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Numerical modeling of shallow tunnels: analysis of the surface settlements

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Abstract. The analysis of shallow tunnels is necessarily related to the study of the excavation influence on the ground surface. As the excavation proceeds, surface settlements are expected to be generated, forming the so-called settlement basin. Thereby, its correct evaluation is important since these movements could create disturbances in surrounding structures. Estimation of tunneling-induced ground movements can be done by analytical, empirical, and numerical methods and, currently, the best assessment of tunneling process consists of finite element modeling. The current paper presents a numerical model elaborated in the software ANSYS with the aim to evaluate the surface settlements induced by tunneling. The 3D finite element model concerns soil and lining elements, using the activation and deactivation tool to simulate the excavation and lining placement. To perform the analysis, the soil mass was represented by a plastic model using the Drucker Prager criterion and the concrete lining is considered elastic. Five reported cases of real tunnels (Heathrow Express, Green Park, Barcelona Subway, Brasília Subway, and São Paulo Paraíso tunnels) are simulated to validate the model with analytical and experimental solutions.

Keywords: tunneling, settlement basin, finite elements method, underground structures

1 Introduction

Increasing concern about the environment, preservation of free areas in the surface, and improvement in urban mobility imply the choice of underground structures instead of surface ones. In this context, tunneling design and construction set relevant issues, since the project should consider the minimization of environmental impacts, as well as economic, social, and safety aspects. For shallow tunnels in urban areas, special attention should be given to surface settlements, which can affect the foundation of nearby buildings.

A tunnel excavation generates a disturbance in the natural stress state of the soil mass, inducing a new equilibrium configuration that mobilizes tangential stresses. The change in the stress state causes movements in the surrounding soil mass. In the case of shallow tunnels, these movements propagate to the ground surface, forming the so-called settlement basins.

Estimation of tunneling-induced ground movements remains a challenge, since it involves many variables and uncertainties, as the complex construction procedures and the ground conditions. Currently, the best assessment of tunneling process consists of finite element modeling which simulates the excavation step by step. Numerical modeling often presents several advantages: allows either 2D or 3D analysis, implementation of different constitutive models for soil mass and lining material, consideration of a nonlinear behaviors, simulation of different cross-sectional shapes, and simulation of the construction procedures.

In this paper, the authors present a 3D numerical model elaborated in a finite element software (ANSYS). The soil mass is represented by an elastoplastic model, considering the Drucker Prager criterion, and the lining, in concrete, is considered with linear elastic behavior. The purpose of the analysis is to predict the soil mass settlements and assess the distinctions between shallow and deep tunnels. Then, to validate the model, five analytical and experimental solutions available are used for comparison, considering real tunnels: Heathrow Express Tunnel, Green Park Tunnel, and Barcelona Subway Network Extension (Loganathan and Poulos [1]); Brasilia Subway (Ortigão et al. [2]); and São Paulo Paraíso Tunnel (Machado [3]).

2 Shallow tunnel characteristics

In contrast with deep tunnels, which present a radial uniform closure, shallow tunnels are subjected to an oval-shaped distortion. Additionally, its stress state can be considered dependent on lateral earth pressure. In practice, the distinction between these two types of tunnels is usually taken from the relation between their depth (H) and their cross-sectional diameter (D), although there is no accordance about the H/D limit to consider the tunnel as a shallow one.

Due to the influence of the proximity with the free ground surface, the cross-sectional deformation of a shallow tunnel is ovalized, and not only related to the volume change of the cavity. Actually, the final deformed shape is associated also to two other displacement components: a distortion and a vertical translation (Pinto and Whittle [4]). Thus, the displacements symmetry found in every point of a deep tunnel deformed cross-section, which causes only compressive stresses, is not observed in shallow tunnels. Instead of this, the lining of shallow tunnels may show bending-compressive stresses, making it more susceptible to the appearance of cracking if the lining is in concrete (Jensen et al. [5]).

2.1 Surface settlements

Another feature that defines a tunnel as shallow is the order of magnitude of the surface settlements. Deep tunnels usually do not cause a great disturbance on the ground surface, presenting a maximum settlement with an irrelevant magnitude. Despite this, the displacements extend for a greater distance from the axis of the tunnel. Shallow tunnels, in turn, show a less extensive settlement basin, but with considerable maximum displacements.

