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A Numerical Study of the Effect of Tunneling on Surface Settlement and Existing Buildings

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ABSTRACT

This study aimed to determine the effect of various influencing parameters such as tunnel diameter (D), depth (H), width (B), length (L), number of floors, and the horizontal distance of the building from the tunnel axis (X), as well as soil properties such as internal friction angle (ϕ), Poisson ratio (υ), modulus of elasticity (E), and cohesion (C) on surface settlement using ABAQUS finite element software. According to the results, the settelment increases with increasing tunnel diameter at a constant depth, while it decreases with increasing tunnel depth. Changes in the width and length of the building also affect the settlement directly; consequently, as the width and length of the building increase due to increasing the cross-sectional area of the building and its rigidity and stiffness, the settlement of the foundation becomes more uniform and resistant to displacement, leading to a decrease in the surface settlement. Also, as the distance of the building from the tunnel axis increases, the settlement decreases and follows a constant trend after a distance equal to the tunnel diameter. Based on the results of the sensitivity analysis, the depth of the tunnel has the greatest effect on the surface settlement, which can be prevented by controlling the depth of the tunnel from the ground surface. Also, among the soil geomechanical parameters, the modulus of elasticity had the greatest effect on settlement in the present study. Finally, according to the results, the effect of tunnel, building, and soil properties on surface settlement is very important, particularly in urban environments.

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NOMENCLATURE

E	soil modulus of elasticity	ν	the Poisson's ratio
K	earth pressure coefficient at rest	ε_L	Lateral strainsurface
Greek Symbols		β	the angular distortion
ε_P	the average maximum main strain		

1. INTRODUCTION

Tunneling affects the surface (such as buildings, bridges, etc.) and underground (urban facilities, tunnels, metro stations, etc.) structures. Therefore, such structures change the behavior of the ground around the tunnel. In urban environments, such deformations have adverse effects on surface and underground structures. Improving the design and construction of underground structures can guarantee the quality, the safety of engineering structures, and coordination between numerical calculations and actual results. The great variety in the factors influencing the surface subsidence (such as the type of soil layering, tunnel depth and dimensions, and tunneling methods) has led to numerous calculations and predictions of subsidence by researchers. All theories related to the surface subsidence calculation show a relationship between the volume of soil that is loosened by tunneling (and fills the excavated space) and the volume of the subsided surface. Given the loosened mass above the tunnel, further deformations and ground subsidence will be inevitable even if the pores between the soil particles are filled. The loosening and subsequent changes in the soil will continue during the tunneling

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process. In fact, it is not possible to eliminate them even with further measures taken inside the tunnel. By addressing these conditions is only possible by restoring the original soil density and level of the subsided mass. Numerous experiments on intact soil samples have shown that soil behavior is nonlinear and stress-dependent. The actual distribution of stresses in the soil requires consideration of its actual behavior. It is noteworthy that the calculation of soft soil substructure force is more accurate, and the error of deformation calculation is larger [1]. In general, studies to predict surface subsidence have focused on finite element methods [2], artificial intelligence [3], fuzzy studies [4], and cracking particle method [5, 6].

Researchers have always known that it is possible to use numerical methods indefinitely to solve engineering problems; however, given a large amount of time and money spent on programming and executing the programs by computers, the use of empirical relationships was more preferable. Nevertheless, experimental methods cannot provide accurate solutions for the problems, despite their ease of use. Obviously, the closer the model made in numerical methods is to reality, the more accurate the answer will be. Numerical methods have obtained more popularity in recent years due to the advancement of technology and related sciences such as computers and their applicability in various fields. The numerical methods are basically classified according to the type of environment used. The most important numerical methods are finite element method, finite difference method, and distinct element method.

Moorak [9] performed an extensive parametric study on the effects of tunnel construction on ground movements and near buildings constructed on clay soil. He used the discrete element method (DEM) for modeling and compared the results obtained from this modeling with the field data. He also proposed an equation for the ratio of tunnel depth to diameter (Z/D) and damage conditions as well as the ground structural destruction for different structures in the form of Equation (1) [12]:

$$\varepsilon_P = \varepsilon_L \cos\theta_{max}^2 + \beta \sin\theta_{max} \cos\theta_{max}; (\tan(2\theta_{max}) = \frac{\beta}{\varepsilon_L} \quad (1)$$

Equation (1) was compared with field observations and the results showed it can be used for structural evaluation in the design phase of underground structures and tunnels in clay soils.

Dalong et al. [10] conducted studies on the land deformation due to tunneling in Shenzhen region of China using monitoring data analysis. They investigated the states with and without the presence of the tunnels and provided an equation to obtain the amount of ground subsidence when tunneling with a shield [10].

Selby [11] modeled tunnels in the UK using the Lagrangian finite difference method. Finally, he compared the results with experimental values and showed that the estimation of ground subsidence by the finite difference method predicted the subsidence through to be shallower and wider than the actual value, and these differences were greater in shallow tunnels. Franzius and Potts [12] conducted a study on the effect of meshing geometry on three-dimensional analysis of tunneling finite elements. They concluded that a distance of 13 times the diameter of the tunnel was sufficient to minimize the effect of boundaries on the results. Extensive studied [13-16] were conducted on the reaction of different structures due to the construction of underground tunnels and ground subsidence by finite element method. They concluded that the reaction of structures significantly depends on the type and shape of the structure as well as soil conditions. To calculate surface settlement under different types of loading, similar studies have been conducted [17-20]. In general, numerical models can provide more complete information than other methods due to their high flexibility. However, incorrect model selection, inaccurate use of parameter values, and misunderstanding of the construction process can lead to erroneous results.

