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Effect of Tunnelling on Settlement of a Building: A Numerical Approach

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ABSTRACT

Land shortages due to population growth and the sustainable development of cities have necessitated the use of underground systems. Although tunnels, which mostly provide solutions to transport problems, are frequently used today, the construction of tunnels in large cities poses significant issues. Regardless of the construction method, deformations are inevitable during tunnelling. Tunneling machines apply pressure to the surfaces during the excavation of the tunnel surface. However, during construction, the pressures are not adjusted correctly, and deformations are observed in the ground. Since these deformations may cause major damage to the surrounding structures when they reach the ground surface, it should be calculated how much deformation may occur prior construction, and necessary precautions should be taken. Therefore, this study aims to define the deformations that will occur on the soil surface. In this context, numerical analyses were performed. During the numerical studies, Plaxis 2D based on finite element method (FEM), was used to create the tunnel modelling in the clayey soil. A tunnel boring machine (TBM) was used during tunnelling in the modelling. The excavation diameter of the tunnel, cover thickness, foundation width and epicentre distance from the tunnel axis to the structure foundation were analysed in the geometric model. The effects of the geometrical parameters of the tunnel, the building and the clay soil on the displacements were determined numerically. As a result, it was determined that tunnel depth, tunnel diameter, cover thickness and foundation width are effective parameters for settlement of buildings constructed on clay soils.

Keywords: Tunnel Boring Machine (TBM), Soil-structure interaction, Tunneling, Clay soil, Finite elements method (FEM), Settlement.

Tünel Açmanın Bir Binanın Oturmasına Etkisi: Sayısal Bir Yaklaşım

ÖZ

Nüfus artışına bağlı olarak yaşanan arazi sıkıntısı ve şehirlerin sürdürülebilir gelişimi, yeraltı ulaşım sistemlerinin kullanımını zorunlu hale getirmiştir. Çoğunlukla ulaşım sorunlarına çözüm sağlayan tüneller, günümüzde sıklıkla kullanılsa da büyük şehirlerde tünel yapımı önemli sorunlar teşkil etmektedir. Yapım yöntemi ne olursa olsun, tünel açma sırasında zeminde deformasyonlar kaçınılmazdır. Tünel açma makineleri, tünel yüzeyinin kazılması sırasında yüzeylere basınç uygular. Ancak inşaat aşamasında bu basınçlar doğru ayarlanmamakta ve zeminde deformasyonlar gözlenmektedir. Bu deformasyonlar zemin yüzeyine ulaştığında çevredeki yapılara büyük zararlar verebileceğinden, inşaat öncesinde ne kadar deformasyon oluşabileceği hesaplanmalı ve gerekli önlemler alınmalıdır. Bu nedenle bu çalışmada zemin yüzeyindeki yapı temelinde oluşacak deformasyonların belirlenmesi amaçlanmıştır. Bu kapsamda sayısal analizler gerçekleştirilmiştir. Sayısal çalışmalar sırasında, killi zeminde tünel modellemesini oluşturmak için sonlu elemanlar yöntemine dayalı Plaxis 2D programı kullanılmıştır. Modellemede tünel açma sırasında bir tünel açma makinesi (TBM) kullanılmıştır. Geometrik modelde tünelin kazı çapı, örtü kalınlığı, temel genişliği ve tünel ekseninden yapı temeline olan episantrik mesafe analiz edilmiştir. Tünelin, yapının ve zeminin geometrik parametrelerinin yer değiştirmeler üzerindeki etkileri sayısal olarak belirlenmiştir. Sonuç olarak, tünel derinliği, tünel çapı, örtü kalınlığı ve temel genişliğinin killi zeminler üzerine inşa edilen binanın oturması üzerinde etkili parametreler olduğu tespit edilmiştir.

Anahtar Kelimeler: Tünel delme makinesi (TBM), Zemin-yapı etkileşimi, Tünel açma, Kil Zemin, Sonlu elemanlar metodu, Oturma.

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1. Introduction

In most major cities, underground transport systems are preferred. Such systems are sometimes built in the soft soils of urban areas and include tunnels. Underground structures are the most well-known challenge for civil engineers in terms of design, survey and construction. The first underground railway was built in London in 1863, and underground transport has been developing in major cities since then (Hellawell et al., 2001). As a result of increasing needs, different usages of tunnels have emerged, and it has become obligatory to construct tunnels in all types of soils. The shield tunnel boring machine (TBM) approach has become popular for its construction, having less effect on the surrounding environment, a relatively high construction rate and so forth. (Verruijt and Booker, 1996; Zhang et al., 2017; Zhou et al., 2017; Wu et al., 2018; Yan et al., 2021; Shen et al., 2022). Tunnel boring machine (TBM) integrating the functions of excavation, support, slag discharge, and transportation is one of the most advanced types of equipment for various tunnel constructions. TBM has gradually replaced traditional excavation in various tunnel projects due to its high efficiency, safety, and environmental protection. However, the adaptability of TBM is often limited by complex geological conditions, tunneling parameters, and the high requirements on the experience of construction personnel, making it difficult to solve the prediction of TBM tunneling parameters effectively. One of the most important engineering issues is the deformations that occur around the tunnel during excavation activities. During and after the tunnel excavation, the stress distribution generally changes in the soil medium. Stress changes start from the ground around the tunnel and continue to the surface; as a result, ground settlement is induced (Pourtaghi and Lotfollahi-Yaghin, 2012; Moghaddasi and Noorian-Bidgoli, 2018; Chen et al., 2019; Zhang et al., 2020). The deformations occurring at the ground surface due to stress changes form the settlement curve. Depending on the type of soil, with the increase in the amount of settlement on the ground surface, deflections and ultimately collapse may occur. The effect of subsidence on the earth's surface during tunnelling excavation can be more severe, especially in the structures around the tunnel (for those classified as historical and sensitive buildings also high structures in length) (Namli and Aras, 2020).

The determination of longitudinal settlement dimensions and settlement magnitude allows the estimation of which buildings or underground facilities will be affected by tunnelling and how much they may settle. The longitudinal settlement profile is generally used to determine the progression of the slope of surface and underground structures along the excavation profile as shown in Figure 1.

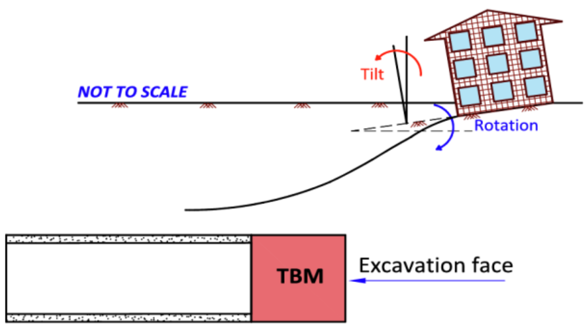

Figure 1. Complications to surface structures due to settlement (Ads et al., 2023)

The basic approach to predicting surface settlement due to tunnelling is the “semi-empirical method” stated by Peck (1969) and subsequently developed on the basis of field data from various tunnelling projects. (O’Reilly and New, 1982; Attewell and Woodman, 1982; Mair et al., 1993; Mair and Taylor, 1997). In addition, using centrifuge tests and case study data, Mair et al. (1993) demonstrate that sub-surface settlement voids in undrained clays can also be well accommodated by a Gaussian curve. The semi-empirical method, based on the assumption of a ‘Gaussian curve’ representing the settlement pit, is an effective tool for the pre-design of urban tunnels, to be complemented by numerical analyses at the detailed design stage (Figure 2).

