.5 meters long, and the height of the floors is 3 meters. All beam and column sections are rectangular (H*D), the plan of the structure is presented in Figure (4) and the dimensions of the elements are presented in Table (2). It should be noted that the weight of the elements is included in the properties of the materials. In this study because of static analyses, the gravity service load is applied to the structure. the dead load and the live load are considered 500 kg/m2 and 200 kg/$m^2$ respectively.

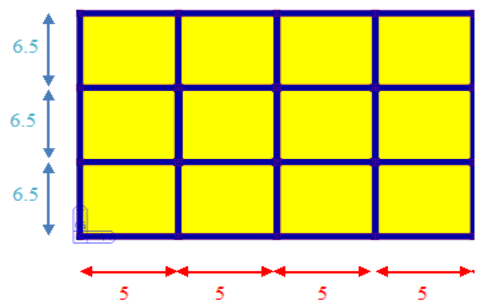



**Fig 4. The plan of the structures used in this research**

**Table 2. Selected sections of beams and columns in different floors**

| Column | Beam | Floors | Structure |
|---|---|---|---|
| H=500 mm<br>B=500 mm | H=500 mm<br>B=400 mm | **floor 1-4** | **Four-story structure** |
| H=500 mm<br>B=500 mm | H=500 mm<br>B=400 mm | **floor 1-4** | **eight-story structure** |
| H=400 mm<br>B=400 mm | H=400 mm<br>B=300 mm | **floor 4-8** | |
| H=600 mm<br>B=600 mm | H=500 mm<br>B=400 mm | **floor 1-4** | **twelve-story structure** |

| | | |
|---|---|---|
| H=500 mm<br>B=500 mm | H=500 mm<br>B=400 mm | **floor 4-8** |
| H=400 mm<br>B=400 mm | H=400 mm<br>B=300 mm | **floor 8-12** |

To select the behavioral parameters of the soil according to the behavioral model of hardening soil, the studies of a real project in the city of Tehran, presented by Eslami et al., have been used [3١]. These parameters are presented in table (3).

**Table 3. Properties of soil materials considered in the analysis**

| $\gamma\left({}^{kN}/_{m^3}\right)$ | $E\left(kPa\right)$ | $E_{oed}\left(kPa\right)$ | $E_{ur}\left(kPa\right)$ | m | C (kPa) | $\varphi$(deg) | $\psi$(deg) | R |
|---|---|---|---|---|---|---|---|---|
| 20 | 25000 | 25000 | 75000 | 0.5 | 5 | 35 | 5 | 0.9 |

Plate element has been used to model the structural elements and tunnel lining. The thickness of the concrete lining of the tunnel is also chosen to be 40 cm. Due to the fact that concrete elements can crack, the bending stiffness of beam sections is multiplied by 0.35 and the bending stiffness of column sections and concrete cover is multiplied by 0.7. The software directly receives the bending and axial stiffness of the material from the user; Therefore, these stiffnesses have been calculated and assigned to the members according to the modulus of elasticity, cross-sectional area and moment of inertia of the section, bending and axial stiffness. The parameters used for plate elements are presented in table (4).

**Table 4. concrete materials**

| **Specifications** | **Value** |
|---|---|
| Modulus of elasticity | $2e7\ \frac{kN}{m^2}$ |
| Poisson's ratio | 0.2 |
| Weight density | $24\frac{kN}{m^3}$ |

Also, the piles are at a distance of 5 meters from each other, the diameter of the piles is 0.5 meters and the length of all pile members is equal to one third of the height of the structure. Also, the bending stiffness is applied in the model as cracked and with a factor of 0.7. The specifications of the pile element are also used in the analyzes according to Table (4).

**4. Analysis of results**

In this study, the effect of various parameters on tunnel-structure interaction and pile group has been investigated. These parameters are: (1) Investigating the effect of tunnel positioning at the bottom of pile group. (2) Investigating the influence of the distance of the tunnel from the tip of the pile group. (3) Investigating the effect of the height of the structure. (4) Examining the effect of the length of the piles. In Figure 5 and Table (5), the values of parameters and constant parameters in each category of analysis are presented. In the following, the steps of analysis and the results of each category of analysis are presented.

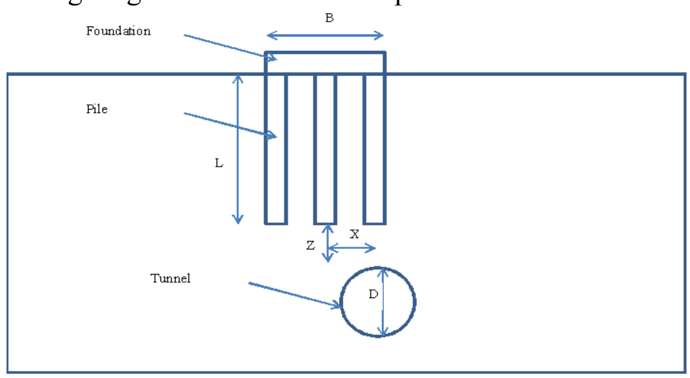



**Fig 5. Definition of the analysis parameters considered**

**Table 5. Analysis parameters considered in the research**

| Variable parameter values | Variable parameter | Constant parameters | Analysis |
|---|---|---|---|
| | A group of 5 piles with a length of 8 meters and a diameter of 0.5 meters | 8-storey structure<br>The diameter of the pile is 0.5 m<br>The length of the pile is 8 m<br>The diameter of the tunnel is 10 m<br>Distance from the crown of the tunnel to the tip of the pile: 2 m | Type 1 |
| **X/0.5B=0,0.5,1,2** | The ratio of the tunnel distance from the foundation center to half the width of the foundation (X/0.5B) | 8-storey structure<br>The diameter of the pile is 0.5 m<br>The length of the pile is 8 m<br>The diameter of the tunnel is 10 m<br>Distance from the crown of the tunnel to the tip of the pile: 2 m | Type 2 |
| **Z/D=0,0.2,0.5,1** | The ratio of tunnel distance from pile tip to tunnel diameter (Z/D) | 8-storey structure<br>The diameter of the pile is 0.5 m<br>The length of the pile is 8 m<br>The diameter of the tunnel is 10 m<br>X/0.5B=0 | Type 3 |
| **4 floors<br>8 floors<br>12 floors** | The height of the structure | The diameter of the pile is 0.5 m<br>The length of the pile is 1.3 times the height of the structure<br>The diameter of the tunnel is 10 meters<br>X/0.5B=0<br>Z/D=0.2 | Type 4 |
| **L=8,10,12 m** | Pile length (L) | 8-storey structure<br>The diameter of the pile is 0.5 m<br>The diameter of the tunnel is 10 m<br>X/0.5B=0<br>Z/D=0.2 | Type 5 |