The evaluation of surface settlements in tunnels is done, usually, by three main methods: empirical, analytical, and numerical. Empirical methods (i.e.: Peck [6], Attewell and Farmer [7]; Atkinson and Potts [8]; O'Reilly and New [9]; Mair et al. [10]) are based on experimental data and field observations, taking account a limited number of parameters (such as the excavation size and depth, some ground conditions, and the ground loss volume). Analytical methods (i.e.: Verruijt and Booker [11]; Loganathan and Poulos [1]; Dormieux et al. [12]; Chou and Bobet [13]; Park [14]) are based on simplifyed assumptions in terms of geometry, ground characteristics, constitutive models, and boundary conditions. Finally, numerical methods (i.e.: Rowe and Kack [15]; Rowe and Lee [16]; Galli et al. [17]) aim to achieve displacements on every point of the soil mass around the excavation and allow an analysis which considers all tunnel characteristics, as geometry, initial stresses, behavior laws of both soil mass and lining, excavation phases, and other details.

In the empirical methods, the settlement basin cross-section is usually approximated by an inverse Gaussian curve, as proposed by Peck [6] and often quoted in the current tunnel engineering literature. Considering this assumption, the transversal settlement function $(u(u_{\max}, x, i))$ is given by the eq. (1):

$$u = u_{\max} \exp\left(-\frac{x^2}{2i^2}\right) \tag{1}$$

where u_{max} is the maximum settlement over the tunnel axis, x is the distance to the tunnel axis and i is the inflection point in the normal distribution curve.

The inflection point (i) is often related to the depth and the radius of the tunnel, as in the solutions of Peck [6], Attewell and Farmer [7], Atkinson and Potts [8], O'Reilly and New [9], and Mair et al. [10]. The type of soil is also included in some proposed equations. From Peck [6], the solution of this parameter is given by eq. (2):

$$\frac{i}{R} = \left(\frac{H}{2R}\right)^n \tag{2}$$

where R is the radius of the tunnel, H is the depth and the parameter n depends on soil properties, ranging from 0.8 to 1, according to the abacus presented in Peck's [6] study.

Tunnel excavation causes stress relief in the soil surrounding the cavity and, consequently, the soil mass moves toward the excavation. These ground movements are characterized by another parameter used to assess the surface settlement, called volume loss (V_L). The volume loss can be obtained from the settlement basin volume (V_S) (area of the Gauss curve in one meter, given by eq. (3)). According to Pinto and Whittle [4], these two cited volumes were frequently equated ($V_L = V_S$).

$$V_S = 2.5 \cdot i \cdot u_{\max} \tag{3}$$

where i is the inflection point and u_{max} is the maximum settlement.

3 Modeling of tunnel excavation

Three-dimensional modeling is almost mandatory when it comes to correctly evaluate the effects of tunnel excavation process. This type of procedure is under continuous development and being applied to increasingly complex problems. Galli et al. [17]; Villalba Fiore et al. [18]; Machado [3]; Liu, Li and Wang [19] and Mroueh and Shahrour [20] are some of the authors that present studies considering 3D finite element models of tunneling excavation. These studies consider different aspects of tunnel engineering, as shallow or deep tunnels, elastoplastic or viscoplastic conditions for the soilmass (or rockmass), different lining settings and construction processes (phasing excavation, for example).

The model used in this paper is created with the software ANSYS. Meshing is done with the finite element SOLID185, used for 3D modeling of solid structures. It is an eight-node element with linear interpolation and each node has three degrees of freedom: translation in the nodal x, y, and z directions. This element allows analysis considering: elasticity, plasticity, viscoplasticity, large deflection, and other characteristics. The mesh characteristics are shown in Fig. 1.

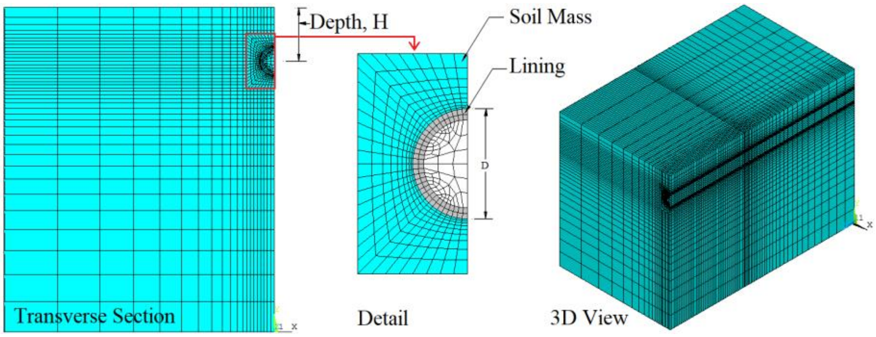

Figure 1 - Three-dimensional model for tunneling.