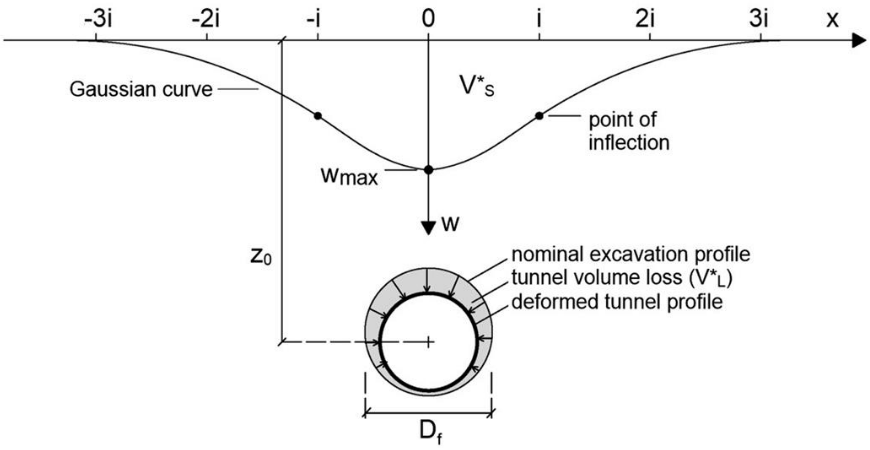

Figure 2. Gaussian curve for transverse settlement trough, nominal tunnel diameter, volume of the settlement trough, V^*_S and volume loss at the tunnel excavation profile, V^*_L (Ads et al., 2023).

The Gaussian curve correctly represents surface settlement in undrained clay, but the settlement pattern in drained soils does not always agree with this curve. The disagreement increases due to the yield density about the tunnel and the occurrence of vertical shear bands, which tend to give a chimney-like mechanism (Mair et al., 1993, Celestino et al., 2000). Curves with additional degrees of freedom, such as modified Gaussian and yield density curves, can provide a better match for a given monitoring section; however, the comparison of data from different tunnels becomes more complex (Vorster et al., 2005; Marshall et al., 2012).

In recent years, a large number of scholars have realized the importance of studying tunnel deformation induced by ground surface surcharge and have carried out a lot of relevant research via numerical simulation [e.g., FEM (Yamamoto et al., 2011, 2012, 2014; Yang et al., 2017) and finite difference element method (Huang et al., 2020; Du et al., 2020; Cheng et al., 2019)], theoretical analysis (Li and Wang, 2008; Wang et al., 2018a, b), and indoor model tests (Atkinson and Potts, 1977; Zhang et al., 2016; Zhai et al., 2020).

The settlement of the ground poses a threat to nearby structures and infrastructures. To minimize the risk of damage, accurate prediction of maximum ground surface settlement is critical to control it within the tolerance. In addition, accurate evaluation and management of Ground surface settlement can help in selecting suitable construction techniques and materials, thereby ensuring the severability of the tunnel over its lifespan. Therefore, a comprehensive understanding of ground settlement is integral not only for the engineering design and construction of the tunnel itself but also for the safety of the ground surface structures. Because of that, this study aims to define the deformations that will occur on the soil surface. In this context, numerical analyses were performed. During the numerical studies, Plaxis 2D program of finite element method (FEM) was used to create the numerical models of tunnels. In the Plaxis 2D program, clay soil was modelled as Mohr-Coulomb (MC) material model. A tunnel boring machine (TBM) was used during the tunnelling of the simulation. The excavation diameter of the tunnel (10, 15, 20 and 25 m), overburden height (10, 15, 20, 25, 30 and 35 m), foundation width (10, 20, 30 and 40 m) and epicentric distance of the tunnel to the structure foundation (0, 10, 15, 20, 25, 30 and 35 m) were analysed in the geometric model. The effects of the geometrical parameters of the tunnel and soil on the displacements were determined numerically.

2. Material and method

Nowadays, the widespread metro transport network passes close to many important administrative and historical buildings, residences and infrastructure systems along its routes. In particular, deformations occur in the tunnel due to volume loss as a result of tunnel excavations, as well as surface settlements, which are extremely dangerous for surface structures. To provide the safety of life and property and also for the progress of these public benefit projects following the work program, meticulous studies are required. Considering that the responses of the structural system and foundations to surface settlements will vary for each building, critical ones should be examined, and measures should be taken accordingly. With the developing technology, computer programs that perform many two and three-dimensional analyses using the FEM are used. Because of its cost-effectiveness, time and applicability, numerical analysis is the method of choice in many geotechnical investigations. Furthermore, the geometry of the failure surface has been the subject of investigation in many numerical analysis studies. In this study, a parametric study was carried out for a tunnel in a clayey medium excavated by TBMs. With the assistance of a comprehensive numerical analysis, the tunnel-soil-structure interaction is investigated in detail.

İdeCAD static (2018) program was used for the determination of the loads originating from the structure to be used in numerical analyses. İdeCAD static is a package program specially developed for modelling, code-compliant design and performance evaluation of building systems. Structures with or without storeys, with or without rigid diaphragms in the storeys, with partially rigid diaphragms or completely without rigid diaphragms can be calculated with the program in question. In this program, slabs, shear walls, beams, columns and foundations can all be analyzed together. To determine the effect of foundation width in numerical analyses, five structures with raft foundations of 10m x 10m, 20m x 20m, 30m x 30m and 40m x 40m dimensions were modelled. In all cases, the number of floors was kept constant at 4. In the modelling, the loads were considered as G = 0.6 tf/m^2 and Q = 0.4 tf/m^2. In addition, column dimensions were determined as 50 x 30 cm, beam dimensions as 30 x 50 cm and slab thickness as 14 cm. As a result of the analyses, the average base pressure was obtained as an average of 80 kN/m^2 (Figure 3).

Plaxis 2D (2010) (v. 8.6), an easy-to-use, off-the-shelf FE software, was used to analyse parameters that influence soil deformations for the single tunnel alignment. Popular with geotechnical practitioners, this software is widely used. It uses an implicit time integration scheme and, therefore, generates a solution faster than programs using explicit time integration. Designed primarily for the analysis of deformation and stability in geotechnical problems, the FE program's advanced output facilities provide a detailed presentation of the calculation results. The default boundary conditions available in Plaxis 2D, which restrict the horizontal deformations at the side boundaries and both horizontal and vertical deformations at the bottom boundary, were used. The dimensions of the model were decided by conducting convergence studies by varying the boundary distances.

