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Numerical Simulation of the Mechanical Response of the Tunnels in the Saturated Soils by Plaxis

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ABSTRACT

The forecast of settlement and movements caused by tunneling represents a significant challenge of technology. The evaluation of these movements is indeed of primary importance in order to prevent them.

The methods of calculation making it possible to evaluate displacements and deformations in the ground due to tunneling give only one approximation of the true amplitudes of the movements in the ground. It is one of the assets of the Finite Element Method (FEM) which makes it possible *a priori* to treat configurations more complex and closer to reality.

Our objective in this study is to calculate numerically the various movements caused by the construction of a shallow tunnel using a shield using PLAXIS 2D, the behavior of the ground is described by a perfectly plastic elastic model based on the criterion of Mohr-Coulomb. A comparison between the various methods: empirical, analytical and numerical in terms of settlement on the surface was carried out. The validation of these results was made by using results drawn from literature.

We have also carried out a parametric study in order to analyze the influence of various geometrical and geotechnical parameters on the behavior of grounds due to tunneling.

Lastly, we have treated the same example by supposing the existence of structures near the tunnel in order to see the influence of the presence of other structures on the profile of the settlements caused by tunneling. Results of our work agreed with those in literature.

KEYWORDS: Tunneling, Plaxis 2D, Settlement, Parametric studies, Interaction.

INTRODUCTION

The development of great agglomerations and the increasing densities of urbanization led to an increasingly frequent use of underground; the only solution is to extend the communication network and to free it from obstructions of the roadway system. However, this construction is a complex process generating many events in the ground. Indeed, progressively with the advance of tunneling, construction generates displacements and deformations causing instabilities in the ground. In urban sites, these disorders can have considerable human and economic consequences. Among the current objectives of research in the field of underground works is the improvement of the forecast of movements induced in the soil by the

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construction of tunnels and in particular the forecast of the potential effects of work on the overlying structures. These problems constitute strong stakes for the underground projects.

Our work developed in this set of themes constitutes, initially, a contribution to the numerical studies of the influence of the construction of a tunnel on the ground from the point of view of settlements and horizontal movements without the existence of a possible superficial structure, by adopting a perfectly plastic elastic law based on the criterion of behavior of Mohr-Coulomb. We also seek to determine the influence of geometrical and geotechnical parameters on the mechanical behavior of the ground.

As a last initiative, we propose to supplement our work by the treatment of the same example in the event of the existence of other structures.

Our goal is to understand this delicate phenomenon and to see the influence of tunneling on the pace of settlements on the surface in the presence of other structures.

Phenomenon of Settlement Due to Tunneling and its Modeling

Settlements of surface result from a double mechanism of interaction ground structure: the interaction between the tunnel and the soil, on the one hand, and the interaction between the soil and its surrounding, on the other (Magnan and Serratrice, 2002).

In our article, we studied the case of a shallow tunnel, and in this case there are various arrivals of ground caused by digging, tending to be propagated towards the surface, where they result in settlements and horizontal displacements on the surface affecting the behavior of existing works. Horizontal displacements tend to follow the face, by changing direction with advance, but few work treated the calculation of these displacements by empirical methods. Acceptable ranges of settlements on the surface for tunnels were observed going from 25 to 40 mm for sand and from 40 to 65 mm for clay (Dolzhenko, 2002).

In addition, *in situ* measurements show that the settlements observed on the surface represent only part of the vertical displacements in the underground. According to Atwa et al. (2001), all these observations were approved by Cording and Hansmire (1977), Ward and Pender (1981), Attewell and Farmer (1977), amongst others. Chapeau (1991) noticed a delay and a damping between settlements of the surface and the in-depth movements. This phenomenon becomes more significant as the height of cover increases. For shallow tunnels, damping is so weak that an error in the procedure of construction can involve a rupture in the block of the cover.

Because of the recent developments in these works, the need for modeling towards a keener demand as regards the forecast of movements induced in the ground was accentuated, whereas the former applications of the numerical models were rather concentrated on the local response of the work (convergence of the walls of the gallery, effort taken again by the structure of supporting).

However, many research was devoted during the last years to the development of models of calculation allowing better taking in account the characteristics of the behavior of the ground in the analysis of the phenomenon of ground-structure interaction suitable for the tunneling in soft soil, mainly with an aim of obtaining forecasts of the settlements caused on the surface by the construction of shallow tunnels. The numerical methods, by their flexibility, have proved to be effective for the study of these movements. They are employed in a quasi-systematic way and impose a good knowledge of displacements of the ground and efforts applied, making it possible to validate the choices carried out or to compare different methods of digging (Dias, 1999).

However, the application of these methods to modeling of tunnels is delicate because of the three-dimensional aspect of the behavior of the ground around the coal face and the complexity of requests induced in the soil by work (Atwa et al., 2001). The use of a two-dimensional model compared to a 3D model proved more advantageous from the points of view that the 2D model is less expensive in computing times, the interpretation of the results is easier and the model of behavior is more complex. Nevertheless, the 3D model remains most suitable since it takes into account the complete aspects of the problem.

Considering the complexity of the movements resulting from tunneling, it appears necessary for the determination of these movements to have a reliable computational tool for the numerical simulation of this extremely delicate behavior.

PRESENTATION OF THE CALCULATION MODEL

It is about a sandy ground which consisted of only one layer, where a tunnel was built. It is a case studied in recent work (Liu, 1997; Kasper and Meschke, 2004; Augarde et al., 1995; Bloodworth, 2002).

The geometry used is that of the model of reference of Liu (1997). The characteristics of the model are drawn from the literature, and they will be modified one by one in order to see the behavior of the ground in response to each modification.

Our initial objective is to evaluate the movements (vertical and horizontal) generated by the construction of a tunnel by the technique of the shield.

In the presentation of the results, we will be interested in settlements and displacements induced after digging, because the concept of safety in underground constructions relates displacements to constraints (Mroueh, 1998).

In the second part, the problem of the influence of the construction of a tunnel on a building will be exposed at various levels in terms of settlements on the surface. Also, the influence of the presence of the tunnel on another tunnel is studied.

Geometry and Data of the Model

The tunnel is circular with a diameter D equal to 5 m. The soil is an isotropic homogeneous sandy ground (Figure 1). The behavior of the ground is described by a perfectly plastic-elastic model based on the criterion of Mohr-Coulomb. Horizontal and vertical displacements are supposed to be null on the level of the substratum which is at the bottom of the soil horizon. Horizontal displacements are blocked on the lateral sides, the ground water is with y=10m.

With regard to the lining of the tunnel, it is composed of a reinforced concrete ring the mechanical characteristics of which are represented in Table (1). The behavior of the lining is supposed to be elastic-linear.

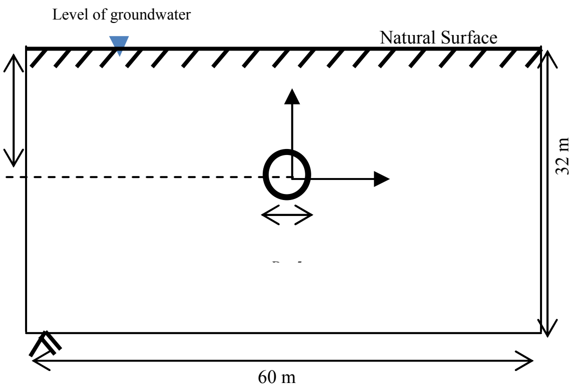


Figure 1: Geometry model

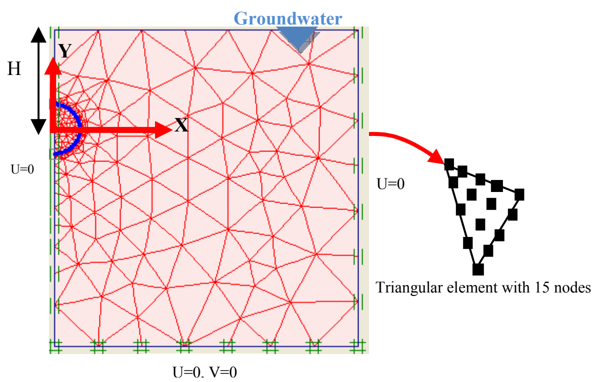


Figure 2: Finite element mesh

Characteristics of Materials

The properties of the ground and the lining which PLAXIS needs to be able to carry out calculations are summarized in Table 1.