The tunnel construction process simulation is done by 37 excavation steps, which measure, each one, one-third of the external tunnel radius. The final model has an excavated and an unexcavated part. A duplicated mesh is generated in the lining region and, then, the excavation and lining placement procedures are simulated by the activation/deactivation method. This method is applied by Birth and Death commands (deactivating soil elements and activating concrete elements, considering the unsupported length).

As boundary conditions, the mesh has a restriction of translation in Y in the lower face and in Z in the front face. A symmetry condition is employed in ZY plan, allowing to simulate half of the total geometry. The loads ($P_v = \gamma \cdot H$ and $P_h = K \cdot P_v$) are applied taking into account the soil specific weight (γ), the depth of the tunnel (H) and the earth pressure coefficient (K). A geostatic initial condition is also applied for the soil elements, with the same values and opposite direction of P_v and P_h, in order to ensure null displacements in the unexcavated soil mass.

To represent the soil mass, an elastoplastic behavior was adopted, considering the Drucker Prager criterion. For that, the main parameters used were the cohesion (C) and the friction angle (φ), besides the elastic modulus (E) and the Poisson coefficient (ν). The lining was considered in concrete, adopting a linear elastic behavior.

A preliminary analysis is conducted to evaluate the most appropriate H/D relation to differentiate shallow and deep tunnel, varying the depth of an example of a circular tunnel ($R_e = 1\ m$) in elasticity ($E = 35\ MPa$, $\nu = 0.5$, $\gamma = 19\ kN/m^3$). So, the results of radial displacements are compared to the ones given by Bernaud and Rousset's solution [21], which is formulated to deep tunnels, in order to determine in which H/D relation the two solutions approach.

Figure 2 presents the convergence curves (radial displacements along the tunnel), for different H/D relations. The continuous lines represent the results obtained by the numerical model elaborated in this study (with the software ANSYS), while the dashed lines represent the results obtained by Bernaud and Rousset's [21] formulation (using the code GEOMEC91). By analyzing the results, it is possible to observe that the convergence solution gets closer to the one given by Bernaud and Rousset [21] when $H/D = 5$ (relative difference equals 6,90% considering the equilibrium value), becoming identical when $H/D = 10$. Considering that the solution of these authors is valid for deep tunnels, it's possible to say that there is a transition zone between deep and shallow tunnels in the range of these two values of H/D.

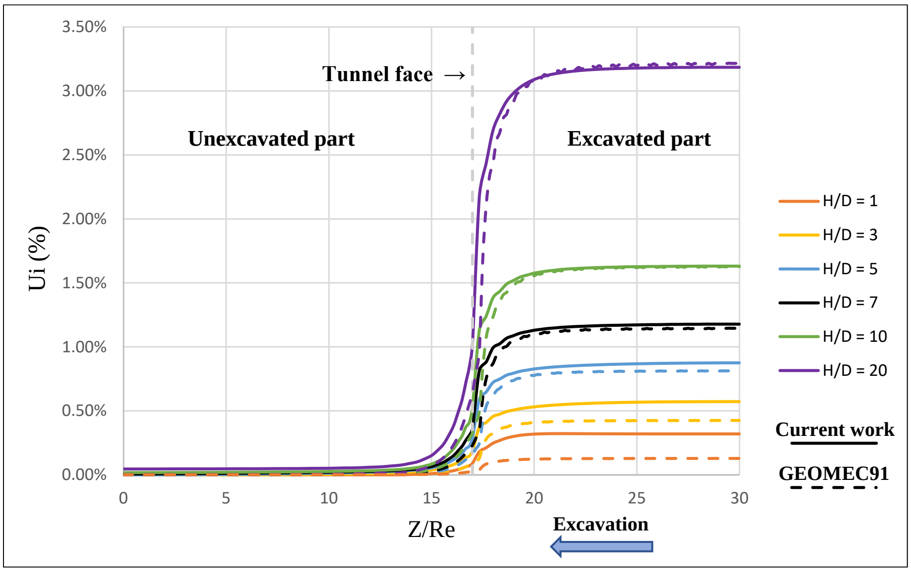

Figure 2 - Convergence curves according to H/D: comparison between Ansys (current paper) and GEOMEC91 (Bernaud and Rousset's [21]) results.