### 4.1. Investigating the effect of the pile group in the structure foundation

In the analyzes of group one, the aim is to investigate the effect of the pile group in the structure foundation. In this group of analyses, the superstructure is 8 stories, the diameter of the tunnel is 10 meters, the diameter and length of the piles are assumed to be 0.5 and 8 meters, respectively. the distance from the tip of the pile to the crown of the tunnel is equal to 0.2 times the diameter of the tunnel (Z/D=0.2, and the ratio of the distance of the tunnel axis from the center of the foundation to the half width of the foundation (X/0.5B) is assumed to be zero. In the following, the results of the settlement, rotation and horizontal displacement of the foundation in the state with and without different pile groups are presented. In Figure (6), the results of the surface settlement of the foundation are presented in two cases with and without the pile group.

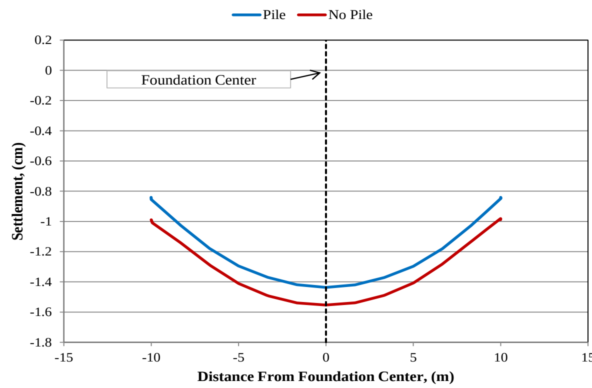



**Fig 6. settlement created on the foundation surface with and without piles**

The horizontal axis indicates the distance from the center of the foundation in meters and the vertical axis indicates the settlement created on the ground surface in centimeters. It can be seen that in the case where the pile group is not located under the foundation, the maximum settlement is equal to 1.55 cm and in the case where the pile group is placed under the structure, the maximum settlement is equal to 1.44 cm. The placement of the pile group leads to a reduction of about 7% of the maximum settlement due to tunneling. The settlement process is quite similar in both cases. Similarly, as seen in figure (7) and (8), the foundation rotation caused by tunneling in both models was almost equal and tunneling did not cause significant horizontal displacement in both foundations. Therefore, it can be seen that the pile group, in the case that the tunneling is in line with the center of the foundation, will lead to a reduction of settlement in the foundation and will not have much effect on the rotation or displacement of the foundation. In figure (7), Tilt R is the rotation on the right side and Tilt L is the rotation on the left side of the foot in degrees.

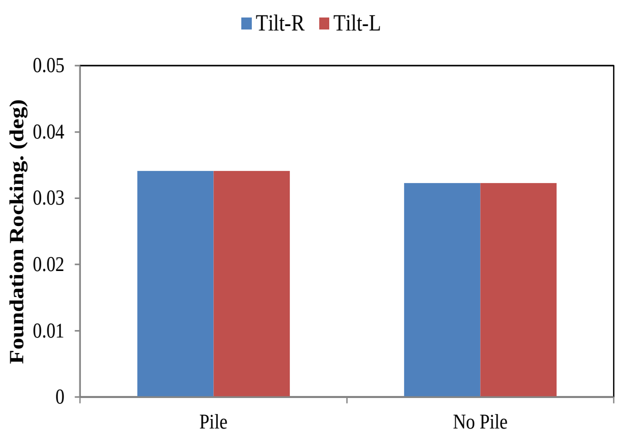



**Fig 7. Moment created on the foundation surface with and without piles**

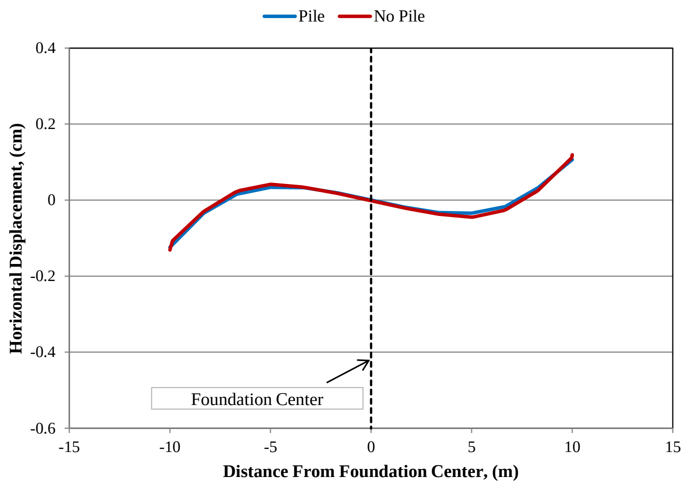



**Fig 8. The foundation surface Horizontal displacement (with and without piles)**

**4.2. The horizontal distance of the tunnel axis from the center of the structure foundation**

In the analyzes of the second group, the aim is to investigate the effect of the horizontal distance of the tunnel axis from the center of the superstructure foundation. In this group of analyses, the superstructure is 8 stories, the diameter of the tunnel is 10 meters, the diameter and length of the piles are assumed to be 0.5 and 8 meters, respectively. the distance from the tip of the pile to the crown of the tunnel is equal to 0.2 times the diameter of the tunnel (Z/D=0.2) and the ratio of the distance of the tunnel axis from the center of the foundation to the half width of the foundation (X/0.5B) is assumed to be zero, 0.5, 1 and 2. In Figure (9), the results of the surface settlement of the foundation at different values of X/0.5B are presented.