Table 1: Characteristics of the soil and lining

Soil properties		Unit
Type of model	Mohr Coulomb	-
Type of behavior	Drained	-
Soil weight above phr.level	17	kN/m^3
Soil weight below phr.level	21	kN/m^3
Young modulus	1.2×10^5	kN/m^2
Poisson's ratio	0.3	-
Cohesion	1	kN/m^2
Angle of friction	33	Degree
Angle of dilatancy	3	Degree
Lining properties		**Unit**
Type of behavior Normal rigidity Rigidity of inflection Equivalent thickness Weight Poisson's ratio	Elastic 1.4×10^7 1.43×10^5 0.35 8.4 0.15	- kN/m kNm^2/m m kN/m/m -

2D FE Numerical Modeling

The mesh selected is presented in Figure 2. In this example, the element with 15 nodes is employed. The model is symmetrical, then, only a half of the model is studied. The mesh includes 320 triangular elements and 2698 nodes.

There must be relatively regular elements and of small size near the tunnel; on the one hand to obtain a good estimate of the initial state and on the other hand to obtain a field of more precise displacement. The mesh will be more refined on the level of the tunnel, because of the concentration of constraints at these places.

Oteo (1982) specifies some criteria in order to obtain good geometrical and mechanical modeling work and high precision in the results. These criteria are as follows:

- The size of the elements around the excavation should be reduced to allow the numerical model to define with precision the results in the vicinity of the tunnel.
- The limits of the model must be placed sufficiently far from the work to study, so that the boundary conditions do not influence or lessen the field of displacements and constraints.

Generation of Hydraulic Conditions

The voluminal weight of water is taken equal to 10 kN/m^3.

The generation of pore water pressure will be carried out starting from the phreatic level (Figure 3).

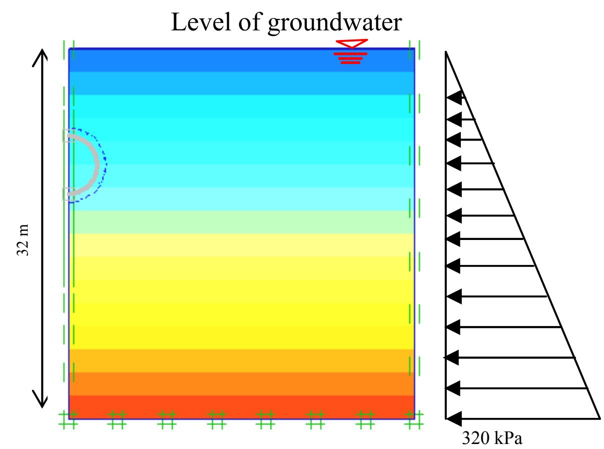


Figure 3: Generation of the initial pore water pressure

Generation of Initial Constraints

In order that PLAXIS calculates the initial constraints, it is necessary to decontaminate the structural elements (tunnel lining), by taking the values of K_0 by defect. The value of the coefficient of grounds at rest is calculated by the software by defect using the formula of Jaky (K_0= 1- sin φ).

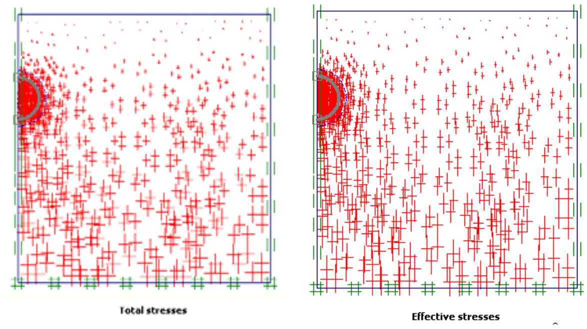


Figure 4: Generation of the field of initial constraints

Table 2: Initial constraints

Constraints	**Numerical calcul.**	**Analytical calcul.**
Maximum normal constraint: σ	668.85 kPa	γ_v. H=672 kPa
Maximum effective constraint: $\sigma' = \sigma - U_w$	348.85 kPa	352 kPa

Numerical and analytical calculations agree.

Analysis and Discussion of the Results

In this section, we chose to expose the results obtained after the construction of the tunnel.

Deformed Mesh

After the construction of the tunnel, we noted that a movement of ground occurred at the level of natural surface, as well as at the level of the excavation (in clay).

The Finite Elements Mesh (Figure 5) clearly shows the existence of a trough caused by the construction of the tunnel.

We noted also a certain shortening of the lining of the tunnel that is due to the various phases of constructions such as the digging, the filling of the annular vacuum, the installation of supporting,… etc.

However, the following points were noted:

- The ground located below the foundation raft remained practically undisturbed.
- The ground located on the surface tended to converge towards the center of the basin.

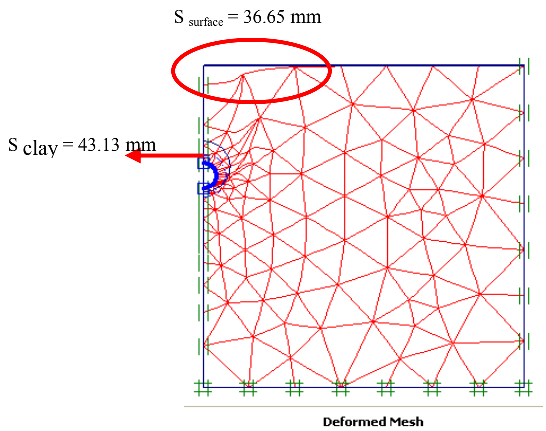


Figure 5: Deformed mesh

Also, according to the observations of Ollier (1997), the ground on the surface generally rocks towards the center of the basin. He bound this phenomenon to the various phases of tunneling with the Tunnel Boring

Machine (TBM) and to the deformation of the lining (Dolzhenko, 2002).

The value of settlement S_{max} on the surface found numerically was about 36.65 mm; the value which is in the interval of the values quoted in the literature is (25mm< S_{max}<40 mm).

By making a horizontal cut AA' at the vertical distance Y=10 m, we obtained the shape of the curve of settlement for the example of calculation.

It is a curve characterized by its maximum settlement S_{max}=36.65 mm, its point of inflection i = 3.8 m and its width L_c = 12.30 m.

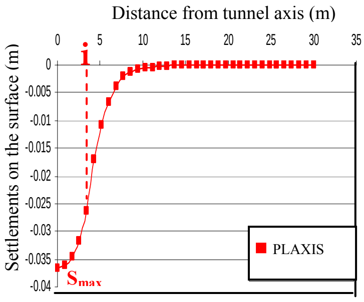


Figure 6: Settlement trough

Calculation of the Settlement Trough by the Empirical Method

There are various methods in order to evaluate settlements which prove to be representative of the potential risks that work can cause to the existing buildings. The empirical method aims at estimating these parameters starting from a number of relatively limited data such as the depth of the tunnel, its diameter, the nature of the ground and the loss of ground generated by the technique of execution (Dias, 1999).