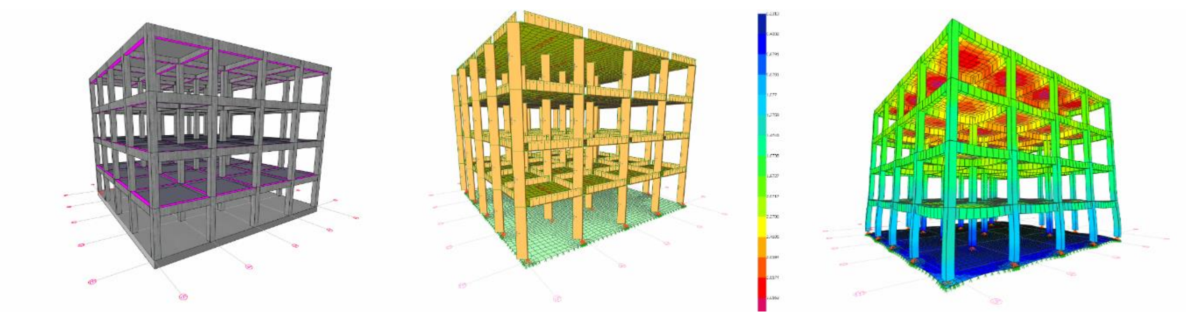

Figure 3. IdeCAD structure model

In two-dimensional analyses, the cross section was taken as 90 x 110 m^2. In the geometric model, the excavation diameter of the tunnel (10, 15, 20 and 25 m), overburden height (10, 15, 20, 25, 30 and 35 m), foundation width (10, 20, 30 and 40 m) and epicentric distance between the tunnel and the foundation (0, 10, 15, 20, 25, 30 and 35 m) were analysed. Figure 4(a) shows the geometrical model for the analyses. Where Q is the surface load due to the superstructure, *D* is the excavation diameter of the tunnel, *H* is the height of the ground above the tunnel (overburden height), *B* is the foundation width, and L is the epicentric distance of the tunnel to the building foundation. In addition, while creating the finite element mesh, the finite element mesh shown in Figure 4 (b) was created by selecting a 'fine' and 15-node solution in the Plaxis 2D program to converge to the result to a great extent in terms of the element size. The main reasoning of the mesh generation process can be defined as separating the treated region into elements of the desired fineness based on the continuity and node coordinate information of the elements entered for a small number of key points. The mesh generation process considers the soil profile, all structural elements, loads and boundary conditions. Due to the large displacement gradient of the corner points of the structural elements and the stress concentrations likely to occur around the tunnel, the finite element mesh can be generated more frequently and precisely than the gradient of the field variables.

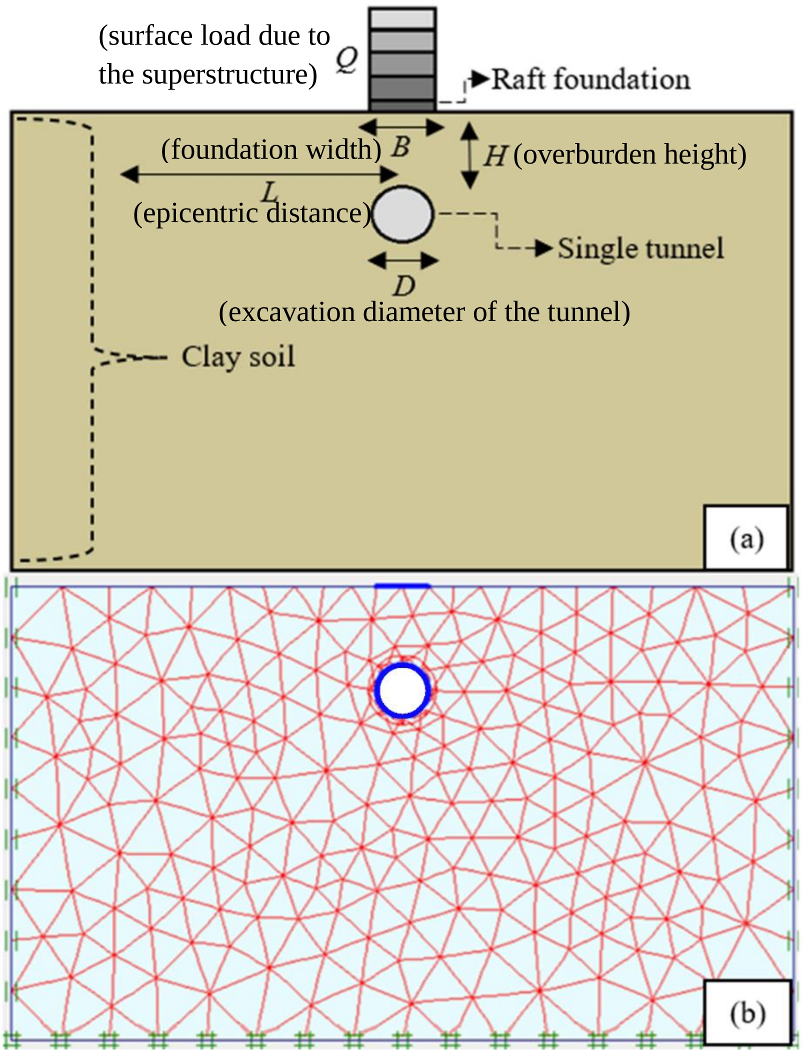

Figure 4. a) Geometric model b) Finite element network

Soft clayey soils were preferred in the analyses and these soil types were not changed throughout the analyses and were used in all analyses. The soil properties of these materials were determined by analyzing previous studies (Yamamoto et al., 2011, 2012, 2014; Yang et al., 2017; Cheng et al., 2019; Huang et al., 2020; Du et al., 2020). The Mohr-Coulomb (MC) material model was selected as the soil material model. While determining the physical properties of the soil, many parameters such as void ratio, shear modulus, and permeability coefficient can be easily entered in the Mohr-Coulomb Soil Model, which is considered as an elastic–perfectly plastic soil. Table 1 shows the soil parameters used in the numerical analyses. The tunnel and foundation structures used during the numerical analyses were created with plate elements used to define such materials in the Plaxis 2D program. For the material properties to be realistic, the most appropriate material properties were selected by utilizing previous literature, studies and thesis on this subject. While creating the numeric model, it was taken into consideration that the groundwater level height is lower than 90 mt, and there is no effect on the analyses. Bending moment (EI) and axial stiffness (EA) are defined. The effect of the difference with the tail radius due to the taper of the TBM was modelled using a 2% contraction. Table 2 presents the selected material parameters for the tunnel and foundation structures.