With regard to the settlement basin and the depth influence, two characteristics could be analyzed: the maximum settlement, bigger for shallow tunnels, and the extension, bigger for deep tunnels. Figure 3 shows the settlement basins, for different H/D relations (the curves show half of the basin since the displacements are symmetric in relation to the tunnel axis).

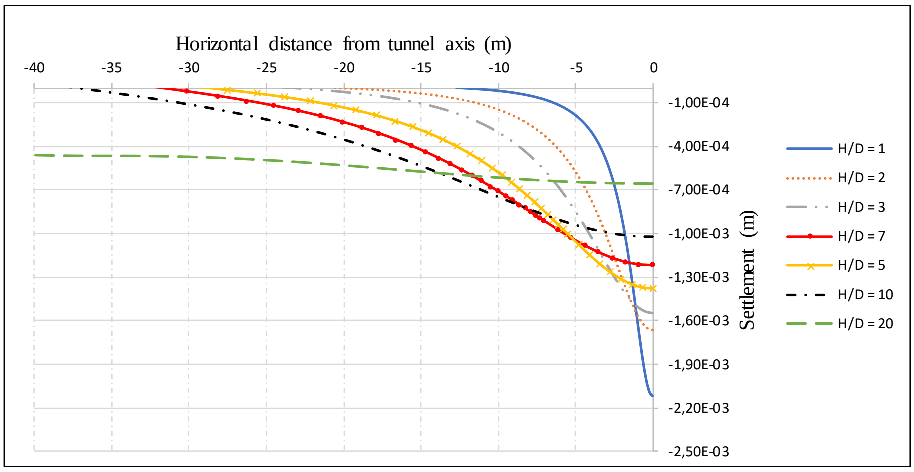

Figure 3 - Settlement basins according to H/D relation.

4 Simulation of real tunnels

In the items below, the five real tunnels analyzed in this paper are presented, bringing some details about the construction, geometry, and materials. For simplification, in the numerical model the lining is treated as homogeneous and with a linear elastic behavior in all tunnels ($E = 30\ GPa$ e $\nu = 0.3$). The numerical results of this study are compared with experimental data presented in the bibliography and with another analytical or numerical result (depending on the example).

4.1 HEATHROW EXPRESS TRIAL TUNNEL

Situated in London (UK), the Heathrow Express Trial Tunnel provides a high-speed rail link between the center of the city and the Heathrow Airport. The $8\ km$ of length tunnel was the first to use the New Austrian Tunneling Method (NATM) in the stiff London Clay, with three different sequences of excavation. The tunnel permanent lining is provided by rings of expanded precast concrete. With $8.5\ m$ of diameter and $19\ m$ of depth ($H/D = 2.2$) the Heathrow Express Trial Tunnel can be considered as a shallow tunnel. The numerical model has been assessed considering the average soil parameters available on Deane and Bassett [22] (source of experimental results) and Loganathan and Poulos [1] (source of analytical results).

4.2 GREEN PARK TUNNEL

Green Park is another London (UK) underground metro tunnel, which has $4.15\ m$ of diameter, approximately $29.4\ m$ of depth and was excavated in the stiff, fissured, heavily overconsolidated London clay (Rowe and Lee [16]). This tunnel was mined by hand excavation and the support is provided by a seven-segmented, bolted, cast-iron lining. This tunnel has a ratio cover ($H/D = 7$) situated in the transition zone (between $H/D = 5$ and $H/D = 10$) established before to consider the tunnel as deep or shallow. Most of the geotechnical parameters adopted by Loganathan and Poulos [13] (analytical results) are described also by Attewel and Farmer [2], the source of the experimental results.

4.3 BARCELONA SUBWAY NETWORK EXTENSION LINE

This subway tunnel with $8\ m$ of diameter was built in 1993 in Barcelona, Spain. The area corresponds to the geological contact between the Besós deltaic zone (gravel and silty sands) and the Barcelona plane deposits (red clay with calcareous inclusions) (Ledesma and Romero [23]). The tunnel was mechanically excavated under a jet-grouting top in a few stages. With $10\ m$ of depth ($H/D = 1.25$), the Barcelona Subway Network Extension Tunnel is shallow. Soil parameters and experimental data are the same used by Loganathan and Poulos [13] and came from the experimental study of Ledesma and Romero [23].