The settlement trough generally appears as a three-dimensional trough (Figure 7), the pace of which, in the transverse plan, follows the normal law of Gauss and is characterized by maximum settlement at the axis of the tunnel, decreasing with the distance from the point of inflection of the curve in the median plane of the work.

The settlement trough on the surface can laterally extend up to 1.5 times the cover from the ground in the case of soft clay. In the case of sand, the extent of settlement is less significant (Dolzhenko, 2002). The extent of the basin depends mainly on the type of ground, the diameter of the tunnel and its proximity of surface.

Settlements on the surface are symmetrical to the axis of the tunnel. This was described for the first time by Marcos (1958). Other authors such as Peck (1968), Schmidt (1969), Cording (1975), Attewell (1977), Clough (1981), O' Reilly (1982) and Rankin (1988) confirmed this result (Cited by Magnan and Serratrice, 2002).

These settlements define a certain volume per linear meter noted V_s corresponding to the surface ranging between the initial level of surface of the ground and the profile of settlements (Figure 7).

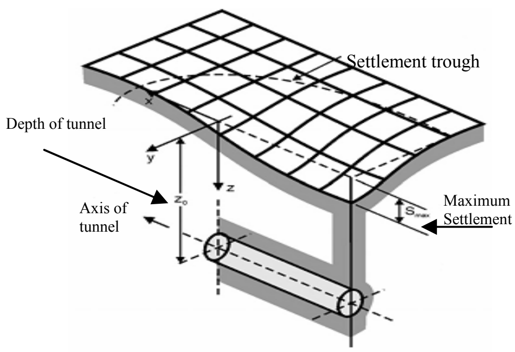


Figure 7: Form of settlement trough on the surface (Vermeer, 2007)

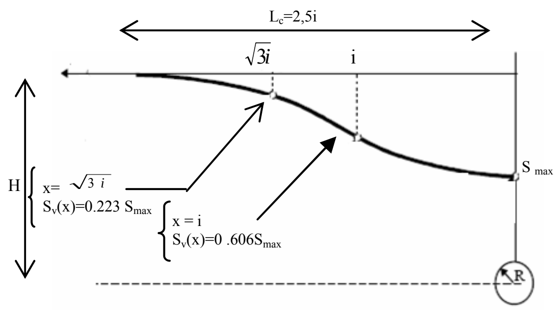


Figure 8: Gaussian profile of the settlement trough (Peck, 1969)

Table 3: Computed values of the point of inflection for various formulae

Oteo and Sagaseta (1982)	i = α H/2 – 0.42 R	i =4.2 m
Dyer et al. (1996)	i=0.29H	i =2.9 m
Atkinson and Potts (1977)	i = 0.25 (C + D)	i =3.125 m dense sand
	i =0.25 (1.5 C +D)	i =4.060 m sand coward
O'Reilly and New (1982)	0.7 D<i<1.22 D	3.5 m< i<6.1 m sand
Mair (1997)	i = k. H avec	i=3.5 m k=0.35 sand

With D=5 m, C=7.5 m, H=10 m. α : cœfficient corrector with 0.7<α<1.3.

The pace of the trough of settlement is characterized by the following analytical formulation:

$$S_v\,(x) = S_{max}\,\exp...\left(\frac{-x^2}{2i^2}\right) \tag{1}$$

where x represents the horizontal distance to the center of the basin, S_v (x) the vertical settlement with the x coordinate, S_{max} the maximum settlement and i the parameter characteristic of the width of the basin.

H is the depth of the tunnel axis and R the ray of the tunnel.

This curve has the following characteristics:

- Its point of inflection for x= i, S (x) = 0.606 S_{max}
- Its curve maximum for $x = \sqrt{3}$ i, S (x) = 0.223S_{max}
- Its half width $L_c = \sqrt{2\Pi}$ i ≈ 2.5 i.
- Its volume moves by excavated unit of length V_s which moves progressively with the phases of tunneling.

According to the formula of Peck (1969), by knowing the parameters i and S_{max}, the volume of the settlement trough can be determined by the integration of formula 1:

$$V_s = (2\Pi)^{1/2} \times i \times S_{max} \approx 2.5 \times i \times S_{max} \tag{2}$$

The model suggested by Peck to approximate the settlement trough on the surface makes it possible to deduce the point of inflection i and the width of the trough, as well as to estimate the volume of the ground lost on the surface.

The x coordinate of the point of inflection can be also calculated by the empirical formulae. We chose some formulae which gave results close to the value found in our numerical work (i = 3.8m).

From these results, we can say that the value of i found is appreciably in agreement with the results suggested in the literature.

In order to analyze settlements on the surface found by our simulations, we decided to make a comparison between two numerical and empirical calculations (model suggested by Peck; Formula 1).

We noted that the two troughs shown in Figure 9 have practically the same pace, which enables us to affirm that the formula of Peck presents settlements on the surface in a correct way. We can also conclude that the formula of Peck is of great utility in the calculations of the preparatory project, in order to obtain an idea about the pace of settlements on the surface.

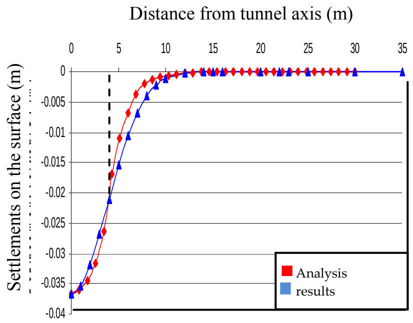


Figure 9: Settlement trough

Calculation of the Settlement Trough by the Analytical Method

This approach is based on the study in an analytical way of displacements in a ground during the excavation. Analytical calculation is always the more useful one, as it makes it possible to obtain orders of magnitude and to carry out parametric studies thereafter.

Unfortunately, models of the analytical calculation of settlements on the surface neglect general geometry and mechanical properties of the ground and the excavation stage of the work completion. Nevertheless, they provide keys for the analysis of measurements and the choice of the forms of the profiles of settlements on the surface of the ground (Dias, 1999).

Researchers worked to develop these methods of calculation to evaluate the movements in the ground. Among them we mention: Panet (1969), Resendiz (1979), Sagaseta (1987), Verruijt and Booker (1996), Verruijt (1997), Loganathan and Poulos (1998) (quoted by Magnan and Serratrice, 2002) and Park (2004).

Sagaseta (1987) presents a solution (Formula 3) for the calculation of the deformations induced by the digging of a circular tunnel in a homogeneous, elastic and incompressible soil. The solution is founded on the effects of a loss of volume caused in a point of the soil by the excavation of a shallow tunnel. This solution makes it possible to evaluate displacements on the surface (Magnan and Serratrice, 2002):

$$S(x) = -\frac{V_t H}{\left(x^2 + H^2\right)\Pi} \tag{3}$$

And we will have for x=0 maximum settlement

$$S_{max} = -\frac{V_t}{\Pi H} \tag{4}$$

where H is the depth of the axis of the tunnel.

We carried out a comparison between the empirical model of the settlement trough for the model of reference and the analytical model calculated by using Formula (3).

V_t is calculated further (V_t = 1. 15 m^3/ml).

The results obtained are illustrated in Figure 10.

The settlement trough of the numerical model gives a pace which is tighter than that of the analytical and more approximate model of the experimental observations (settlement trough is deeper and less broad; Addenbrooke et al. (1997), quoted by Hejazi, 2007). This difference is allotted to explanations of Verruijt and Booker (1996) which indicate that the analytical formulae represent only one coarse schematization of the real behavior of the ground, but at the same time they provide keys for the analysis of measurements and the choice of the forms of the profiles of settlements on the surface of the ground (Dias, 1999). We point out that analytical calculation does not take account of all the parameters necessary for a good approximation of the reality observed during the operation of tunneling.