Table 1. The input parameters for the Mohr-Coloumb (MC) material model

Symbol	Soil Parameters	Value
-	soil condition	drained
-	soil model	MC
γ_{unsat}	soil unit weight above phreatic level (kN/m^3)	15.00
υ	poisson’s ratio	0.30
ψ	dilatancy angle	0.00
E	young’s modulus (kN/m^2)	6,000
c	cohesion (kN/m^2)	60.00
$k_x = k_y$	permeability (m/day)	1.00E-04

Table 2. The input parameters for the tunnel and foundation

Symbol	Parameters	Value	
		Tunnel	Foundation
-	material model	elastic	elastic
EA	bending moment (kN/m)	1.40E+07	5.00E+08
EI	axial stiffness kN/m^2/m	1.42E+05	1.00E+07
d	Thickness (m)	0.35	0.50
υ	Poisson’s ratio	0.15	0.15

3. Results

Within the scope of the study, the tunnel was modelled and analyzed using the Plaxis 2D computer program using the FEM, considering the investigated cross-section and soil parameters. As a result of 4 stages of finite element analyses (initial, structure, tunnel and shrinkage), the vertical displacements (*u*) due to tunnel excavation for a tunnel constructed by the TBM method were obtained for different parameters. In addition, based on the results of the building assessment, protection requirements are discussed. If the calculated settlements exceed the acceptable limits of the buildings, additional measures can be considered. The calculated settlements can be used to correlate the damage condition with the prediction. To minimize damage when passing through these areas, the shoring should be reinforced, and the excavation speed should be reduced. Some authors have suggested limits for the maximum allowable total foundation settlements for a range of structures

(Skempton and MacDonald, 1956; Polshin and Tokar, 1957; Wilun and Starzewski, 1972). In all cases, it is necessary to take account project-specific details, including the type of structure, the type or sensitivity of the contained machinery and the actual ground conditions. A combination of these criteria forms a useful basis from which to develop a tentative framework for relating settlement and maximum ground slopes to potential structural damage and, hence, risk assessment for tunneling projects in urban areas. According to Rankin (1988), typical critical values of building settlements that have been used for planning and design purposes, as well as optimizing alignments, are presented in Table 3. Thus, a risk assessment was made for the settlements occurring in the structure due to tunnel excavation.

Table 3. Typical values of maximum building settlements for damage risk assessment (Rankin, 1988)

Risk Category	Maximum Settlement of Building (mm)	Description of Risk
1.	Less than 10	Negligible: superficial damage unlikely.
2.	10 to 50	Slight: Possible superficial damage, which is unlikely to have structural significance.
3.	50 to 75	Moderate: Expected superficial damage and possible structural damage to buildings, possible damage to relatively rigid pipelines
4.	Greater than 75	High: Expected structural damage to buildings. Expected damage to rigid pipelines, possible damage to other pipelines.

3.1. Effect of Tunnel Depth (*H*)

Tunnel depth is one of the main parameters of tunnel design and has a great effect on ground surface settlements. In the numerical analyses, the tunnel depth is denoted as '*H*', and the depth is investigated for H = 10, 15, 20, 25, 30 and 35 meters. In this series of analyses, the tunnel diameter and foundation width were considered as D = 10 m and B = 10 m, respectively. The amount of superstructure-induced uniform pressure is 80 kN/m^2, and the only variable parameter is the H. Figure 5 shows the relationship between tunnel depth and vertical displacement. As the tunnel depth increases, the vertical displacement in the clay soil medium decreases. When the lowest tunnel depth is 10.0 m, the settlement at the ground surface is 71.82 mm and when the highest tunnel depth is 35.0 m, the settlement at the ground surface is 39.43 mm. Therefore, it can be said that the vertical displacements in the clay soil are directly related to the tunnel depth, and this displacement decreases as the tunnel depth increases.

The relationship between the depth of the tunnel and the settlement of the foundations of the superstructure is shown graphically in Figure 6. It can be seen that as the tunnel depth increases, the surface settlement decreases. An increase in the tunnel depth from 10 m to 35 m resulted in a 39% reduction in the foundation settlement. Also, the amount of settlement is inversely proportional to the tunnel depth and its effect on the superstructure is limited beyond H = 25 m.

In the risk assessment made according to Table 3, it is seen that if the tunnel depth is less than 20 meters, acceptable settlement values are exceeded, so structural damage may occur in the existing structure. However, after the tunnel depth exceeds 20 meters (2D), the settlement of the structure decreases and remains within the acceptable values.

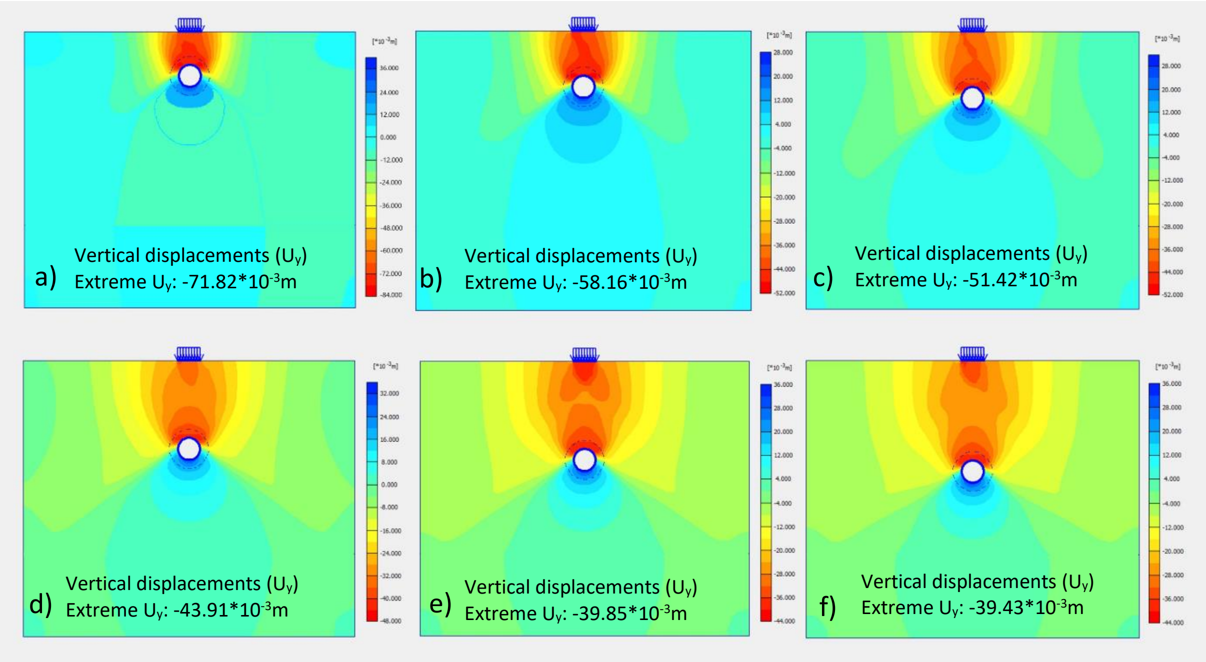

Figure 5. General presentation of vertical displacements (U_y) a) for *D*=10 m, *H*=10 m, b) for *D*=10 m, *H*=15 m, c) for *D*=10 m, *H*=20 m, d) for *D*=10 m, *H*=25 m, e) for *D*=10 m, *H*=30 m, f) for *D*=10 m, *H*=35 m