Although many studies have been conducted to determine the amount of ground subsidence due to tunneling in different conditions, investigation of subsidence concerning underground structures is still one of the most challenging issues in the field of geotechnical engineering. Considering the importance of this issue, the present study has investigated the effect of soil, building, and tunnel parameters on the ground subsidence using numerical modeling with ABAQUS [16]. The importance of these parameters on the ground subsidence due to tunneling has been also examined while performing sensitivity analysis between the parameters.

2. NUMERICAL MODELING

Since practical experiments are very costly, the use of finite element simulations can be an alternative tool in the soil-structure interaction analysis. Among the software using the finite element method to analyze engineering problems, ABAQUS software is one of the most useful research and practical computer programs for finite element analysis due to its unique capabilities. Therefore, ABAQUS software was used in this study to investigate the interaction between soil and tunnel structure and examine the effect of different parameters on surface subsidence.

The characteristics of soil, tunnel, building, and configuration of the elements used in this study are described in the following. As shown in Fig. 1, a hypothetical tunnel with a diameter of D and depth of H in a soil with parameters such as internal friction angle, Poisson ratio, cohesion, and modulus of elasticity, along with a building with specified length and width is modeled in the ABAQUS software [16] environment. After making the desired geometric model, introducing the properties of the materials used, and defining the analytical methods and boundary conditions in the ABAQUS software, the environment is meshed into finite elements and then the analysis method is defined. The ABAQUS software works based on dividing the model into smaller components. Accordingly, continuous element with linear interpolation and an eight-node reduction integration (C3D8R) of regular hexagonal type has been used for soil and tunnel meshing. The continuous element with linear interpolation and a 10-node reduction integration (C3D10) of quadrilateral type has been selected for structural meshing. Also a number of 7624, 8546, and 33640 elements were considered for the building, the tunnels, and the soil, respectively. The selection of mesh dimensions in different parts of modeling has been conducted. Trial and error was applied in a way that in addition to high accuracy of results, the modeling speed was also acceptable. Investigations showed that the finer mesh dimensions have no effect on the output. Fig. 1 shows the schematic geometric drawing of tunnel of the studied models.

2. 1. Soil Properties The soil properties considered in this study were according to clayey sand soil with internal friction angle (ϕ) of 15, 20, 25, and 30 degrees, cohesion (C) of 10, 20, 30, and 40 kPa, modulus of elasticity (E) of 13, 23, 33, and 44 MPa, and Poisson's coefficient (υ) of 0.2, 0.3 and 0.4 according to Table (1). Various models have been proposed by researchers to determine the criterion of soil failure. The elastoplastic model is the best model in determining soil behavior. Soil is neither elastic nor a completely plastic material and shows a combination of the elastoplastic behavioral model. Accordingly, the Mohr-Coulomb model has been used in this study to determine soil behavior.