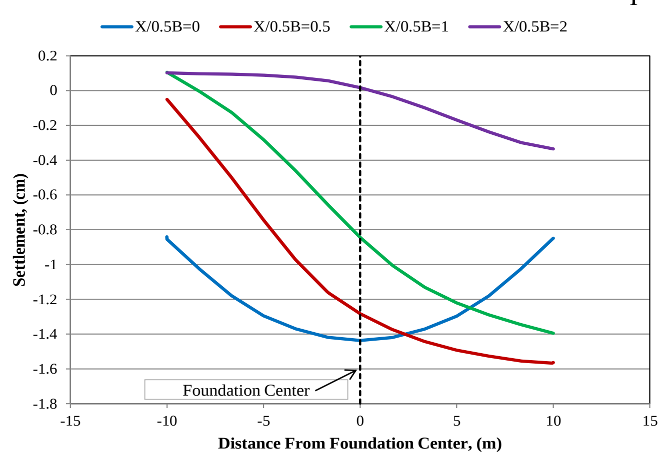



**Fig 9. Settlement created on the foundation surface at different values of X/0.5B**

The horizontal axis indicates the distance from the center of the foundation in meters and the vertical axis indicates the settlement created on the ground surface in centimeters. It can be seen that in the case where the axis of the tunnel coincides with the center of the foundation, the settlement in the center of the foundation is equal to 1.4 cm and it is the maximum value, and the amount of settlement decreases by moving towards the sides of the foundation. In this case, the settlement is completely symmetrical. As the tunnel moves to the right side of the foundation, the settlement is out of symmetry and the maximum settlement occurs on the side where the tunnel is located. The highest amount of settlement equal to 1.6 cm occurs in the case where X/0.5B=0.5 and the tunnel is located between the center and the right corner of the foundation. This behavior shows that the placement of the superstructure in the rising part creates a more critical condition than the placement of the superstructure in the depression part of the settlement. This case is consistent with the results of previous studies and is caused by the less impact of structure stiffness in this area. With more displacement of the tunnel and when the tunnel is placed exactly in the right corner of the foundation, the amount of settlement is reduced, but the settlement process is similar to the case of X/0.5B=0.5. It can also be seen that when the tunnel leaves the area under the foundation and the distance between the center of the tunnel and the center of the footing is equal to the width of the footing, the tunnel is practically unaffected by the settlement of the footing and the maximum settlement will be 0.2 cm. Considering how the tunnel affects the structure settlement, the range of the tunnel's effect on the foundation settlement can be considered as two lines with an angle to the horizon equal to the soil friction angle. If the structure is located within these lines, significant settlement will occur under the influence of the tunnel. Otherwise, the settlement caused by tunneling in the structure can be ignored. These lines are shown in different X/0.5B mode in figure (10).

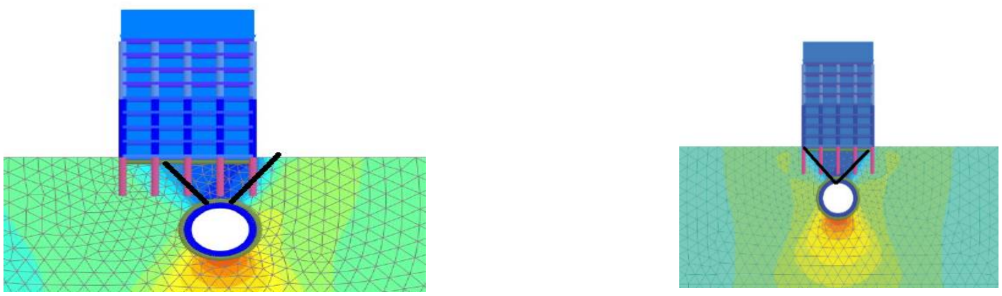


**Fig 10. Lines of the effect of the tunnel on the settlement created on the foundation surface at different values of X/0.5B**

The rotation of both sides of the foundation in different states of X/0.5B is presented in Figure (11). Tilt R is the rotation on the right side and Tilt L is the rotation on the left side of the foundation in degrees. The maximum rotation on both sides of the foundation occurred in X/0.5B=0.5, which corresponds to the maximum settlement. Therefore, the maximum rotation also occurs in the structure when the structure is placed in the rising part of the deformation. In the case of X/0.5B=1.0, because the maximum settlement occurred in the right corner of the foundation, no rotation was reported for the left side. It can also be seen that when the tunnel is out of the area under the foundation and the distance between the center of the tunnel and the center of the foundation is equal to the width of the foundation, the rotation of foundation will not be affected by the tunnel.

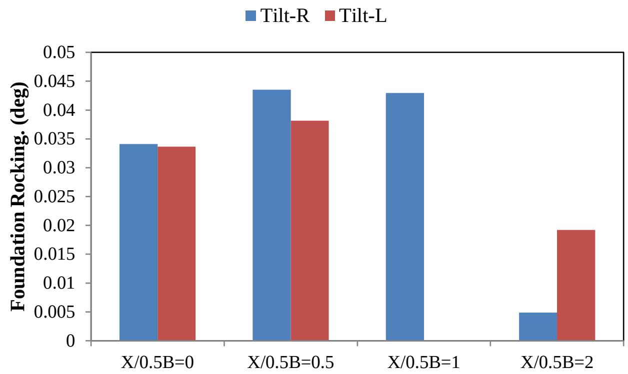



**Fig 11. rotation created on the foundation surface at different values of X/0.5B**

The horizontal displacement created on the foundation surface is also examined in figure (12). The horizontal axis indicates the distance from the center of the foundation in meters and the vertical axis indicates the horizontal displacement created on the ground surface in centimeters. In general, the amount of horizontal displacements occurred in the foundation surface is insignificant and is three millimeters; Therefore, they cannot have an effect on the performance of the structure.