Augarde (1997) studied settlements on the surface due to the construction of the subway of Caracas by using the method of Sagaseta (1987) and the model of Peck and arrived at a basin broader than envisaged. For him, the model of Peck is closer to reality.

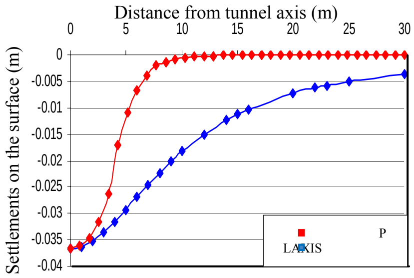


Figure 10: Settlement profile

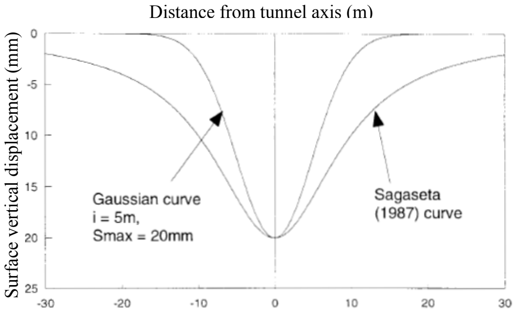


Figure 11: Profiles of settlement trough (Augarde, 1997)

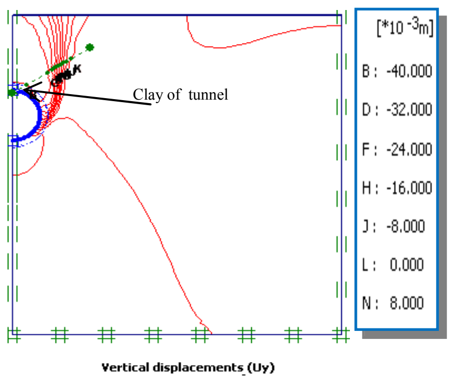


Figure 12: Vertical displacements

Vertical Displacements

According to several authors, among whom are Chapeau (1991) and Panet (1991), it appears that the movements would probably not be significant on surfaces, but in extremely higher cases (key of the tunnel), they become more extensive.

In Figure 12, we note a certain maximum displacement (U_{ymax} = 43 mm), being just near the top of the tunnel at a distance y = 2.5m.

In order to better see the variations of vertical displacement, we drew other curves of displacement for various depths: y = 2.5 m (what corresponds to the key of the tunnel) and y = 6.0 m (Figure 13). We observe clearly from Figure 13, that when the depth increases the displacement also increases. Moreover, *in situ* measurements showed that the settlements observed on the surface represent only part of the vertical displacements induced in the in-depth soil (results confirmed by Chapeau (1995), Adachi (1985), Al-Abram (1999) and Dolzhenko (2002)).

Table 4 gathers the various values of vertical displacement at various depths.

Obviously, according to Table (4), the difference can appear tiny, but when it is about digging in underground, each millimeter is counted.

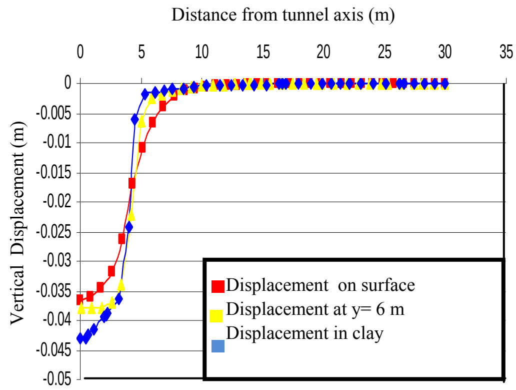


Figure 13: Vertical displacements

Losses of Volume in Underground

The movements of ground which occur at the court of the excavation correspond to a volume of ground lost on the level of the tunnel which one names V_t (Figure 14).

According to Magnan and Serratrice (2002), the volume lost in underground is difficult to evaluate, because of the impossibility of making measurements of convergence before the installation of the supporting, which makes that part of deformations escape monitoring, the difficulty in making measurements of convergence in erasing, as well as the existence of movement of extrusion towards the tunnel with the coal face and the defects of contact between the ground and the supporting.

Table 4: Vertical displacement U_y (mm)

	In clay: Y = 2.5	At Y = 6m	On surface Y =10m	At the base Y = -2.5 m
Uy (mm)	-43.13	-37.90	-36.65	Rising of about +6.58

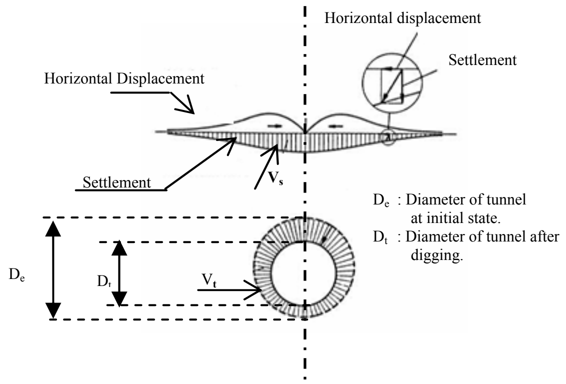


Figure 14: Movements of ground. Loss of volume (Uriel, 1989. Cited by Dolzhenko, 2002)

Volume lost V_t constitutes a significant index in the expression of settlements on the surface. Its amplitude depends on several parameters; nature of the ground, presence of water, method of construction, diameter and depth of the cavity (Magnan and Serratrice, 2002).

We will adopt:

- For the calculation of V_s, Formula 2.
- Knowing S_{max} and i, we find the loss of volume on the surface: $V_s = 0.35$ m^3/ml.
- For the calculation of V_t , we use Formula 1, to find that the loss of volume in underground: $V_t = 1.15$ m^3 / ml.
- According to Ortigo (1996), the sand used in this study is dilating: $V_s/V_T = 0.3 < 1$.

Calculation of the Damping of Displacement Entering the Key of the Tunnel and the Surface of the Ground

Maximum settlement on the surface S_{max} of the ground is smaller than that at the higher point of the tunnel called S_{clay}. The ratio of damping is expressed by S_{max} / S_{clay}.

The C.E.T.U. (1993) proposes the following formula:

$$\frac{S_{max}}{S_{clay}} = k\,\frac{R}{H} \tag{5}$$

with R and H are the initial ray and depth of the tunnel and K is the damping ratio; in this example: K= 3 for $0.10 < R / H < 0.25$.

$S_{max}/S_{clay} = 0.75 = 75$ % (K=3).

In this work, we found $\frac{S_{max}}{S_{clay}} = \frac{36.65}{43.13} = 85\%$.

The difference is about 10 %.

Horizontal Movements

O'Reilly and New (1982) present the following formula for the calculation of horizontal displacement.

$$S_H(x) = \frac{x.S_v(x)}{H} \qquad (6)$$

where $S_H(x)$: horizontal displacement, H: depth of tunnel, S_v (x): vertical displacement, x: horizontal distance from the axis of the tunnel.

Figure 15 presents the horizontal displacements in the following sections:

- At Y=10 m (corresponding to the surface of the ground).
- At Y=5 m.
- At Y=0 m (corresponding to the center of the tunnel).
- At Y=-2.5 m (corresponding to the base of the tunnel).