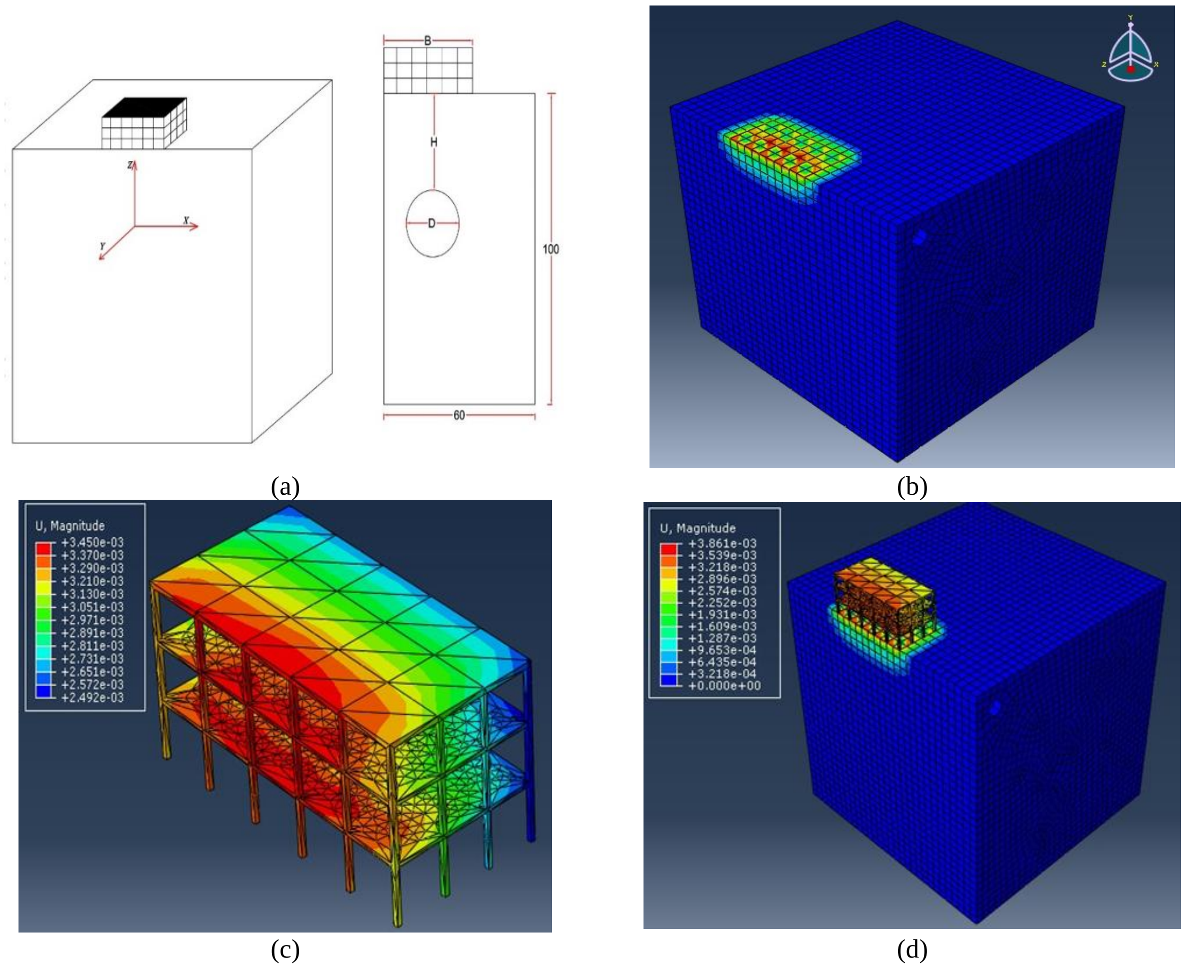

Figure 1. The geometry of the studied models a) Schematic of tunnel and building position b) deformations without building c) deformations of building; U in mm d) deformations with building; U in mm

TABLE 1. The properties of soil used in modeling

υ	E(MPa)	C(kPa)	Φ
0.2	23	20	20
0.3	33	30	25
0.4	44	40	30

2. 2. Tunnel and Buildings Properties The specifications of building and tunnel lining parameters used in modeling are given in Table 2.

The results of the present study are first compared with previous studies, after which modeling of a tunnel with different diameters and depths, and a building with specific length, width, and distance from the tunnel axis on a soil with different internal friction angle, modulus of elasticity, Poisson ratio, and cohesions were carried out and the effect of these parameters on surface settlement were investigated.

TABLE 2. Specifications of building and tunnel parameters used in this study

Building Parameters					Tunnel Lining Parameters			
No. of Stories	Distance from the tunnel axis (X)	Width of Building (B) (meters)	Length of Building (L) (meters)	Poisson ratio (υ)	Lining diameter (cm)	Modulus of elasticity (E) (MPa)	Tunnel Diameter (D) (meters)	Tunnel Depth (H) (meter)
3	10	5	10	0.2	30	37000	3	30
3	20	10	15	0.2	30	37000	5	50
3	30	15	20	0.2	30	37000	7	70
3	40	20	25	0.2	30	37000	9	90

3. RESULTS AND DISCUSSION

3. 1. Comparison of the Present Study with the Previous Research In this section, the surface settlement has been calculated for different tunnel depths (30, 50, 70, and 90 meters) using equations defined by Atkinson [7]. Then, the surface settlement has been calculated for the tunnel diameter of 9 meters and the internal friction angle (ϕ)and modulus of elasticity (E) of 30 degrees and 17 MPa, r by increasing the distance of the building from the tunnel, the impact of the tunnel on the settlement of the building decreases, resulting in the decreasing of the surface settlement. Indeed, the ground in the parts outside the tunnel acts as a suppor, .espectively along with the Poisson's coefficient (ν) equal to 0.3. Finally, the results have been compared.

According to Figure. 2, the amount of settlement calculated by ABAQUS software is greater than the experimental relationships, and the graph obtained from Atkinson [7] relationships is closer to numerical modeling. Also, at a depth of 30 meters, the amount of settlement in Atkinson [7] relation is equal to 4.6 mm, while at the same depth, the amount of settlement obtained from ABAQUS software is equal to 6 mm, which shows about 30% higher values. Fig. 3 compares the amount of surface settlement with increasing distance from the tunnel center in the analytical relationships presented by Cao et al. [13] and Bobet [8] with the numerical modeling used in the present study. In this comparison, the diameter of the tunnel is equal to 3 meters, and the tunnel burial depth is equal to 30 meters. The soil parameters include modulus of elasticity, Poisson ratio, and internal friction angle, which are 17 MPa, 0.3, and 30 degrees, respectively.

According to Figure 3, the curve obtained from the ABAQUS software is closer to the curve obtained by the Cao et al. [13] method and shows some overlap. Also, the two curves obtained from the numerical modeling and Cao et al. [13] intersect at a distance of 15 meters from the tunnel axis, which can be due to the boundary conditions defined by Cao et al. [13] method obtained from experimental observations and simple hypotheses. Besides, these relationships are just for undrained conditions.

3. 2. Numerical Study in the Present Study Generally, with increasing the horizontal distance of the building from the tunnel, the effect of the tunnel on building settlement decreases, leading to decreasing of the surface settlement. Indeed, the ground around the tunnel acts as a support. This section investigates the effect of different parameters on surface settlement.

3. 2. 1. Effect of the Tunnel Depth Relative to Diameter (H/D) and Internal Friction Angle of the Soil on Surface Settleme Figure 4 shows the results of numerical modeling for the case where a building with the width and length of 10 and 20 meters, respectively, is located above the tunnel axis and the diameter of the tunnel is equal to a constant value of 3 meters and different depths of 30, 50, 70, and 90 meters.