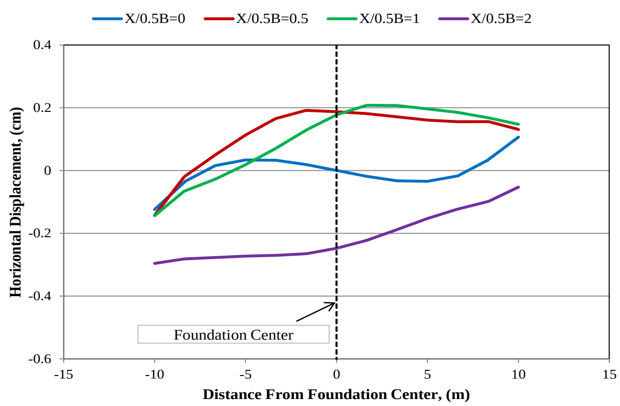



**Fig 12. Horizontal displacement created on the foundation surface at different values of X/0.5B**

The amount of change in the values of the axial force in the piles on the right, center, and left sides of the foundation has also been investigated as a result of tunneling. The position of these piles is presented in figure (13). It should be noted that the values of these forces are different in the tunnel construction phase and the load application phase; In other words, the values of the presented forces are the amount of change in the structural efforts caused by tunneling.

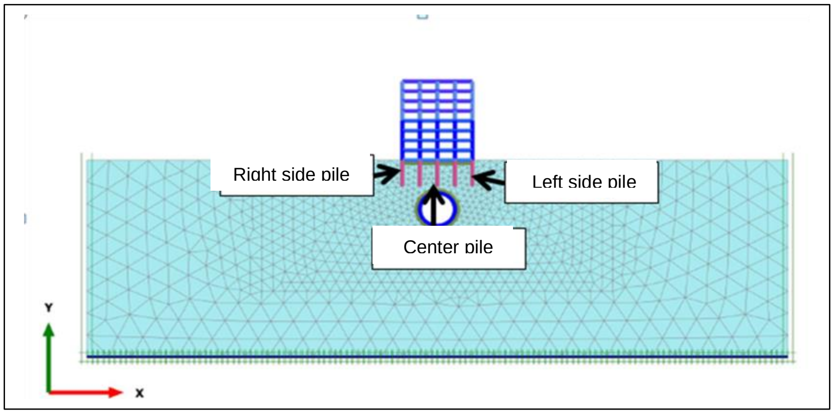



**Fig 13. Position of piles on the right, center and left side of the foundation**

Negative values indicate a decrease in efforts due to tunneling and positive values indicate an increase in efforts due to tunneling. Figure (14) shows the amount of change in the axial force of the right, center, and left piles along the length of the piles. In the right pile, it can be seen that with the increase of the X/0.5B ratio, the values of the axial force also decrease. In the two cases of X/0.5B=0 and X/0.5B=0.5, the reduction of the axial force along this pile is insignificant; But as the distance of the tunnel from this pile increases, the reduction of the axial force increases. The reason for this can be justified according to the deformation mode of the foundation surface. In the two cases X/0.5B=1 and X/0.5B=2.0, along with the foundation rotation, the right side of the foundation experiences uplift (upward deformation of the foundation); In other words, tension has occurred in this pile and it leads to a significant reduction of the axial force due to tunneling compared to the condition without tunneling. The biggest drop of axial force in this pile is at X/0.5B=1 and at the level of the pile head and is 23.8 kilonewtons, which indicates a drop of about 4% of the axial force in this pile. In the center pile, there is a different behavior compared to the pile in the right corner. In this pile, the greatest reduction of the axial force occurs when the tunnel excavation occurs exactly at the tip of the center pile (X/0.5B=0). In this case, the axial force of the pile decreases by about 70 kilonewtons at the level of the pile head, which shows a 10% drop in the axial force after drilling. The reason is the creation of a hole under the pile, which leads to a decrease in the bearing capacity and endurance force by the pile. This reduction occurs to a very small amount in the case of X/0.5B=0.5; But in the other two cases and with the distance of the tunnel from the central pile, there is no more changes in the axial force of the pile. It can also be seen in the pile of the left corner, by digging the tunnel in the left corner (X/0.5B=1), it can be seen a slight decrease of 2 KN in the amount of axial force. In the rest of the cases, the amount of change in the axial force in the piles is small and insignificant; Therefore, it can be concluded that the central pile will experience the greatest effect of tunnel excavation when the tunnel axis is in line with the foundation axis in the pile group.