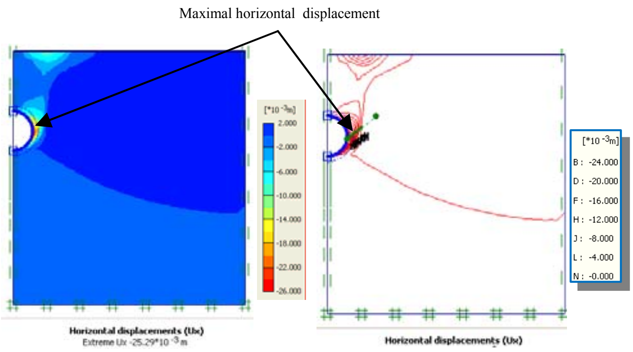


Figure 15: Horizontal displacements

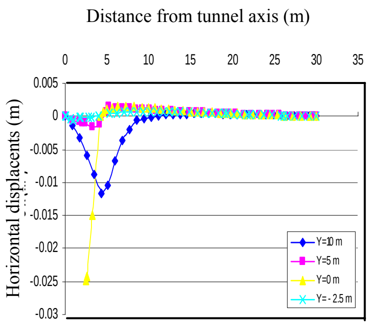


Figure 16: Horizontal displacements at different depths

The horizontal displacements obtained after the construction of the tunnel are presented in Figure 16.

Figure 16 shows that horizontal displacements are almost null at the lower part of the tunnel and that maximum displacement is present at the level of the sides of the tunnel (at the point: x=2.5 m; y=0 m). This phenomenon can be explained by the effort exerted by the shield which tends to push back the ground at the level of the sides of the tunnel (Galli et al., 2004). These results were also confirmed by Dolzhenko (2002), Bloodworth (2002) and Massin and Herle (2003).

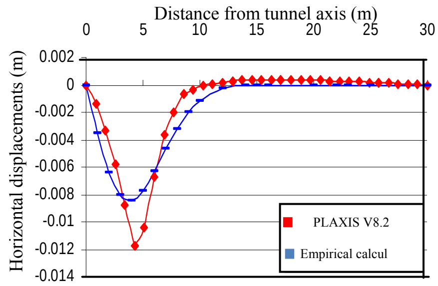


Figure 17: Comparison between displacement curves

In order to compare numerical calculation with empirical calculation, we used the formula of O' Reilly and New (1982) for the tracing of the curve of horizontal displacements on the surface (Figure 17).

The curve resulting from empirical calculation proposed by O'Reilly and New takes practically the same form as that resulting from numerical calculation, except for the amplitude of maximum settlement. Numerical calculation overestimates maximum displacements compared to the empirical model.

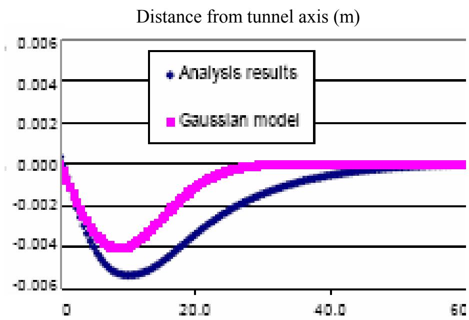


Figure 18: Horizontal displacements on the surface (Bloodworth, 2002)

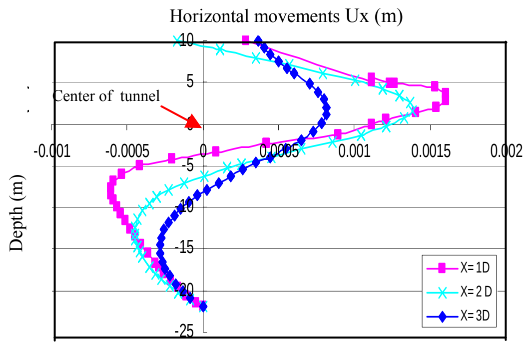


Figure 19: Curves of horizontal displacements at various distances vertical to the center of the tunnel

Figure 18 presents a comparison between the empirical model and the numerical model of horizontal movements on the surface carried out by Bloodworth (2002). The author noted that the two models proved to be convergent, except for the maximum movement obtained by the numerical calculation which is approximately 30% larger than that obtained by the empirical calculation.

The displacements practically reach their maximum at the level of the center of the tunnel and decrease by intensity while going up towards the surface. The ground below the tunnel is practically undisturbed.

These results were confirmed by Ollier (1997). The author noted a certain repression of the ground at the level of the kidneys of the subway. He also noted that the ground on the surface generally rocks towards the center of the trough.

The study of horizontal displacements within the ground in the vertical sections located at three horizontal distances x; where x=1D, x=2D and x=3D gave the results illustrated in Figure (19).

It is noted that the more one moves away from the tunnel, the more the horizontal displacements diminish. Broadly the ground seems to be pushed back towards outside. These results are confirmed by Chapeau (1987) quoted by Dolzhenko (2002) and Galli et al. (2004). Galli et al. (2004) affirmed that the more one moves away from the tunnel, the more the horizontal movements decrease:

- At x=4 D, the maximum horizontal displacement is about 0.095m.
- At x=3 D, the maximum horizontal displacement is about 0.087m.
- At x=2 D, the maximum horizontal displacement is about 0.06m.

It is always noticed that in the lower part of the tunnel the horizontal movements are almost null. The ground is not disturbed any more.

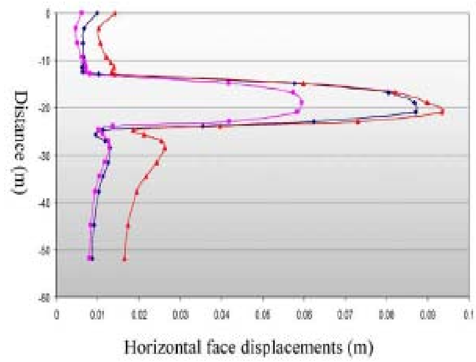


Figure 20: Horizontal surface movements for various diameters (Galli et al., 2004)

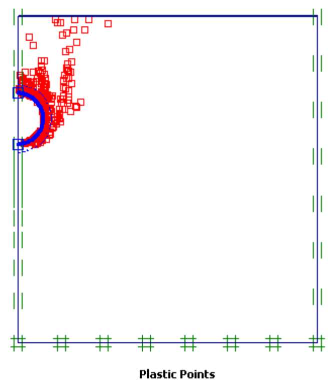


Figure 21: Plasticized zones

Plasticized Zones

Verruijt and Booker (1996) and Verruijt (1997) confirmed that the presence of plastic deformations concentrated above the tunnel involves larger displacements out of key and more intense compared to those noted on the surface.

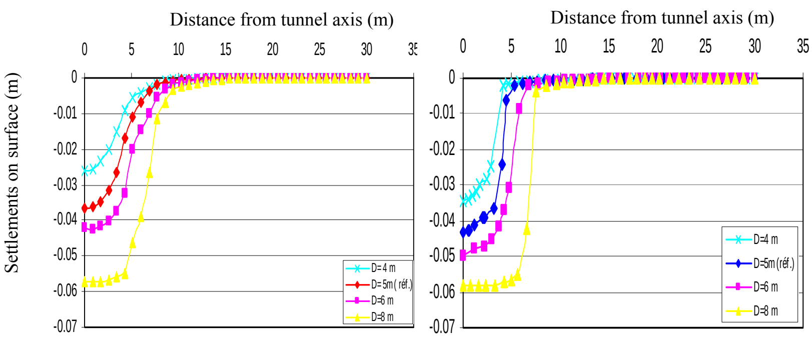
Figure 21 shows the existence of a plasticized zone at the periphery of the excavation. This observation is confirmed by Mroueh (1998) among others.