The internal friction angle of the soil is 15, 20, 25, and 30 degrees in this case. According to Figure 4, the maximum settlement is for the internal friction angle of 15 degrees and the tunnel depth of 30 meters.

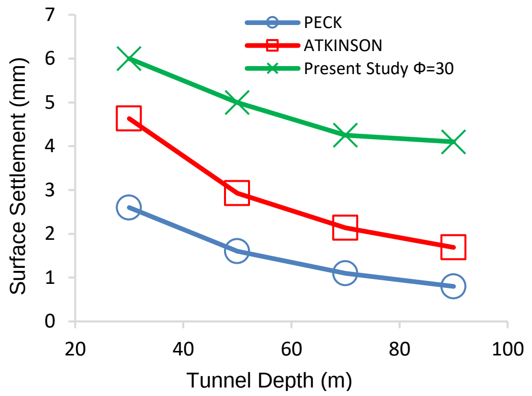

Figure 2. Comparing the amount of surface settlement in experimental and numerical relations

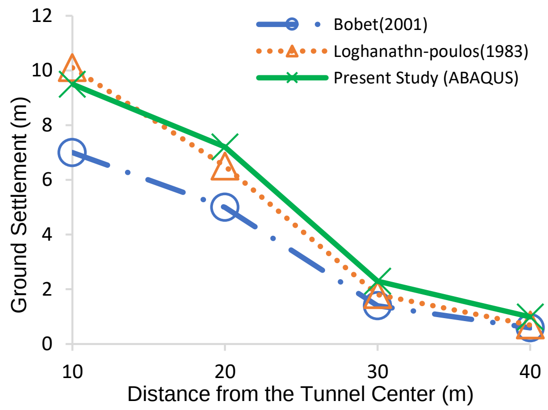

Figure 3. Comparison of the amount of settlement in analytical and numerical methods

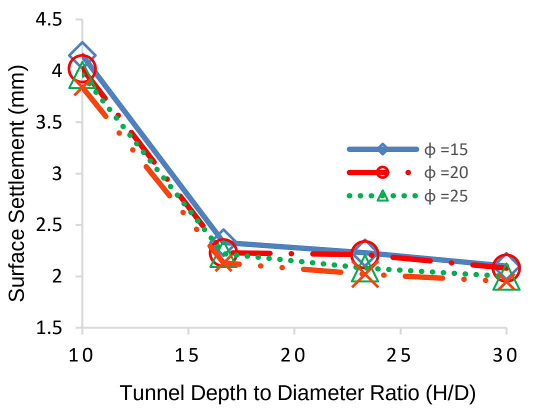

Figure 4. Surface settlement changes for the tunnel depth to diameter (H/D) ratio, where D is 3 meters

According to this figure, the settlement decreases with increasing the internal friction angle of the soil. In other words, the amount of surface settlement is more when the ratio of the tunnel depth to diameter is equal to 10 compared to when this ratio is equal to 30.

3. 2. 2. Effect of Cohesion Relative to Modulus of Elasticity (C/E) and Internal Friction Angle of the Soil on Surface Settlement

The effect of cohesion relative to the soil modulus of elasticity is investigated in this section for different values of the internal friction angle of sand-clay soils. Figure 5 shows the results of numerical modeling for the case where a building with the width and length of 10 and 20 meters, respectively, is located above the tunnel axis.

The soil modulus of elasticity is considered as 13 MPa, and its cohesion is 10, 20, 30, and 40 kPa, respectively. The tunnel burial depth and the diameter of the tunnel are 50 and 5 meters, respectively. Besides, the internal friction angles of soil are 15, 20, 25, and 30, while the Poisson's ratio has been considered to be equal to 0.3.

According to Figure 5, the maximum amount of settlement is for the internal friction angle of the soil equal to 15 degrees and the soil cohesion of 10 kPa. Based on the observations, the settlement decreases with increasing the soil internal friction angle. As can be observed, for a constant modulus of elasticity equal to 13 MPa, surface settlement decreases with the increasing ratio of the soil cohesion to modulus of elasticity.

3. 2. 3. Effect of the Building Length Relative to the Tunnel Depth (D/L) and the Soil Internal Friction Angle on the Surface Settlement

The effect of the Building length relative to the tunnel diameter is investigated for different internal friction angles in sandy-clay soils. The width and length of the building are

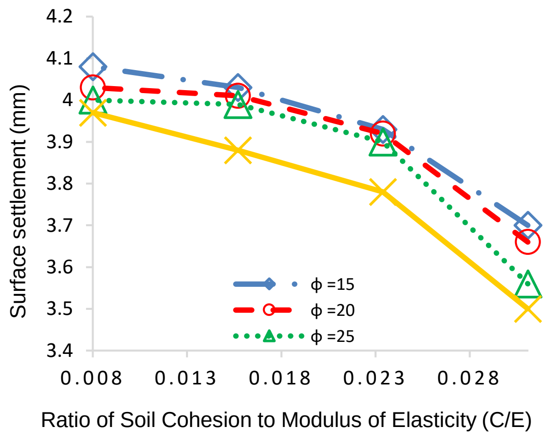

Figure 5. Changes in the surface settlement for the ratio of soil cohesion to modulus of elasticity (C/E) where modulus of elasticity is 13 Mpa

10 meters. The tunnel diameter is variable and equal to 3, 5, 7, and 9 meters with a burial depth of 50 meters. The soil internal friction angles are 15, 20, 25, and 30, while the modulus of elasticity, cohesion, and the Poisson's ratio of the soil are 17 MPa, 20, and 0.3, respectively. Figure 6 shows the results of modeling. As shown in Figure 6, the surface settlement decreases with an increase in the soil internal friction angle.