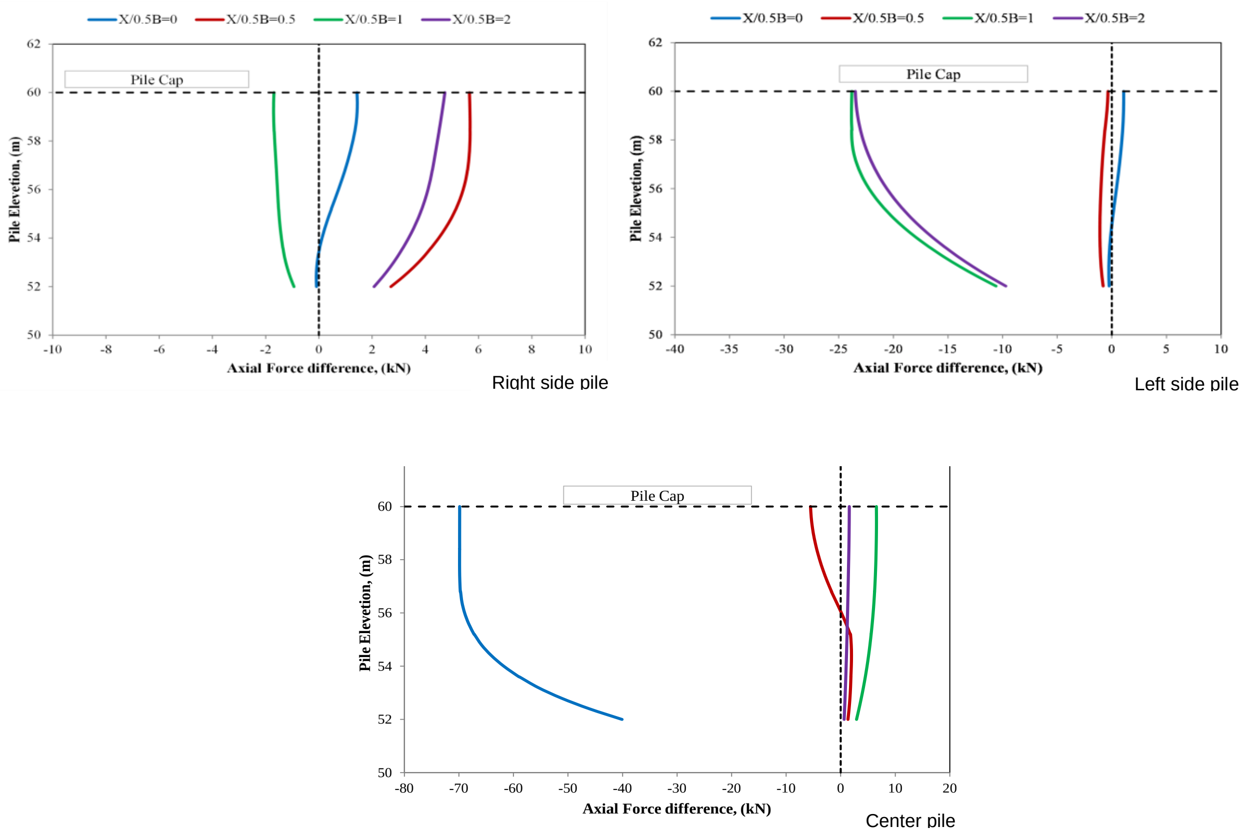



**Fig 14. The change of axial force values along the left, right and center piles with different values of X/0.5B**

**4.3. Investigating the effect of structure height on tunnel-soil-structure interaction**

In the analyzes of the third group, the aim is to investigate the effect of the height of the superstructure on the tunnel-soil-structure interaction based on the pile group. In this group of analyses, the diameter of the tunnel is 10 meters, the diameter of the piles is 0.5 meters, the length of the piles is 8 meters, the distance from the tip of the pile to the crown of the tunnel is equal to 0.2 times the diameter of the tunnel (Z/D=0.2) and the ratio of the tunnel axis distance from The center of the foundation is chosen to be half the width of the footing (X/0.5B) equal to zero (tunnel axis coincides with the footing axis). The structure is assumed to be 4, 8 and 12 story structure and its effect on the settlement, rotation and horizontal displacement of the foundation and the axial force of the piles is investigated further. Figure (15) shows the results of foundation settlement in different values of pile length.

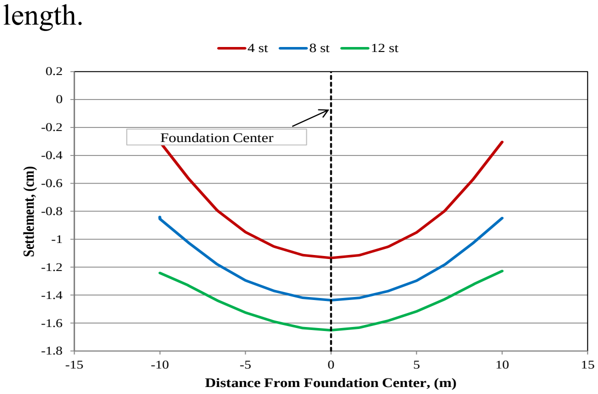



Fig 15. The settlement created on the foundation level at the height of different structures

The horizontal axis indicates the distance from the center of the foundation in meters and the vertical axis indicates the settlement created on the ground surface in centimeters. It can be seen that in all cases, the settlement of the footing is symmetrical, which is completely logical due to the fact that the axis of the tunnel and the footing coincide. The minimum amount of settlement is equal to 1.13 cm in the 4-story structure and the maximum settlement is equal to 1.65 cm in the 12-story structure. The reason for the increase in settlement with the increase in the height of the structure is the increase in the weight of the structure, which leads to an increase in settlement. The rotation of both sides of the foundation in different states of pile diameter is presented in figure (16).

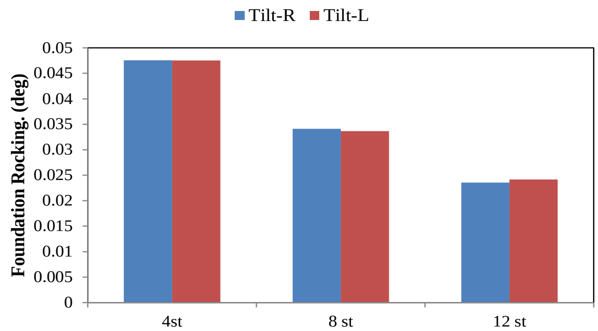



**Fig 16. Moment created at the foundation level at the height of different structures**

Tilt R is the rotation on the right side and Tilt L is the rotation on the left side of the foundation in degrees. In all cases, the amount of rotation on both sides of the foundation is equal to each other, which is caused by the symmetrical settlement of the foundation with respect to the center line of the foundation. It can be seen that although the 4-story structure has caused the least amount of settlement, it has the maximum rotation; In other words, although the amount of settlement is less in this case, the amount of differential settlement is the highest and in this sense, it can create more risks for the structure. Also, the amount of rotation in the 12-story structure is the lowest value and it shows that increasing the structure's floors reduces the differential settlement due to the increase in the stiffness of the system. The horizontal displacement created on the foundation surface is also examined in Figure (17). The horizontal axis indicates the distance from the center of the foundation in meters and the vertical axis indicates the horizontal displacement created on the ground surface in centimeters. In general, the amount of horizontal displacements occurred in the foundation surface is insignificant and is at the maximum level of two millimeters; Therefore, they cannot have an effect on the performance of the structure.