The plasticized zone (modeled by the red squares) is concentrated around the excavation and decreases by intensity while going up towards the surface.

Mroueh (1998) affirms that the existence of this zone is created before the installation of the supporting, and it persists even after the installation of the supporting. The red squares indicate that the constraints in this zone are on the surface of the envelope of rupture of Mohr-Coulomb.

Table 5: Influence of diameter of the tunnel on the movements of the ground

Diameter (m)	S_{max} (mm)	S_{clay} (mm)	L_c (mm)
4	26.05	34.62	10.20
5 (model of ref.)	36.65	43.13	12.30
6	42.40	50.10	14.50
8	57.24	58.26	15.80



(a) vertical displacements on surface (b) Vertical displacements in clay

Figure 22: Influence of diameter on movements of the ground

Table 6: Influence of the depth of the tunnel on the movements of the ground

H (m)	S_{max} (mm)	S_{clay} (mm)	S_h (mm)	L_c (mm)
H= 1D=5 m	42.83	45.03	25.02	6.73
H= 2D=10 m (Model of ref.)	36.65	43.13	25.29	12.30
H= 3D=15 m	28.20	39.63	25.19	24.10
H= 5D=25 m	12.86	36.14	25.36	36.80

Table 7: Influence of coefficient of the grounds at rest

K_0	S_{max} (mm)	S_{clay} (mm)	S_H (mm)	L_C (m)
0.455(model of ref.)	36.65	43.13	25.29	12.3
0.5	36.23	43.03	25.30	13.4
0.8	32.05	42.57	25.10	> 30
1	26.08	41.71	25.08	> 30

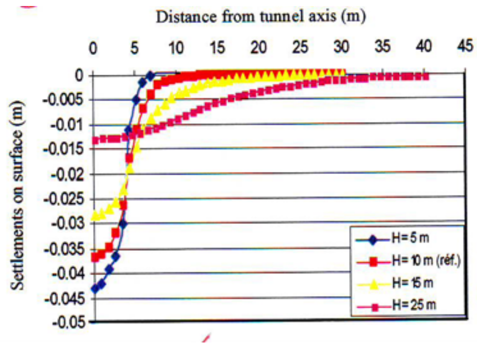
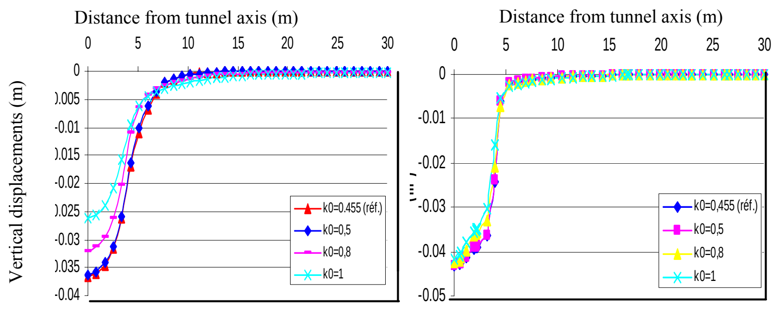


Figure 23: Influence of the depth of the tunnel



(a) Vertical displacements on surface (b) Vertical displacements at key

Figure 24: Influence of coefficient of the grounds at rest (K_0)

Effects of Geometrical and Geotechnical Parameters

The impact of the tunneling on the soil depends on various factors, such as the deformation properties of the soils met and their stratification, the size tunnel, its form and its depth, the method of execution adopted and the succession of the various phases of construction.

In this section, we will study the influence of depth and diameter of the tunnel, as well as certain mechanical characteristics, such as the coefficient of the grounds at rest, the angle of friction, the Poisson's ratio and the angle of dilatancy on the movements in the soil.

Effect of Diameter of the Tunnel

We carried out three calculations for different diameters lower and higher than the diameter of the tunnel of the model of reference, in order to study the influence, of the variation of the tunnel diameter on the movements of the ground. The other data of calculations are the same as those retained in the calculation of reference (D = 5 m).

A comparison between the various troughs of settlement for these various diameters is illustrated in Figure 22. Also, Table 5 gathers the values of settlements found, as well as the values of the width of the trough.

We clearly see that the more the diameter increases, the more the movements increase. This can be explained by the fact that settlements on the surface are in strong relationship to the convergence of the ground at the level of the excavation. In the same way, radial displacements around the tunnel are influenced by the variation of the diameter (radial displacement increases by the increase in diameter; Panet, 1995), which brings us to a less significant arching on the contour of the excavation; thus settlements will be more significant.

The curves of vertical displacements for the same diameters were plotted out of key for the various values of diameter. The same observations were obtained.

Effect of the Depth of the Tunnel

The depth of the tunnel has a significant influence on the behavior of the ground, which was clearly highlighted thanks to the three calculations carried out for various depths of the tunnel.

Table (6) shows the results of these calculations.

Figure 23 presents the settlement trough for the various depths quoted previously. It is noted that the increase in the depth of the tunnel affects the maximum settlement and decreases its amplitude. In fact, it is the arching around a tunnel which is at the origin of this reduction; it limits the propagation of the movements on the surface. This was confirmed by (Hejazi, 2007; AITES, 1989; Panet, 1991; Sagaseta, 1987; Attewell, 1977; Peck, 1969, cited by Mroueh, 1998).

Effect of Coefficient of the Grounds at Rest (K_0)

Logically, the geotechnical parameters have effects on the behavior of the ground with respect to the digging of the tunnels. Initially, we will study the influence of the parameter K_0 in order to note the influence of the anisotropy of the initial constraints.

Table 7 and Figure 24 show that settlements on the surface are influenced by the coefficient of the grounds at rest. Indeed, we note a reduction of the maximum settlement on the surface of about 28 % when K_0 passes from 0.455 to 1. In another manner, we can say that when the anisotropy of the initial constraints is low, settlement decreases and the basin is broader. However, side displacements do not seem to be affected. This enables us to say that the influence of the coefficient of the grounds at rest is significant on the final results of settlement. These results were confirmed by Mroueh (1998) and Dolzhenko (2002).

Table 8: Influence of φ

Angle of friction	S_{max}(mm)	S_{clay}(mm)	S_H(mm)	L_C (m)
30°	34.57	42.32	25.13	12.30
33° (model of ref.)	36.65	43.13	25.29	12.30
38°	43.61	45.87	25.71	12.30

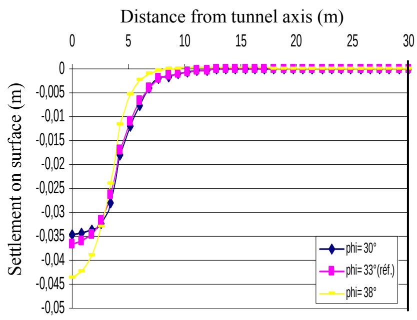


Figure 25: Influence of angle of friction of the ground

Effect of Angle of Friction of the Ground (φ)

The influence of this angle on the behavior of the grounds which undergo an excavation is clearly shown in Figure 25 for the values of φ = 30° and φ = 38°. The results found are shown in Table (8).

We note a reduction of the amplitude of maximum settlement of about 6% when the angle of friction passes from 33° to 30°. When it passes from 33° to 38°, the increase in settlement is approximately 20%. We note also an appreciable increase in horizontal displacements.

The width of the trough seems not to be influenced by the variation of this parameter.

However, we expected to have opposite results; indeed, a more significant value of this angle helps the arching to develop in the soil, which leads to less significant settlements (confirmed by Hejazi, 2006). This is the opposite of which we found by the numerical simulation.