At a constant length of 10 meters for the building, the surface settlement increases with an increase in the tunnel diameter. As the diameter of the tunnel increases, the settlement increases due to the increasing excavation volume, the removal of part of the soil mass, and the occurrence of strains leading to the settlement.

3. 2. 4. Effect of the Building width Relative to its Length (B/L) and the Poisson's Ratio on the Surface Settlement Figure 7 shows the modeling results for a building with a constant length of 20 meters

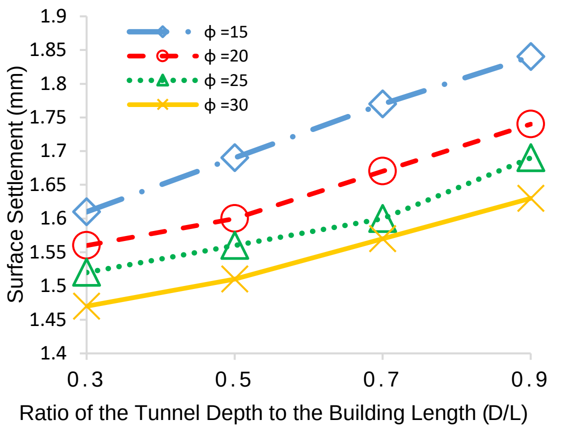

Figure 6. Changes in the surface settlement for the ratio of the tunnel depth to the building length (D/L) where the building length is 10 meters

and variable widths of 5, 10, 15, and 20 meters. The soil Poisson Ratios were 0.1, 0.2, 0.3, and 0.4. The tunnel diameter is 5 meters with a burial depth of 50 meters, and the internal friction angle, cohesion, and modulus of elasticity were 30 degrees, 20 kPa, and 23 MPa, respectively. With increasing the width of the building, the ratio of the building width to length grows from 0.25 to 1, increasing the stiffness and rigidity of the building and decreasing the surface as well as building settlement. Similarly, by increasing the soil Poisson ratio from 0.1 to 0.4, the surface settlement also increases.

3. 2. 5. Effect of the Building Width Relative to its Length (B/L) and the Soil Cohesion on the Surface Settlement The effect of building width on land settlement for different amounts of soil cohesion has been investigated. A building with different widths of 5, 10, 15, and 20 meters and a constant length of 10 meters is located above the tunnel axis. The tunnel diameter is 5 meters and its burial depth is 50 meters. Besides, the soil cohesion values are 10, 20, 30, and 40 kPa. According to Figure 8, the maximum settlement is for the soil cohesion of 40 kPa and the building width of 20 meters. It is also observed that with increasing soil cohesion, settlement decreases. Therefore, the soil with the cohesion of 30 kPa has less settlement than soil with cohesion of 10 kPa. As the width of the building increases at the constant building length equal to 20 meters, the stiffness of the building increases, and settlement decreases.

3. 2. 6. Effect of the Building width Relative to its Length (B/L) and the Soil Modulus of Elasticity on the Surface Settlement Figure 9 shows the numerical modeling results for a building with a length of 20 meters and different widths of 5, 10, 15, and 20, respectively. The soil modulus of elasticity is different and equal to 13, 23, 33, and 44 MPa. The tunnel burial

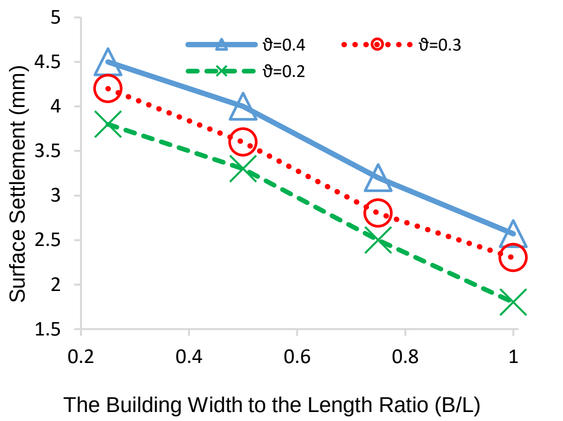

Figure 7. Changes in the surface settlement for the ratio of the building width to the length (B/L) for different Poisson ratios (L = 20 meters, ϕ =30°)

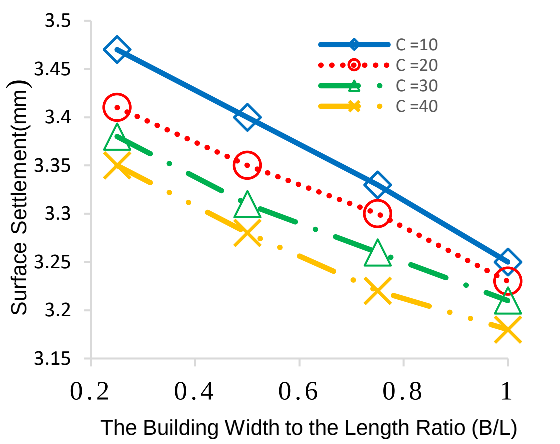

Figure 8. Changes in the surface settlement for the ratio of the building width to the length (B/L) for different soil cohesions (C) (L=20 meters, ϕ= 30°)

depth is 70 meters and its diameter is 5 meters.The maximum settlement is for the soil modulus elasticity of 13 MPa and the building width of 5 meters. It is also observed that the settlement decreases with the increasing modulus of elasticity. Accordingly, the soil with a modulus of elasticity of 44 MPa has less settlement than the case of 13 MPa. As the building width of the building, while the length is constant and equal to 20 meters, the surface settlement decreases. According to Figure 9, when the ratio of building width to length is equal to 1, the settlement is 1.9 mm for the soil with a modulus of elasticity of 13 MPa, and 1.75 mm for the modulus of elasticity of 44 MPa. This indicates that with an increase in modulus of elasticity from 13 to 44 MPa, the settlement decreased by about 8%.