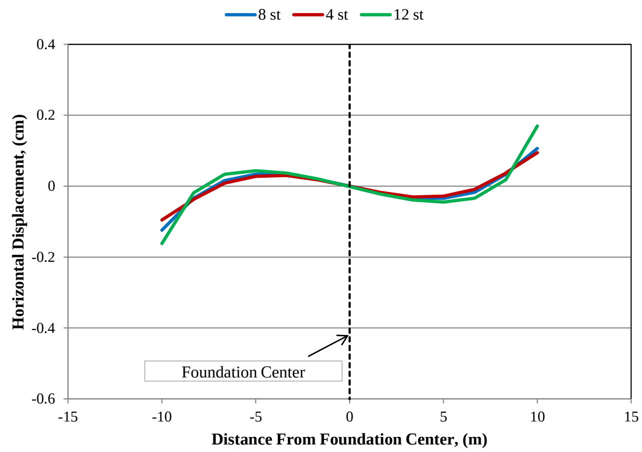



**Fig 17. Horizontal displacement created on the foundation surface at the height of different structures**

The amount of change in the values of the axial force in the piles on the right, center, and left sides of the foundation has also been investigated as a result of tunneling. The values of these forces are different in the tunnel construction phase and the load application phase; In other words, the values of the presented forces are the amount of change in the structural efforts caused by tunneling. Negative values indicate a decrease in efforts due to tunneling and positive values indicate an increase in efforts due to tunneling. Figure (18) shows the amount of change in the axial force of the right, center, and left piles along the length of the piles.

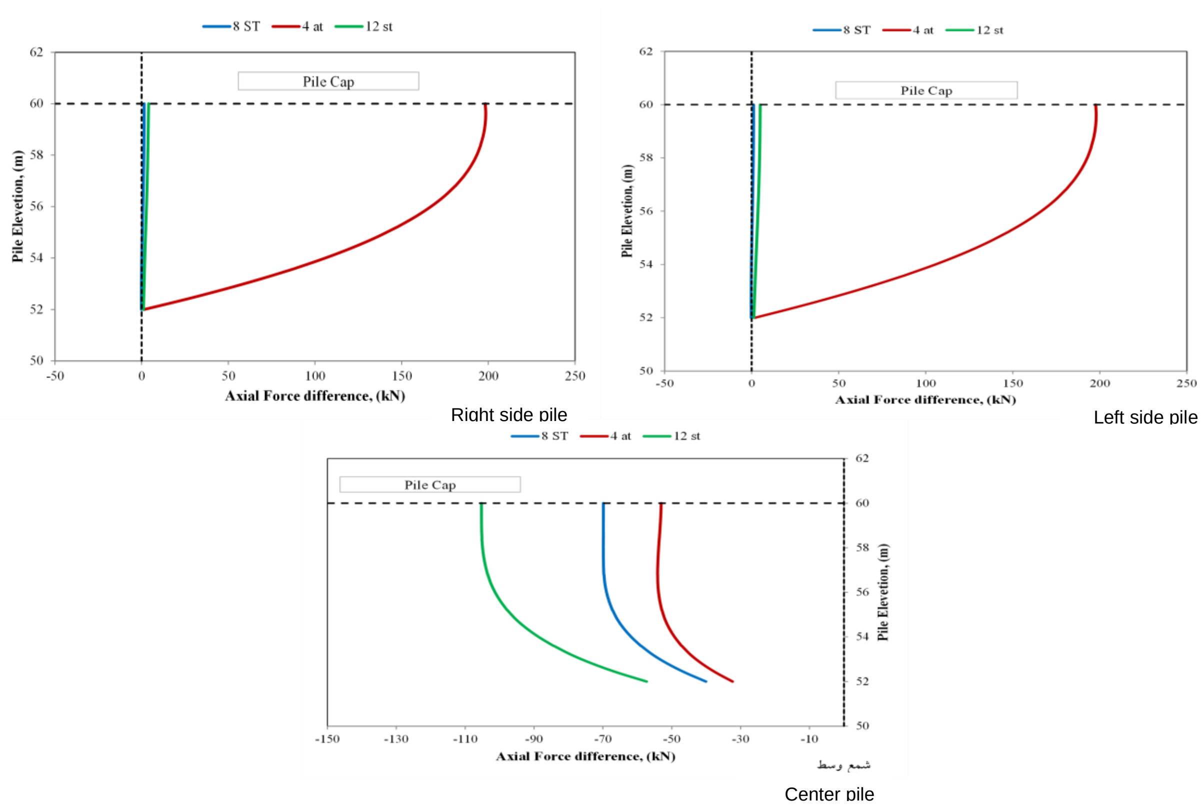


**Fig 18. Changes in axial force values along the left, right and center piles with the height of different structures**

In the right pile, it can be seen that the axial force increases significantly in the 4-story structure. While in the other two structures, the amount of change is insignificant. So that in this structure, the axial force increases by about 196 kilonewtons, which indicates an increase of about 42% of the axial force. In the center pile, a different behavior is observed compared to the right corner pile, and the axial force is reduced in this pile. The greatest reduction of the axial force occurs when the structure is 12 stories. In this case, the axial force of the pile decreases by about 110 kilonewtons at the level of the pile head, which shows a 15% drop in the axial force after drilling. The reason for this is the creation of a hole in the tip of the pile, which leads to a decrease in the bearing capacity and the indurance force by the pile. By reducing the floors of the structure, the reduction of the axial force also decreases. In such a way that in the 4-story structure, the reduction rate of 53 kilonewtons (about 10%) occurs. The left corner pile behaves the same as the right corner pile. Considering the symmetrical settlement of the foundation with the change of pile diameter, this behavior is expected; Therefore, all the things mentioned for the right corner pile are also true for the left corner pile. An increase in the height of the structure at the same time indicates an increase in stiffness and weight. By increasing these two items, we will see a decrease in the effectiveness of the side piles and an increase in the effectiveness of the middle pile. According to the review of previous studies presented in the introduction section, increasing stiffness leads to a decrease in settlement and increasing overhead leads to its increase; Therefore, it can be claimed that in this research, the effect of overhead is more.