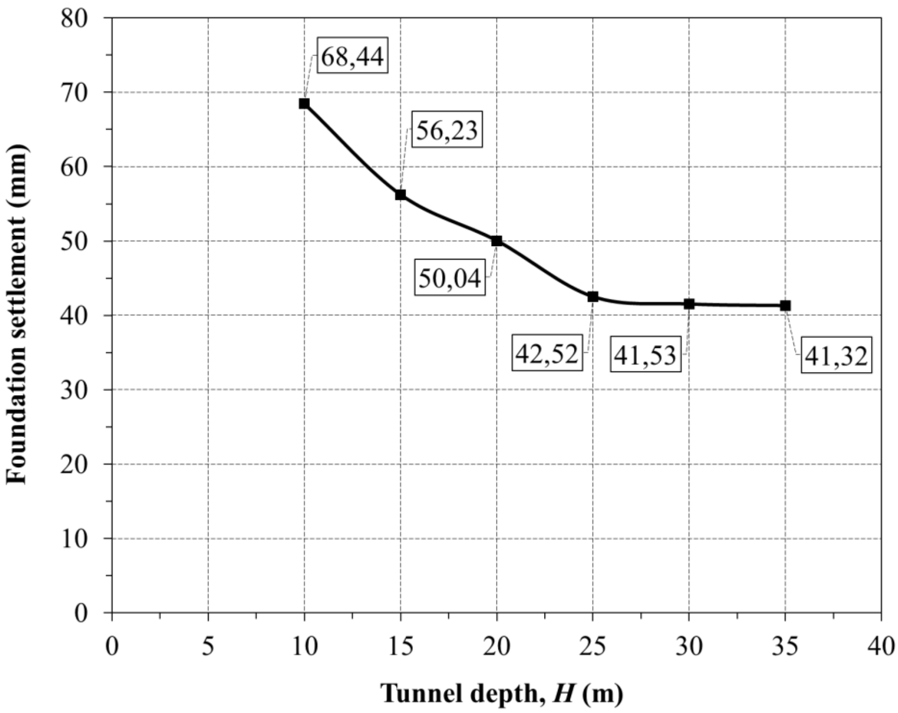

Figure 6. Tunnel depth-foundation settlement curve

3.2. Effect of Tunnel Diameter (*D*)

One of the main parameters of tunnel design is the tunnel diameter, which has a great effect on ground surface settlements. In the numerical analyses, the tunnel diameter is denoted as '*D*', and the depth is analyzed for *D* = 10, 15, 20 and 25 meters. In this series of analyses, the tunnel depth and foundation width were considered as *H* = 25 m and *B* = 10 m, respectively. The amount of surface load caused by the superstructure is 80 kN/m^2, and the variable parameter is only the *D*.

Figure 7 shows the relationship between tunnel diameter and vertical displacement. It is seen that as the tunnel diameter increases, the vertical displacements in the clay soil increase. When the minimum tunnel diameter is 10.0 m, the vertical displacements in the clay soil are 63.51 mm, and when the maximum tunnel diameter is 25.0 m, the vertical displacements in the clay soil are 151.16 mm. Therefore, it can be said that the increase in vertical displacement in the clay soil is directly related to the *D*, and the settlements increase as the tunnel diameter increases.

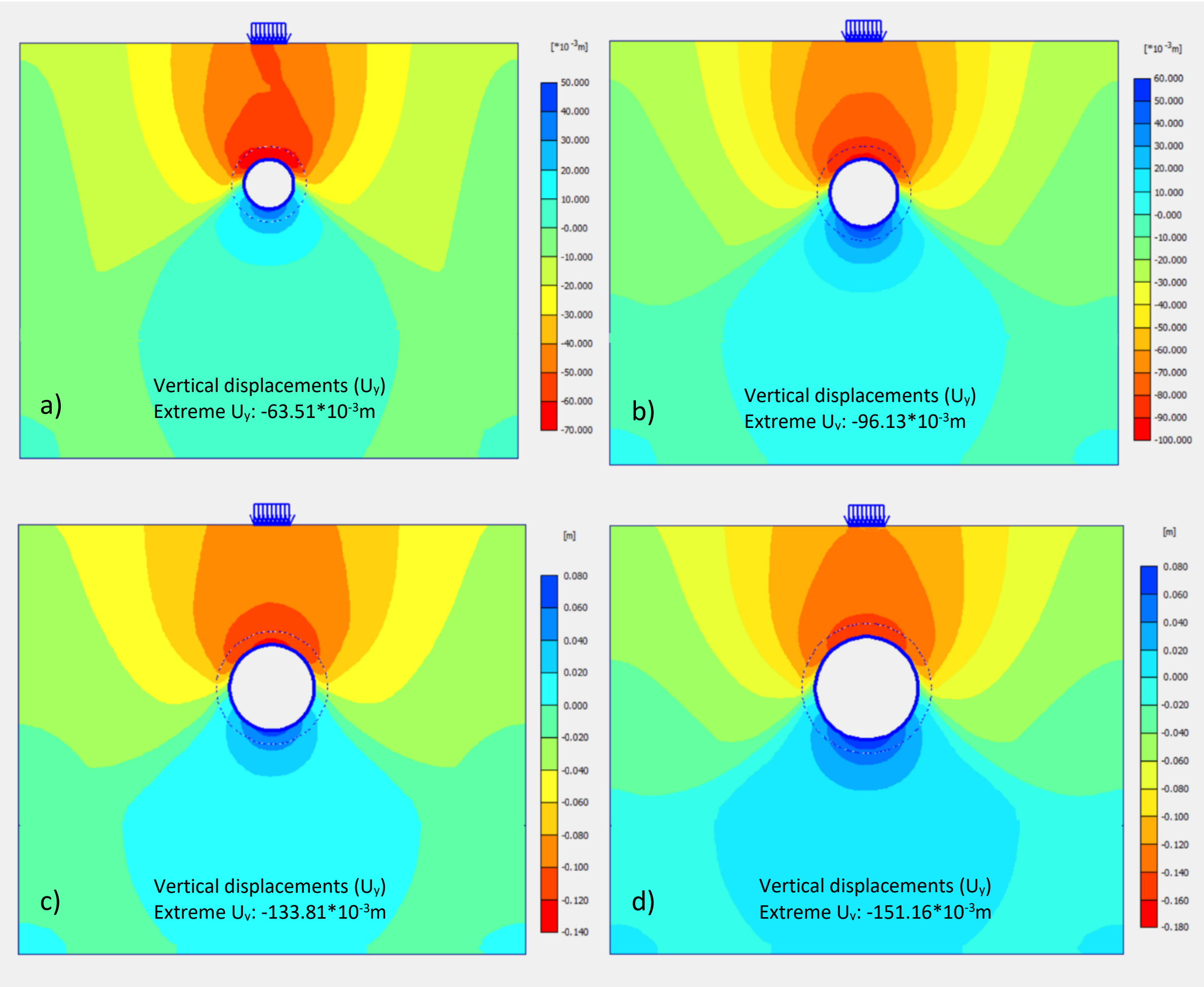

Figure 7. General presentation of vertical displacements (U_y) a) for *D*=10 m, *H*=25 m, b) for *D*=15 m, *H*=25 m, c) for *D*=20 m, *H*=25 m, d) for *D*=25 m, *H*=25 m