4.4 BRASÍLIA SUBWAY NETWORK TUNNEL

Concentrated in the South-wing of the city of Brasília - Brazil, this tunnel has $9.6\ m$ of equivalent diameter (with a horseshoe shape) and was built in a depth of $14\ m$. According to Ortigão et al. [2], the tunneling method used in Brasília had the following stages: excavation, placement of ribs, shotcreting the primary layer of the lining, closing the invert, and finally placing the final (secondary) layer of the lining. Based on its characteristics ($H/D = 1.46$), the Brasília Subway Network Tunnel is classified as a shallow tunnel. For this tunnel, the results are compared only with experimental values obtained by Ortigão et al. [2].

4.5 PARAÍSO SUBWAY NETWORK TUNNEL

The Paraíso metro tunnel is located close to the Paulist Avenue in São Paulo – Brazil and integrates the Line 2 of the city's subway network system. The excavated section is an ellipsoid with $8.41\ m$ of horizontal and $11.5\ m$ of vertical radius, equivalent to a $9.84\ m$ diameter tunnel. The height of the Paraíso tunnel is $7.6\ m$ and, according to its characteristics ($H/D = 1.22$), is considered as a shallow tunnel. The tunnel was excavated in the sedimentary typical Sao Paulo red clay with the construction process based on NATM and the use of metallic profiles and shotcrete as support. Soil parameters are the same used by the numerical study of Machado [3], and the experimental results based on Almeida and Sousa [24].

4.6 Results

Table 1 presents the maximum surface settlement results obtained in current work, in reference studies and the experimental data (identified "observed"). The inflection point is another value that could be analyzed and compared. By using these two values, it is possible to calculate the settlement volume (V_S) by eq. (3) presented before and, with the relation between V_S and the volume of the excavation, is obtained the volume loss (V_L), in %.

Table 1 - Comparison of Estimated and Observed Surface Settlement Basin Parameters

Tunnel	**H/D**	**Maximum surface settlement (mm)**			**Inflection point (m)**		**Volume loss (%)**
		Reference	**Current study**	**Observed**	**Reference**	**Current study**	
Heathrow Express	2.22	36.3	38	39	10.1	10	1.67
Green Park	7	5.8	5.5	6	13.9	15	1.53
Barcelona Subway	1.25	23.2	24.7	24	5.6	6	0.74
Brasília Subway	1.46	300	289	300	8	8.5	8.48
Paraíso Subway	1.22	70	68	84	9	9	2.01

In general, the results present good agreement between the model elaborated in the current study and the studies of reference (including analytical and experimental models). The only relevant percentual error (19.05 %) is found in relation to the Paraíso tunnel experimental result of maximum surface settlement. However, the value is very similar with Machado's [3] study result, which mentions that the instrumented settlements results for this tunnel case could be intensely disturbed by neighboring buildings and foundations.

5 Conclusions

There are several peculiarities about the tunnels closest to the surface, such as its greater influence on the free ground. To consider a tunnel as shallow, its relation between its depth and its diameter (H/D) is generally used. Thus, this study performed an analysis in which the results of the model elaborated in ANSYS software were compared with those of a deep tunnel code (Bernaud and Rousset's [21]). From this analysis, it was concluded that there is a transition zone between the relations $H\ /\ D\ =\ 5$ and $H\ /\ D\ =\ 10$, since from these values the solutions begin to approach, being identical when $H\ /\ D\ =\ 10$. Additionally, it was possible to verify the influence of the depth in the surface settlement characteristics. For shallow tunnels, the maximum settlement presented bigger values and the extension of the basin was shorter. As the tunnel became deeper, displacements decreased and the basin became wider.

The influence of an excavation on the ground surface depends also on the soil conditions, as seen in the cases analyzed in the present study. The solution for Brasília clay, for example, performed high settlements due to a low-resistance soil and low covering ratio ($H/D\ =\ 1.22$). On the other hand, the Green Park tunnel, considered as deep ($H/D = 7$) and excavated in the stiff London clay, developed a small surface settlement.

Current design practice to predict tunneling-induced ground movements is based primarily on empirical methods, which have several limitations, such as their applicability to the different conditions presented by tunneling: varied geometries, ground conditions, and excavation techniques. Although the model used in this article also has some limitations, as considering an average soil sample for simulate the tunnels, disregarding the stratification of the soil mass, adopting a simple lining in concrete with linear behavior and disregarding the pore-pressure effects, the results performed good agreements of settlement basins in most of the tunnels analyzed.

By using this numerical model, it is also possible to assess the cross-section displacements and the longitudinal settlement basin. So, it is a useful model to assess the three-dimensional behavior of tunneling. Otherwise, it is possible to improve it, by setting the varying characteristics of the soil through either the layering of the soil or inputting the parameters as functions of the site conditions.

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