We explained this by the fact that PLAXIS use Jacky's formula for the calculation of K_0.

Effect of Poisson's Ratio (ν)

The parameter ν is the Poisson's ratio which characterizes the elastic behavior of a material.

With the aim of studying the influence of the Poisson's ratio on the behavior of the grounds, we carried out two calculations with Poisson's ratios of 0.1 and 0.4 (the value of reference being 0.3).

The results found for these values enabled us to conclude that this parameter does not practically influence the amplitude of settlements.

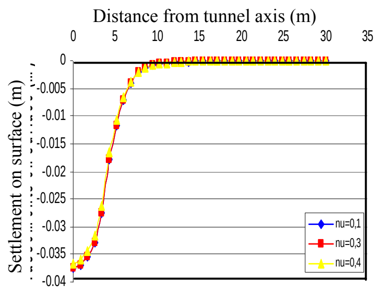


Figure 26: Influence of Poisson's ratio

Effect of Angle of Dilatancy (Ψ)

The angle of dilatancy represents the increase in the volume of the soil composition which occurs during the shearing of the ground. This angle expresses the rearrangement of the grains which causes an increase in volume during shearing. The variation of Ψ seems to mark the behavior in the ground. Indeed, vertical displacements decreased by the increase in Ψ. However, horizontal displacements remained almost the same.

Thanks the definition of the angle of dilatancy, the explanation of the numerical results appears simple; the increase of dilatancy in the ground makes settlements decrease within it.

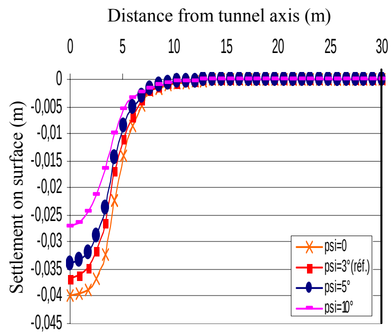


Figure. 27: Influence of the angle of dilatancy

Models of Compartment

The behavior of the ground used in this study is governed by a perfectly plastic-elastic law. We chose to modify this behavior in a linear elastic model; this says that this behavior underestimates much vertical displacements, what endangers work in the tunnel and consequently the neighboring structures. This is clearly shown in Figure 28.

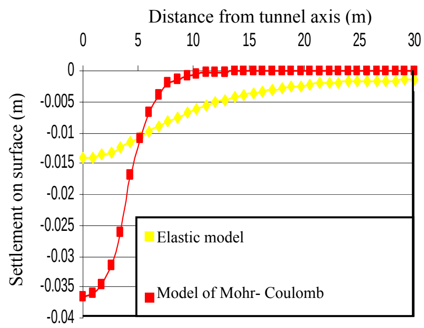


Figure 28: Influence of model

INTERACTION OF GROUND-STRUCTURE ON THE SURFACE

The attention concentrated-up to now-on the behavior of the ground due to tunneling. The presence of an external structure in the zone of the influence of the tunnel will be now included.

The position of the structure plays a paramount role on the trough of settlements on the surface.

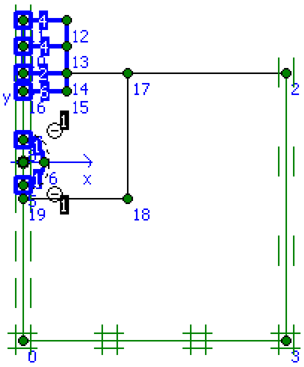


Figure 29: Selected model

As above-mentioned, the construction of a tunnel generates movements on the surface in the form of a basin. In urban sectors, this depression can affect the superficial structures, knowing that these were not calculated to support with the lower part of them the construction of a tunnel (a vacuum under its foundations).

We will be satisfied to study the vertical movements which occur at the level of the surface of the ground following the existence of the structure, by analyzing the variations of the profile of the settlement trough.

Table 9: Influence of ν

ν	S_{max} (mm)	S_{clay} (mm)	S_H (mm)
0.1	37.37	42.70	25.28
0.3 (model of ref.)	36.65	43.13	25.29
0.4	36.61	43.76	25.27

Table 10: Influence of angle of dilatancy ψ

Angle of dilatancy ψ	S_{max}(mm)	S_{clay}(mm)	S_H(mm)
0	39.74	43.33	25.53
3 (model of ref.)	36.65	43.13	25.29
5	34.00	42.89	25.17
10	27.03	40.33	25.14

Table 11: Material properties of the building (plate properties)

Parameter	Name	Value	Unit
Material model	model	elastic	-
Normal stiffness	EA	5.10^6	kN/m
Flexural rigidity	EI	9000	kNm^2/m
weight	w	5.0	kN/m/m
Poisson's ratio	υ	0.0	-