In Figure 8, the relationship between tunnel diameter and foundation settlement of the superstructure is presented graphically. It is clearly seen that as the tunnel diameter (*D*) increases, the settlement of the superstructure foundation increases. Increasing the tunnel diameter from 10 m to 25 m increased the settlement of the superstructure by 166%. Our risk assessment, as detailed in Table 3, provides a clear path forward: a tunnel diameter below 10 meters (*B*) is not only safe but also ensures that the settlement of the structure remains within acceptable values. This finding should instill confidence in the project's progress. However, if the tunnel diameter exceeds 10 meters (*B*), for example, 20 meters (2*B*), the settlements increase considerably and significant structural damage may occur.

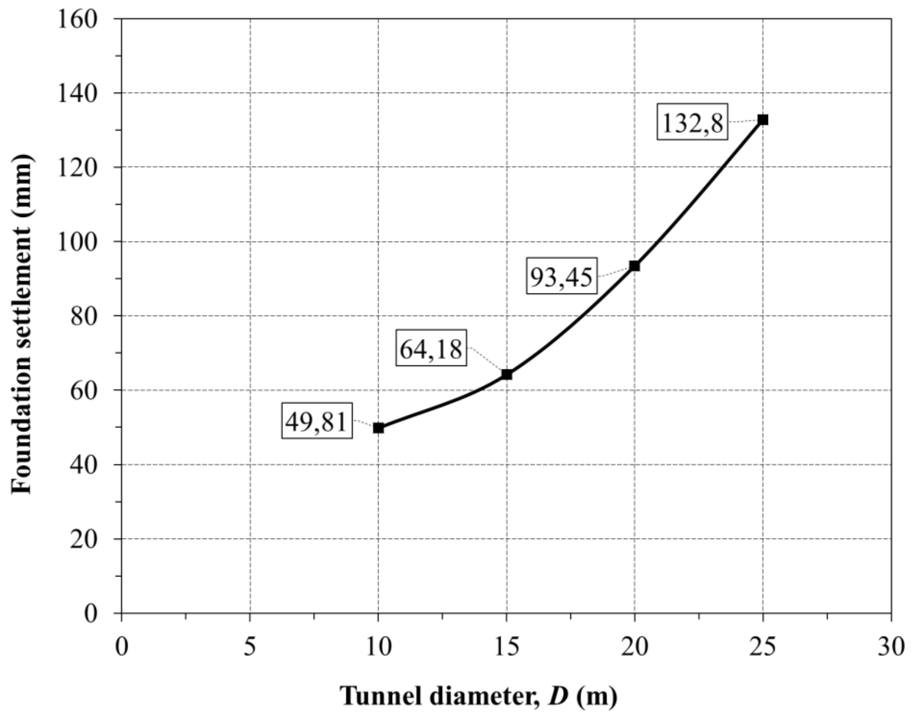

Figure 8. Tunnel diameter-foundation settlement curve

3.3. Effect of Epicentric Distance (*L*)

In the numerical analyses, the epicentric distance of the tunnel to the centre of the structure foundation is denoted by '*L*' and was investigated for $L = 0$, 10, 20 and 30 meters. In this series of analyses, the tunnel depth, tunnel diameter and foundation width were considered as $H = 25$ m, $D = 10$ m and $B = 10$ m, respectively. The amount of surface load caused by the superstructure is 80 kN/m^2, and the only variable parameter is the epicentric distance (*L*) of the tunnel from the centre of the structure foundation. Figure 9 shows the relationship between tunnel epicentric distance and vertical displacements. As the epicentric distance of the tunnel from the centre of the foundation increases, the vertical displacements in the clay soil decrease. When the lowest epicentric distance is 0.0 m, the settlement at the foundation is 43.91 mm and when the highest epicentric distance is 30.0 m, the settlement at the foundation is 43.83 mm. Hence, it can be said that the vertical displacements in the clay soil are indirectly related to the epicentric distance of the tunnel to the foundation up to a certain distance, and the vertical displacements in the clay soil partially decrease as the epicentric distance of the tunnel to the centre of the foundation increases. This is thought to be due to the shrinkage and vertical soil movements around the excavation diameter of the tunnel.

In Figure 10, the relationship between the epicentric distance of the tunnel and the foundation settlement of the superstructure is presented graphically. It is notoriously seen that as the epicentric distance (*L*) of the tunnel from the foundation of the structure increases, the settlements in the foundation of the structure decrease. Increasing the tunnel epicentric distance from 0 m to 30 m reduced the settlement of the superstructure by 49%.