3. 2. 7. Investigating the Effect of Building Weight on the Surface Settlement and Surface Building

The effect of the building weight on the surface settlement is investigated in the following. Given that with increasing the load of the building on the surface surface, the settlement also increases.

Figure 10 presents the results of modeling with and without considering the building. The tunnel diameter was 5 meters, and the buried depths were 30, 50, 70, and 90 meters, along with a 3-story building with a width of 10 m and a length of 20 meters and a load of 1600 kg/m^2 due to the weight of the building. The results show that surface settlement increases with increasing the load on the soil and the addition of the building.

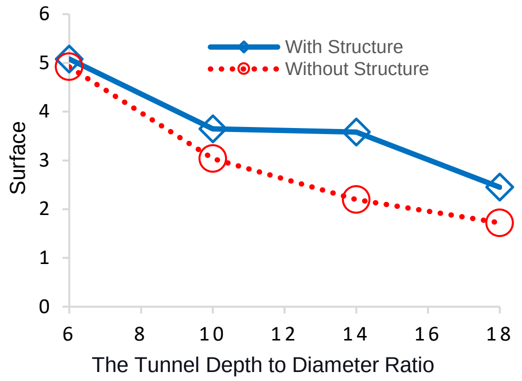

Figure 10. Changes in the surface settlement for the ratio of the tunnel depth to diameter with and without considering the building (D=5 meters)

3. 8. Effect of the Building Distance from the Tunnel Center Relative to the Building Length (X/L) and the Tunnel Depth on the Surface Settlement

Figure 11 shows the numerical modeling results for a building located at distances of 10, 20, 30, and 40 meters from the tunnel axis and constant width and length of 10 and 20 meters, respectively. The tunnel diameter is constant at 9 meters with variable depths of 30, 50, 70, and 90 meters. As the distance of the building from the tunnel axis increases, the settlement dramatically decreases; therefore, that after a certain distance, settlement decreases to almost zero. Increasing the distance between the building and the tunnel leads to reduced surface settlement, but the trend becomes constant after a distance equal to the diameter of the tunnel. The maximum increase in settlement is for the range of 0-10 meters because most changes in vertical and lateral pressure have occurred in this range.

3. 3.Sensitivity Analysis

One of the primary measures after modeling is to determine the sensitivity of the target modeled to input parameters. As a general rule, all parameters were kept constant except one parameter, which was changed to a certain percentage, to determine the impact of the input parameters on the target [15]. Table 3 presents the results obtained in this study based

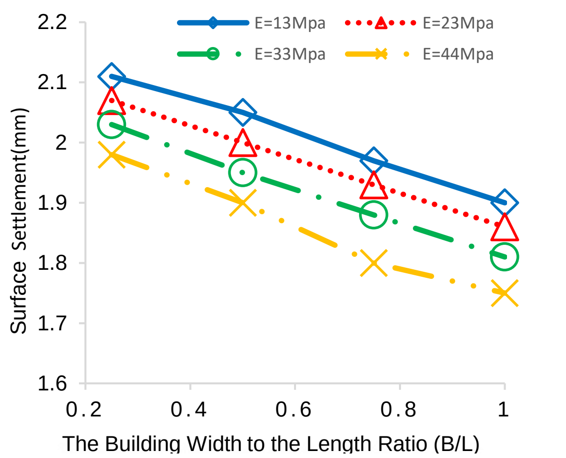

Figure 9. Changes in the surface settlement for the ratio of the building width to the length (B/L) for different soil modulus of elasticity (E) (L=20 m, ϕ= 30°)

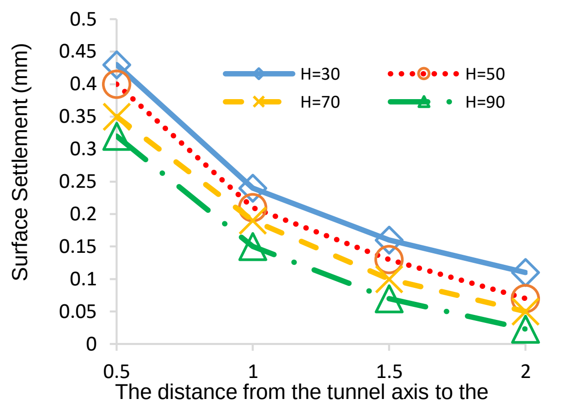

Figure 11. Changes in the surface settlement for the ratio of the distance from the tunnel axis to the building length (X/L) for different tunnel depths (H in meters) (ϕ =30°)

TABLE 3. The effect of increasing the input parameters up to 20% on the surface settlement (%)

Parameters	D	H	C	E	ν	Φ
Values Obtained from Sensitivity Analysis	0.85	1.05	0.52	0.97	0.74	0.67

*D: Tunnel Diameter; H: Tunnel Depth; C: Cohesion; E: Modulus of Elasticity; ν: Soil Poisson's Ratio; Φ: Internal friction angle

on a 20% increase in the mentioned parameters. The significant difference between the actual values indicates the greater impact of the deleted parameter on the results. Accordingly, the effect of various parameters used in modeling was investigated. Generally, values greater than 0.9 indicate a significant impact of the parameter on the output (settlement), and values less than 0.8 represent a weak effect on the output parameter [14].