**4.4. Investigating the effect of pile length on tunnel-soil-structure interaction**

In the analyzes of the fourth group, the aim is to investigate the effect of the pile length on the tunnel-soil-structure interaction based on the pile group. In this group of analyses, the superstructure has 8 floors, the diameter of the tunnel is 10 meters, the diameter of the piles is 0.5 meters, the distance from the tip of the pile to the crown of the tunnel is equal to 0.2 times the diameter of the tunnel (Z/D=0.2) and the ratio of the distance of the tunnel axis from foundation center is chosen to be half the width of the foundation (X/0.5B) equal to zero (the axis of the tunnel coincides with the axis of the foundation). The length of the pile is assumed to be 6, 8 and 10 meters and its effect on the settlement, rotation and horizontal displacement of the foundation and the axial force of the piles are investigated further. Figure (19) shows the results of foundation settlement in different values of pile length

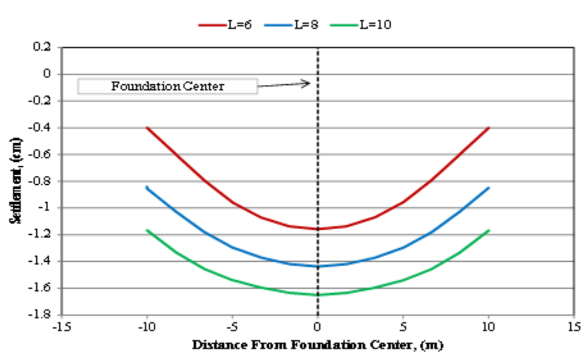



**Fig 19. settlement created on the foundation surface at different values of pile length**

The horizontal axis indicates the distance from the center of the foundation in meters and the vertical axis indicates the settlement created on the ground surface in centimeters. It can be seen that in all cases, the settlement of the footing is symmetrical, which is completely logical due to the fact that the axis of the tunnel and the footing coincide. The minimum amount of settlement is equal to 1.16 cm in the length of 6 meters of the pile and the maximum amount of settlement is equal to 1.65 cm in the length of 10 meters of the pile. The reason for the increase in settlement with the increase in the diameter of the pile can be investigated according to the change in the axial force of the piles, which will be explained later. The rotation of both sides of the foundation in different states of pile length is presented in figure (20).

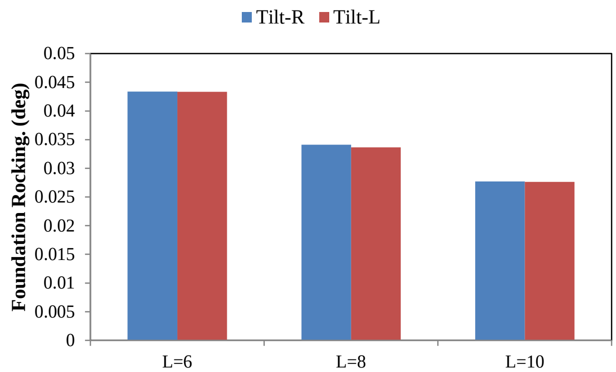



**Fig 20. Moment created on the foundation surface at different values of pile length**

Tilt R is the rotation on the right side and Tilt L is the rotation on the left side of the foundation in degrees. In all cases, the amount of rotation on both sides of the foundation is equal to each other, which is caused by the symmetrical settlement of the foundation with respect to the center line of the foundation. It can be seen that the pile length of 6 meters has caused the lowest amount of settlement, but it has the maximum rotation; In other words, although the amount of settlement is less in this case, the amount of differential settlement is the highest and in this sense, it can create more risks for the structure. Also, the amount of rotation in the 10-meter pile length is the lowest value, and it shows that increasing the length of the pile reduces the differential settlement due to the increase in the stiffness of the system. The horizontal displacement created on the foundation surface is also investigated in figure (21).

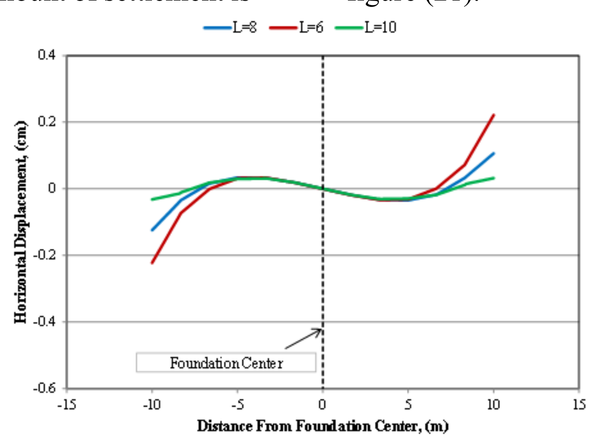



**Fig 21. Horizontal displacement created on the foundation surface at different values of pile length**

The horizontal axis indicates the distance from the center of the foundation in meters and the vertical axis indicates the horizontal displacement created on the ground surface in centimeters. In general, the amount of horizontal displacements occurred in the foundation surface is insignificant and is at the maximum level of two millimeters; Therefore, they cannot have an effect on the performance of the structure. The amount of change in the values of the axial force in the piles on the right, center, and left sides of the foundation has also been investigated as a result of tunneling. The values of these forces are different in the tunnel construction phase and the load application phase; In other words, the values of the presented forces are the amount of change in the structural efforts caused by tunneling. Negative values indicate a decrease in efforts due to tunneling and positive values indicate an increase in efforts due to tunneling.