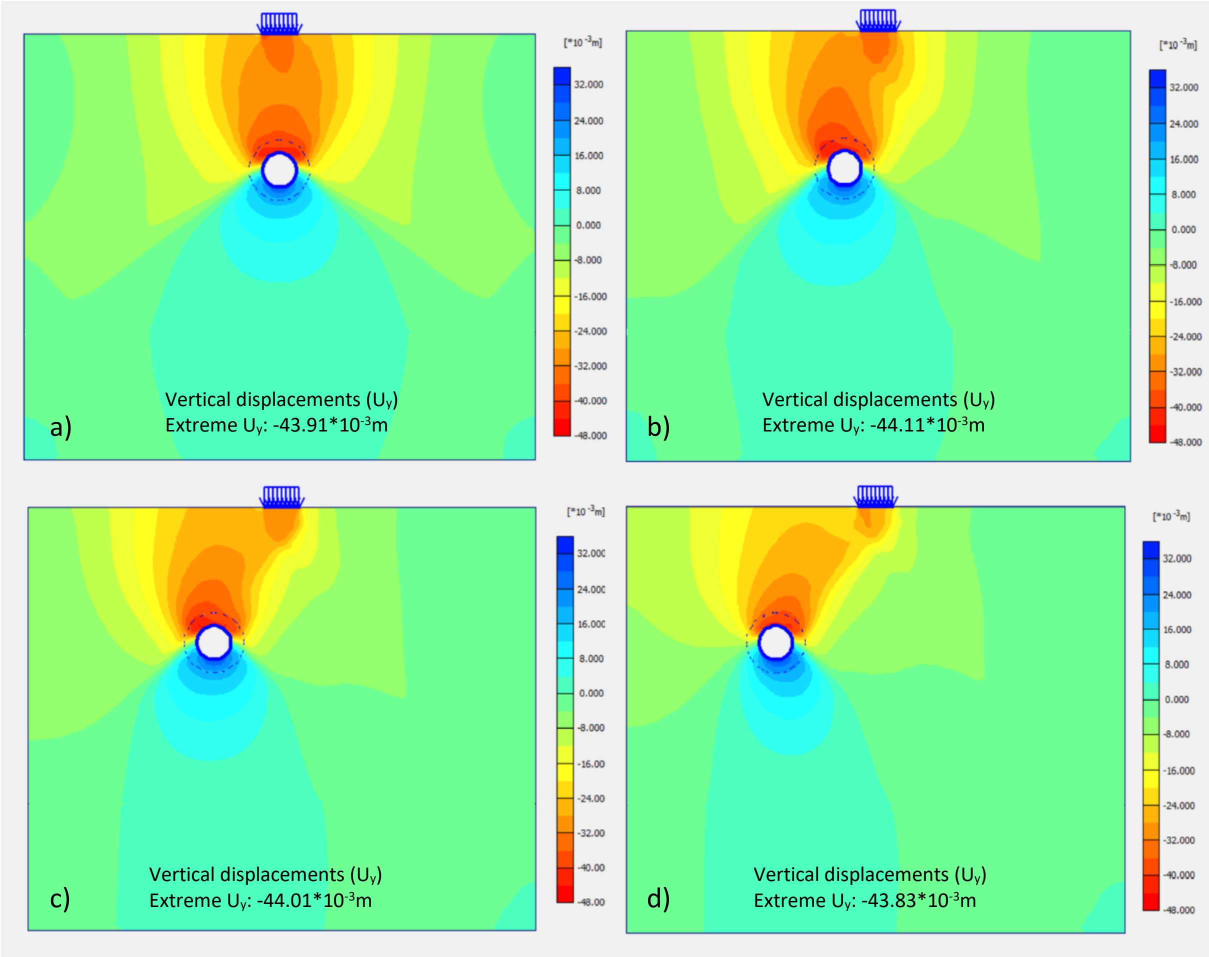

Figure 9. General presentation of vertical displacements (U_y) a) for *D*=10 m, *H*=25 m, *L*=0 m, b) for *D*=10 m, *H*=25 m, *L*=10 m, c) for *D*=10 m, *H*=25 m, *L*=20 m, d) for *D*=10 m, *H*=25 m, *L*=30 m

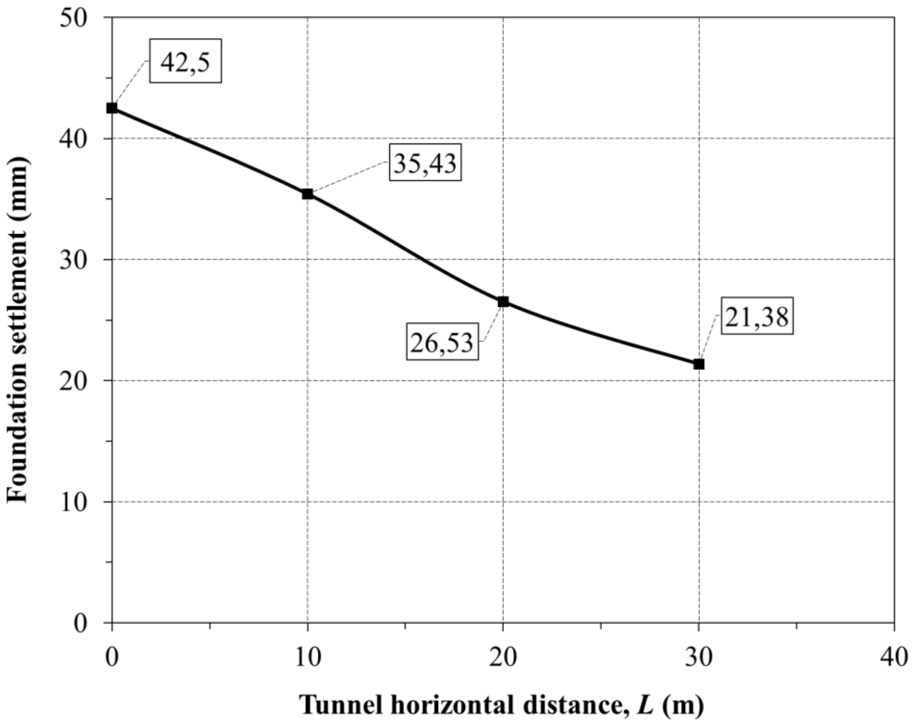

Figure 10. Tunnel epicentric distance-foundation settlement curve

3.4. Effect of Foundation Width (*B*)

One significant parameter in tunnel design is the foundation width, and it is important to evaluate the foundation width in terms of settlements. In the numerical analyses, the foundation width is denoted by '*B*', and the width is analyzed for *B* = 10, 20, 30 and 40 meters. Tunnel depth of 25 meters and tunnel diameter of 10 meters were considered in the analyses. The amount of surface load caused by the superstructure is 80 kN/m^2, and the only variable parameter is the width of the foundation (*B*). Figure 11 shows the relationship between the width of the foundation and the vertical displacement due to tunnelling in clay soil. When the minimum foundation width was 10.0 m, the vertical displacements in the clay soil were 43.91 mm, and when the maximum foundation width was 40.0 m, the vertical displacements were 46.01 mm. Hence, it can be said that the vertical displacements in the clay soil are indirectly related to the foundation width of the tunnel to the foundation up to a certain foundation width, and the vertical displacements in the clay soil partially increase as the width of the foundation. This is thought to be due to the shrinkage and vertical soil movements around the excavation diameter of the tunnel.