According to Table 3, the depth of the tunnel had the highest effect on the surface settlement, which can be prevented by controlling the tunnel depth relative to the surface. Also, among the geomechanical parameters of the soil, the modulus of elasticity and cohesion parameters had the highest and the lowest effects on the surface settlement, respectively.

4. CONCLUSION

In this study, finite element numerical modeling aimed to predict the effect of tunneling on surface settlement in sand-clay soils. According to the obtained results and comparing the numerical modeling with the results of other researchers, the modeling performed with ABAQUS software provides acceptable results. Therefore, the use of ABAQUS software is recommended as a useful tool to model and predict the surface settlement under the influence of tunneling. According to the output of the modeling, the surface settlement increases with an increase in the tunnel diameter (D), which is related to the increase in excavation volume and the removal of part of the soil mass along with the occurrence of strains that leads to surface settlement. Also, as the depth of the tunnel (H) increases, the settlement decreases. The results of the sensitivity analysis showed that out of the tunnel parameters studied in this study, the depth of the tunnel had the most impact on the surface settlement, and it is possible to avoid surface settlement by controlling the tunnel depth. As the width (B) and length (L) of the building increase, the settlement decreases; but this decrease is more for changes in the width of the building, which can be attributed to the greater cross-section of the foundation and an increase in its stiffness so that the settlement of the foundation becomes more uniform and more resistant to displacement. As the lateral distance between the building and the tunnel (X) increases, the surface settlement increases initially, and after an approximately equal distance to the tunnel diameter, the settlement changes show a steady trend. The highest increase in settlement is between 0 and 10 meters because most vertical and lateral pressure changes occur in this range. As the internal soil friction angle (ϕ), soil cohesion (C), and the modulus of elasticity (E) increase, the surface settlement decreases. According to the results of sensitivity analysis, among the geomechanical parameters of the soil examined in this study, the modulus of elasticity and cohesion had the highest and lowest effect on the surface settlement, respectively. In general, the results of numerical modeling showed that if the exact parameters of soil and building are available, numerical modeling provides acceptable results in the estimation of surface settlement resulted in from the surface building.

5. REFERENCES

1. Zhu H., Shi L. "Application of Typical Engineering. In: Methodology of Highway Engineering Structural Design and Construction." ***Advanced Topics in Science and Technology in China***, Vol. 59. (2021), 73-231. DOI: https://doi.org/10.1007/978-981-15-6544-1_5
2. Chen I, Rabczuk T, Bordas S, Liu GR, Zeng KY, Kefriden P. "Extended finite element method with edge-based strain smoothing (esm-xfem) for linear elastic crack growth." ***Computer Methods in Applied Mechanics and Engineering***, Vol. 209, (2012), 250-265, DOI: 10.1016/j.cma.2011.08.013
3. Chen, R., Zhang, P., Wu, H., Wang, Zh., Zhong, Zh." Prediction of shield tunneling-induced ground settlement using machine learning techniques". ***Frontiers of Structural and Civil Engineering***, Vol. 13, (2019), 1363-1378. DOI: https://doi.org/10.1007/s11709-019-0561-3
4. Zhuang X, Zhou S, Sheng M, Li G. "On the hydraulic fracturing in naturally-layered porous media using the phase field method." ***Engineering Geology.*** Vol. 266, (2020), DOI:10.1016/j.enggeo.2019. 105306
5. Zhou, F., Molinari, J.F. "Dynamic crack propagation with cohesive elements: a methodology to address mesh dependence", ***International Journal of Numerical Methods in Engineering***, Vol. 59, No. 1, (2004), 1-24. DOI: https://doi.org/10.1002/nme.857
6. Rabczuk, T., Belytschko,T., "Cracking particles: a simplified meshfree method for arbitrary evolving cracks ***International Journal of Numerical Methods in Engineering,*** Vol. 61, No. 13, (2004), 2316-2343. DOI: https://doi.org/10.1002/nme.1151
7. Atkinson, J.H., Potts, D.M. "Subsidence above Shallow Circular Tunnel in Soft Ground", ***Journal of Geotechnical Engineering Division, ASCE,*** Vol. 103, G.T.4, (1977), 307-325. DOI: http://worldcat.org/oclc/3519342
8. Bobet, A. "Analytical Solutions for Shallow Tunnels in Saturated Ground", ***Journal of Engineering Mechanics***, Vol. 127, No. 12, (2001), 1258-1266. DOI: https://doi.org/10.1061/(ASCE)0733-9399(2001)127:12(1258)
9. Moorak, S. "Response analysis of nearby structures to tunneling-induced ground movements in clay soils", ***Tunneling and***

Underground Space Technology, Vol. 56, (2016), 90-104. https://doi.org/10.1016/j.tust.2016.01.032