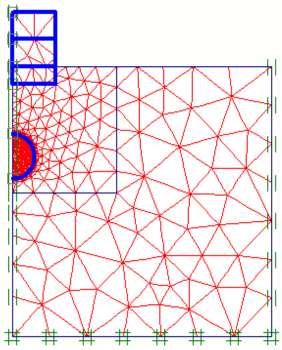


Figure 30: Finite element mesh

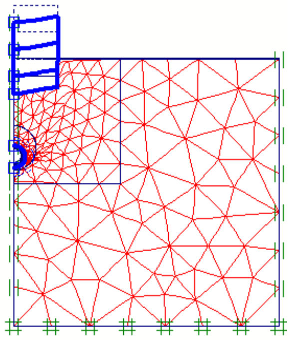


Figure 31: Deformed mesh

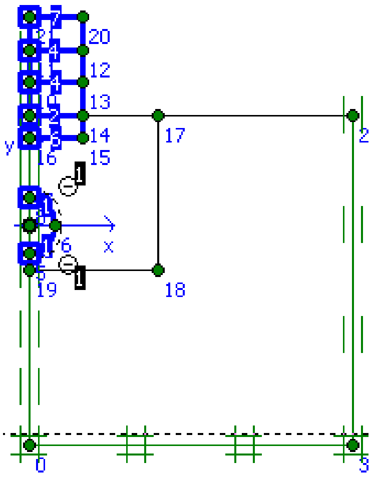


Figure 32: Selected model

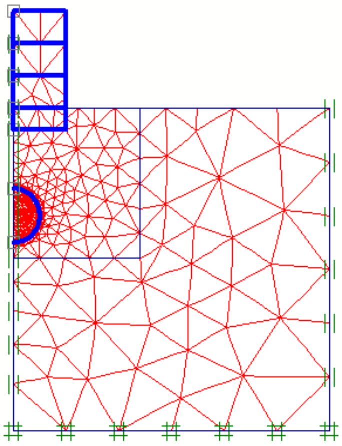


Figure 33: Finite element mesh

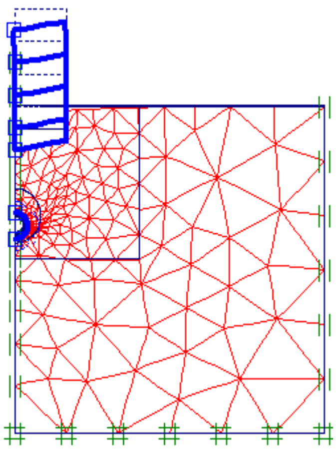


Figure 34: Deformed mesh

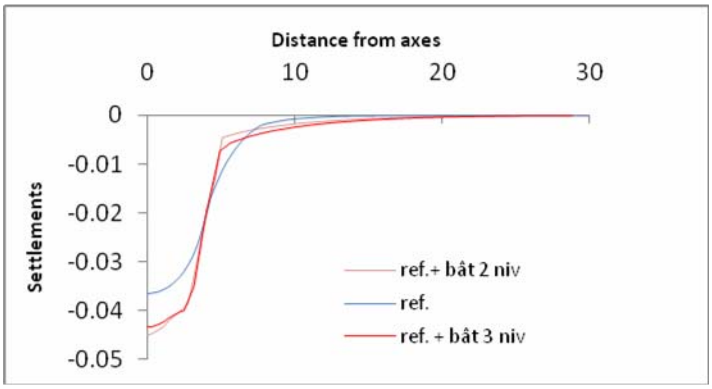


Figure 35: Comparison between settlements

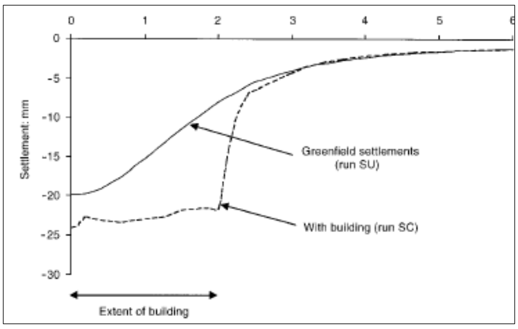


Figure 36: Comparison between settlements (Burd et al., 2000)

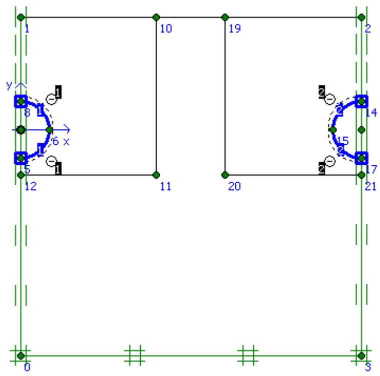


Figure 37: Geometry model

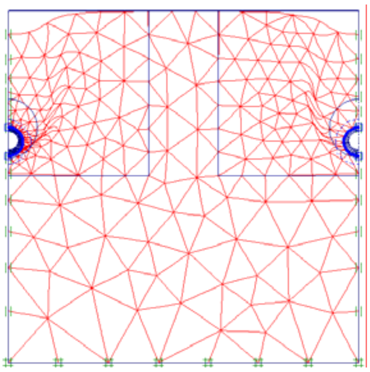


Figure 38: Deformed mesh

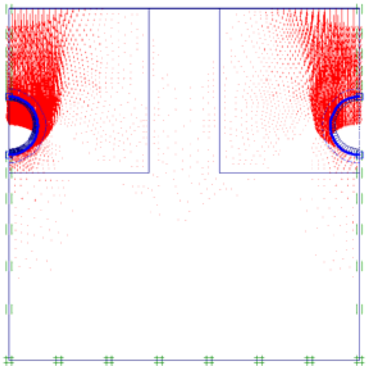


Figure 39: Vertical displacements

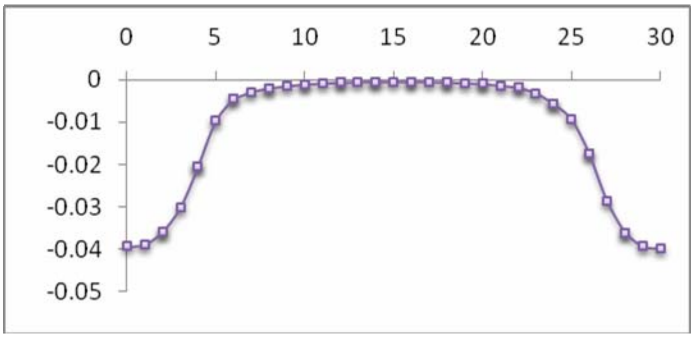


Figure 40: Settlement trough

Geometry and Fact of the Case

We chose to study the same problem as that in the first part to be able to compare the results with those found in the presence of the structure.

Let us note that in the construction, the building was built initially and the tunnel afterwards. The building consists of 2 floors and a basement. It is 5 m wide. The total height from the ground level is 2 x 3m = 6m, and the basement is 2 m deep. One supposes the structure centered around the tunnel, which enables to study a half of the field by symmetry. The building is also considered to be linear elastic. The walls and the floors have similar plate properties, which are listed in Table 11.

Modeling by Finite Elements

Figure 30 presents the finite element mesh retained for a half of the model because of symmetry.

Figure 31 shows the results due to the volume loss. The deformed mesh indicates a settlement trough at the ground surface.

From Figure 31, one notes that the existence of the building has a remarkable influence on the settlement trough. The maximum settlement is about 45.13mm; it is higher than that found in the first part by approximately 9 mm.

It is also noticed that the settlement trough supposes that the consequence of a tunneling is the loss of its form of origin. The variations of settlements are concentrated around the center of the structure, being on the axis of the tunnel. Indeed, the weight of the building is concentrated around the center of this last. On the other hand, these variations decrease by intensity while moving away from the center.

In order to examine the influence of the building weight on the behavior of the ground, we chose to add another level to the building, and the result was different from that expected (Figure 32).

The deformed mesh for this calculation is represented in Figure 34. The maximum settlement is about 43.85mm; this value is lower than that found for the building with 2 levels.

We always note the maximum variation of settlement at the level of the center of the structure.

The three cases are gathered in Figure 35.

As a reference, Figure 36 illustrates a comparison of the troughs of settlements between two numerical and empirical calculations by Burd et al. (2000).

The pace of the trough seems to be affected by the existence of the building.

As a case of study, we wanted to know, in the event of the construction of two tunnels one near the other, which results we could have; knowing that the two tunnels have the same mechanical and geometrical properties. The distance between the centers of the tunnels was about 30 m.

The following results were found. Maximum settlement obtained was at the level of the key of the tunnel, with a value equal to 48 mm; while at surfaces it was about 39 mm; these values are higher than those found in the presence of only one tunnel. This enables us to say that the presence of another tunnel increases settlement.

Figure 40 shows the settlement profile in the event of the presence of two tunnels. The two tunnels are identical, and this is why the troughs of settlements are the same for both of them.

CONCLUSIONS

The movements of the grounds caused by tunneling are inevitable. We cannot be opposed to convergences at the level of excavation and displacements on the surface; nevertheless, by looking further into our knowledge in this field, we can measure them, prevent them and consequently cure the situation.

The methodology which we applied to the construction of a shallow tunnel gave movements of ground, qualitatively comparable with those drawn from literature.

Parametric study was of a great utility to us, since it enabled us to study the influence of the geometrical and geotechnical parameters on the behavior of the ground.

The geometrical parameters H and D seem to have an outstanding influence on the behavior of the ground. Also, the coefficient of grounds at rest affects the movements in the ground, emphasizing the need for a good determination of this parameter. Maximum settlement on the surface decreases with the depth of the tunnel. As for horizontal displacements, they are pushed back towards the outside of the tunnel and reach their maxima at the level of the kidneys of the tunnel.

The increase in the angle of friction decreases the intensity of the movements; however, our results were reversed owing to the fact that PLAXIS uses the formula of Jacky in calculations.

Each modified parameter presents an influence on the behavior of the ground caused by the construction of tunnels. However, the ground behaves differently from one parameter to the other.

In urban sites, tunneling presents more concern considering the complexity of the phenomenon of ground-structure interaction. Being always in the context of parametric study, our study is extended to investigate the incidence of tunneling on settlements on the surface in the presence of a building. These settlements are of increased amplitude, more particularly, at the level of the tunnel axis.

We also noted that the presence of another tunnel influences the amplitude of settlement; this is why a thorough preliminary study is essential for better dimensioning the various structures.

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