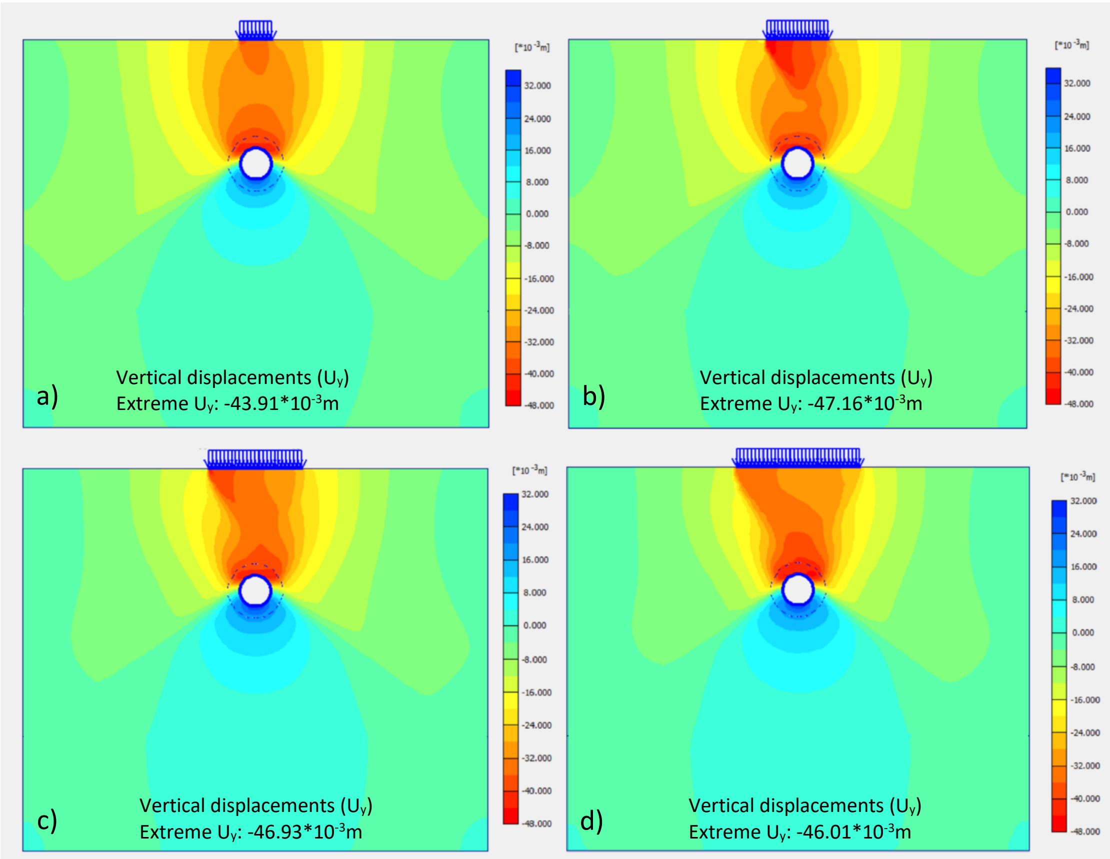

Figure 11. General presentation of vertical displacements (U_y) a) for *D*=10 m, *H*=25 m, *B*=10 m, b) for *D*=10 m, *H*=25 m, *B*=20 m, c) for *D*=10 m, *H*=25 m, *B*=30 m, d) for *D*=10 m, *H*=25 m, *B*=40 m

Figure 12 shows the relationship between foundation width and superstructure settlement for clayey soil in which a tunnel was constructed. It can obviously be seen that the settlements increased with increasing foundation width up to *B* = 20 m, while the settlements decreased with increasing foundation width after *B* = 20 m up to *B* = 40 m. The settlements in the superstructure were reduced by 18% by increasing the foundation width. Our risk assessment, as detailed in Table 3, provides a clear path forward: a foundation width over 40 meters (4*B*) is not only safe but also ensures that the settlement of the structure remains within acceptable values. This finding should instill confidence in the project's progress.

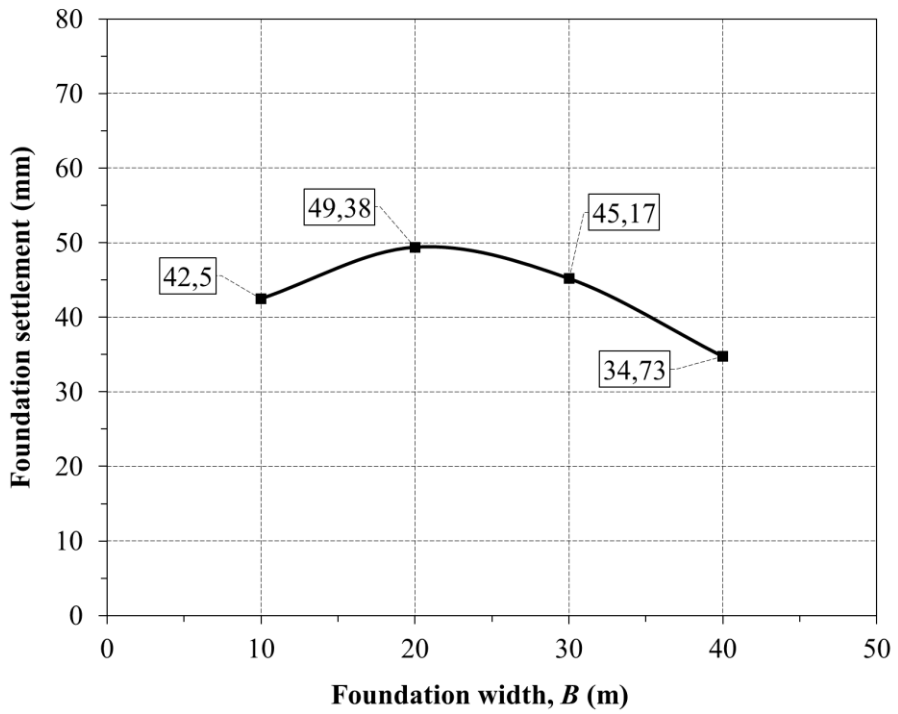

Figure 12. Foundation width-foundation settlement curve

4. Conclusion

In this study, the cross-section of a single tunnel was modelled and analyzed employing the Plaxis 2D program depending on the FEM, considering the geometrical and mechanical properties of the clay soil and tunnel system. As a result of 4 stages of finite element analyses (initial, structure, tunnel and shrinkage), the vertical displacements and foundation settlements of the clay soil due to tunnel excavation for a tunnel constructed by the TBM method were obtained for different parameters. For a single tunnel line, sample modelling was carried out to examine the deformations in the ground by changing the parameters that will affect the deformations in the ground. In two-dimensional analyses, the cross section was taken in 90 m x 110 m dimensions. Excavation diameter (10, 15, 20 and 25 m), cover thickness (10, 15, 20, 25, 30 and 35 m), foundation width (10, 20, 30 and 40 m) and epicentric distance of the tunnel to the structure foundation (0, 10, 20 and 30 m) were analyzed in the geometric model. The main results obtained from this study are as follows:

- As the tunnel diameter (*D*) increases, the vertical displacements in the clay soil increase. When the tunnel diameter increased from 10 m to 25 m, the settlements of the superstructure increased by 166%.
- As the epicentric distance (*L*) of the tunnel to the foundation of the structure increases, the vertical displacements of the soil surface decrease. Increasing the epicentric distance of the tunnel from 0 m to 30 m decreased the settlements in the foundation by 49% due to tunnel excavation.
- By the way of the tunnel depth (*H*) increases, the vertical displacements in the soil decrease. When the tunnel depth increased from 10 m to 35 m, the settlement of the foundation decreased by 39%. It can also be said that the amount of settlement is inversely proportional to the tunnel depth, and its effect on the superstructure is limited after $H = 25$ m.
- The settlement of the building foundation decreased as the foundation width increased, especially from $B = 20$ m up to $B = 40$ m. Increasing the foundation width reduced the settlements occurring in the superstructure by 18%.

Author Contributions

B. Ateş: Methodology; investigation, numerical analysis; software; data processing; writing-original draft; **E. Şadoğlu**: Supervision; methodology; data processing; writing-original draft and editing.

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Conflict of Interest

All the authors declare no conflict of interest.

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