10. Dalong, J., Dajun, Y., Xinggao L., Haotian, Z. "Analysis of the settlement of an existing tunnel induced by shield tunneling underneath", ***Tunneling and Underground Space Technology*** Vol. 81, (2018), 209-220. DOI: https://doi.org/10.1016/j.tust.2018.06.035
11. Selby, A.R. "Tunneling in Soil Ground Movement and Damage to Building in Workington, UK", ***Geotechnical and Geologocal Engineering,*** Vol. 17, (1999), 351-371. DOI: https://doi.org/10.1023/A:1008985814841
12. [12] Franzius, J.N., Potts, D.M. "Influence of mesh geometry on three-dimensional finite element analysis of tunnel excavation", ***ASCE International Journal of Geomechanics*** Vol. 5, No. 3, (2005), 256-266. DOI: https://doi.org/10.1061/(ASCE)1532-3641(2005)5:3(256)
13. Cao, L., Zhang, D., Fang, Q. “Semi-analytical prediction for tunneling-induced ground movements in multi-layered clayey soils”, ***Tunneling and Underground Space Technology***, Vol. 102, (2020), DOI: https://doi.org/10.1016/j.tust.2020.103446
14. Barla, C. "Continuum and Discontinuum Modeling in Tunnel Engineering", Italian Ministry for University and Technological Research (M.U.R.S.T) as part of the Research Program, Tunneling in Difficult Condition, Vol. 12, No. 1, (2000), 45-57. DOI: https://hrcak.srce.hr/5033
15. Mahmoudi, M., Rajabi, A.M “Application of numerical back analysis for determination of soil mass specifications during tunnel construction”. ***Arabian Journal of Geosciences***, Vol. 13, No. 19, (2020), 1-9. DOI: https://doi.org/10.1007/s12517-020-05935-1
16. Manual, A.: ABAQUS documentation version 6.13. Dassault Systems SIMULIA Corp., Providence, RI, USA (2013)
17. Civaleka, Ö., Öztürkb B. “Discrete singular convolution algorithm for non-linear transient response of circular plates resting on Winkler-Pasternak elastic foundations with different types of dynamic loading." ***Indian Journal of Engineering & Materials Sciences***, Vol. 16 (2009), 259-268. DOI: http://hdl.handle.net/123456789/6038
18. Cengiz, C., Guler, E. “Load bearing and settlement characteristics of Geosynthetic Encased Columns under seismic loads.” ***Soil Dynamics and Earthquake Engineering***, Vol, 136, (2020), 106244. DOI: https://doi.org/10.1016/j.soildyn. 2020.106244
19. Feng, W-Q., Yin, J-H., Chen, W-B., Tan M D-Y., Wu P-Ch. “A new simplified method for calculating consolidation settlement of multi-layer soft soils with creep under multi-stage ramp loading.” ***Engineering Geology***, Vol. 264, (2019), 105322. DOI: https://doi.org/10.1016/j.enggeo. 2019.105322
20. Wu, P.-Ch., Feng, W-Q., Yin, J-H. “Numerical study of creep effects on settlements and load transfer mechanisms of soft soil improved by deep cement mixed soil columns under embankment load.”, ***Geotextiles and Geomembranes***, Vol. 48, (2020), 331-348. DOI: https://doi.org/10.1016/j.geotexmem. 2019.12.005

Persian Abstract

چکیده

در این مطالعه با استفاده از نرم‌افزار اجزای محدود آباکوس، تاثیر پارامترهای مختلف از جمله قطر تونل (D)، عمق تونل (H)، عرض (B)، طول (L)، تعداد طبقات و فاصله افقی ساختمان از محور تونل (X) و ویژگی‌های خاک شامل زاویه اصطکاک داخلی (ϕ) نسبت پواسون (υ)، مدول الاستیسیته (E) و چسبندگی (C) روی نشست خاک مورد بررسی قرار گرفته است. نتایج نشان می‌دهد که با افزایش زاویه اصطکاک داخلی خاک، میزان نشست کاهش یافته و با کاهش مدول الاستیسیته و چسبندگی خاک به علت سخت شدن خاک نشست افزایش می‌یابد. همچنین در یک عمق ثابت با افزایش قطر تونل نشست زمین افزایش می‌یابد در حالی که با افزایش عمق قرارگیری تونل میزان نشست کاهش می‌یابد. تغییرات عرض و طول ساختمان نیز اثر مستقیم بر روی نشست دارد؛ به طوری که با افزایش عرض و طول ساختمان به علت افزایش سطح مقطع پی ساختمان و افزایش صلبیت و سختی آن، نشست پی سازه یکنواخت‌تر و در برابر جابجایی از خود مقاومت بیشتری نشان می‌دهد و نشست زمین کاهش می‌یابد. همچنین با افزایش فاصله سازه از محور تونل نشست زمین کاهش پیدا کرده و پس از فاصله‌ای معادل با قطر تونل، روند ثابتی داشته است. نتایج آنالیز حساسیت انجام گرفته نشان می‌دهد در بین پارامترهای انتخاب شده، عمق قرارگیری تونل بیشترین تاثیر را در نشست سطح زمین دارد که با کنترل عمق قرار گیری تونل از سطح زمین می‌توان از نشست‌های سطح زمین جلوگیری نمود. همچنین دربین پارامترهای ژئومکانیکی خاک، در این مطالعه پارامتر مدول الاستیسیته بیشترین تاثیر را روی نشست سطح زمین دارد. در نهایت نتایج این مطالعه نشان می‌دهد تاثیر مشخصات تونل، سازه و خاک بر روی نشست زمین به خصوص در محیط‌های شهری بسیار حائز اهمیت است و بایستی مورد توجه طراحان قرار گیرد.