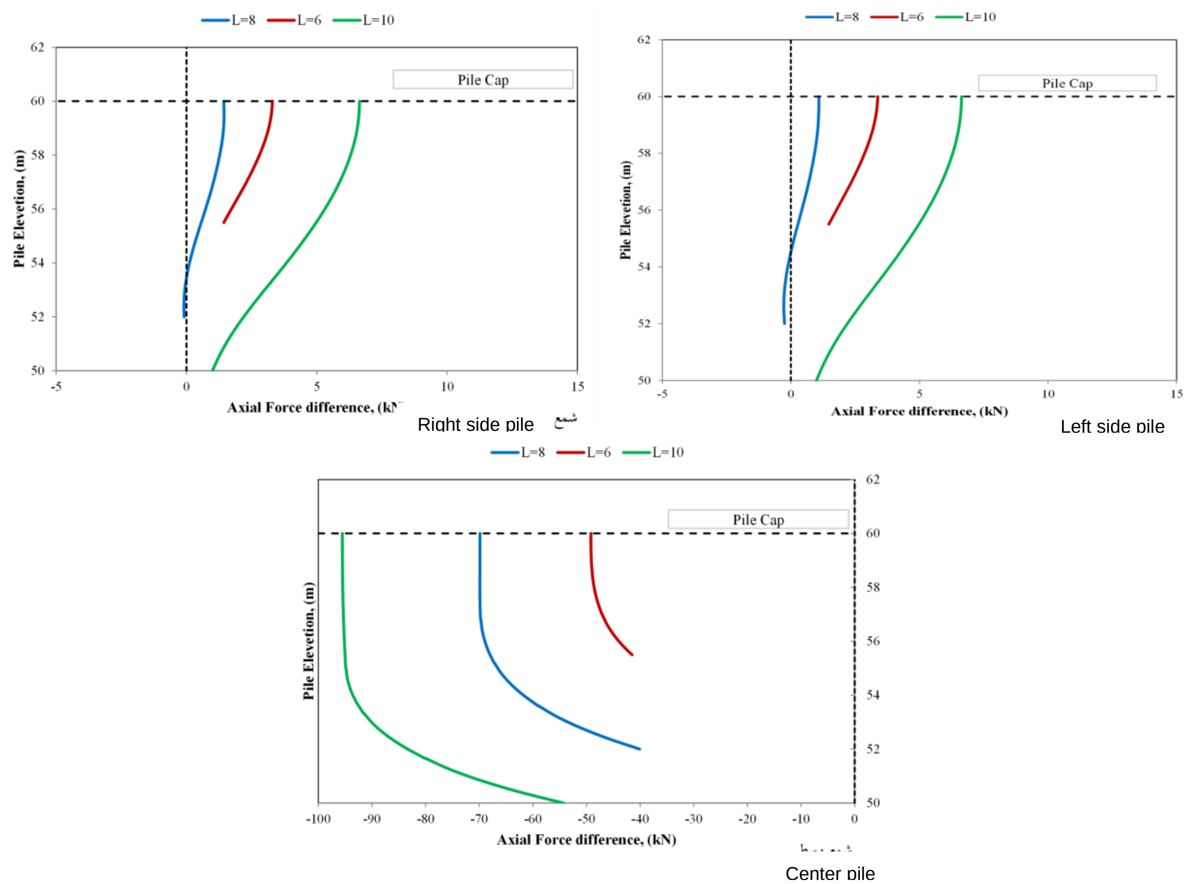



**Fig 22. Variation of axial force values along the left, right and center piles for different values of the pile length**

In the right pile, it can be seen that the change in the axial force of the piles with the change in diameter is not significant. As can be seen, a maximum of 6 kilonewtons of force increases at the top of the pile with a length of 10 meters, which indicates an increase of less than one percent of the axial force compared to the previous state of tunneling; Therefore, it can be said that the behavior of the right pile will not be affected by the length of the pile. In the center pile, it is observed a different behavior compared to the pile in the right corner. In this pile, the axial force is reduced. The greatest reduction of the axial force occurs when the length of the pile is equal to 10 meters. In this case, the axial force above the pile is reduced by about 95 KN which shows a 12% drop in axial force after drilling. The reason is the creation of a hole in the tip of the pile, which leads to decrease in the bearing capacity and the Endurance force of the pile. The reduction of the axial force in the pile with a length of 6 meters is the lowest. In fact, this pile has received the least impact from tunnel excavation. The reduction of the axial force of this pile is about 49 kilonewtons, which shows a reduction of about 8% of the axial force. The left corner pile behaves the same as the right corner pile. Considering the symmetrical settlement of the foundation with the change of pile diameter, this behavior is expected; Therefore, all the things mentioned for the right corner pile are also true for the left corner pile. Therefore, it can be observed that by increasing the length of the pile, the pile will accept more impact from tunneling. The reason for this phenomena is the increase in the stiffness of the pile with the increase in length. The higher the stiffness of the element, the more significant the change in axial force will be. So, in this regard, the stiffness of the pile will be very important, and piles with higher stiffness will have a greater effect on tunneling.

## 5. Conclusions

The results of the research are summarized as follows:

1) The distance of the tunnel axis from the center of the foundation is a very important factor in the deformation of the structure and the axial force of the pile group caused by tunneling. Placing the superstructure in the raised part of the soil is more destructive due to the occurrence of more rotation in the superstructure. In the present research, by placing the tunnel at X/0.5B=0.5, the most critical state of deformations will be created and the most critical position of the tunnel will be obtained. If the distance of the tunnel from the center of the foundation is greater than the width of the foundation, the tunnel will not have any effect on the structure.

2) As the X/0.5B distance increases, the axial force in the far corner pile (right) decreases and remains almost unchanged in the nearer corner pile (left). The central pile will experience the greatest effect when the tunnel is exactly aligned with the structure foundation.

3) The value of Z/D=0.5 will be a critical depth for the effect of the tunnel on the structure settlement; But the rotation of the structure decreases with the increase of Z/D. As Z/D increases, the axial force of the corner piles will not be affected much; However, the amount of reduction in the axial force of the central pile due to tunneling is less.

4) With the increase in the length of the pile, due to the increase in the stiffness of the pile group, the reduction of the force of the central pile due to tunneling increases and the settlements increase; But with the increase of the length of the pile, the amount of rotation or differential settlement of the superstructure decreases. Also, with the increase in the length of the pile group, the force of the central pile will decrease more.

5) As the height of the structure increases, the overhead and stiffness of the structure increases. As a result of this incident, the settlement of the structure caused by more tunneling and the rotation caused by it will be reduced. Also, with the increase in the height of the structure, the force of the central pile will decrease more. In general, the central pile in a pile group is affected by tunneling compared to other piles and can have up to 15% reduction in axial force.

6) If the distance from the tunnel crown to the tip of the pile compared to the diameter of the tunnel (Z/D) is between zero and 0.5 and the horizontal distance from the center of the tunnel to the center of the foundation is less than half the width of the foundation (X/0.5B), the greatest impact of the tunnel will occur on the structure located on the pile group. The higher the stiffness of the pile

group or the higher the structure overhead, the more severe the effect of tunneling will be.

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