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Three dimensional finite element analysis of the influence of the umbrella arch on the settlements induced by shallow tunneling

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Abstract:

This paper presents an analysis of the influence of the umbrella arch on the settlements induced by shallow tunneling, based on three-dimensional finite element simulations using CESAR-LCPC. The approach takes into account the actual geometry of the umbrella arch and the lining, and the various aspects of staged construction, notably the cycle of installation of the pipes. The results show that the influence of the umbrella arch on the settlements remains modest, at least for the range of parameters adopted in this study. Also, the results show that the numerical analysis can be carried out with a simplified geometry.

1 Introduction

This paper deals with the numerical modelling of the “umbrella arch”, a reinforcement technique used in the construction of tunnels through weak grounds. It consists in installing, prior to the excavation of a length of tunnel, a set of sub-horizontal pipes forming a kind of “umbrella” above the ground to be excavated (Figure 1).

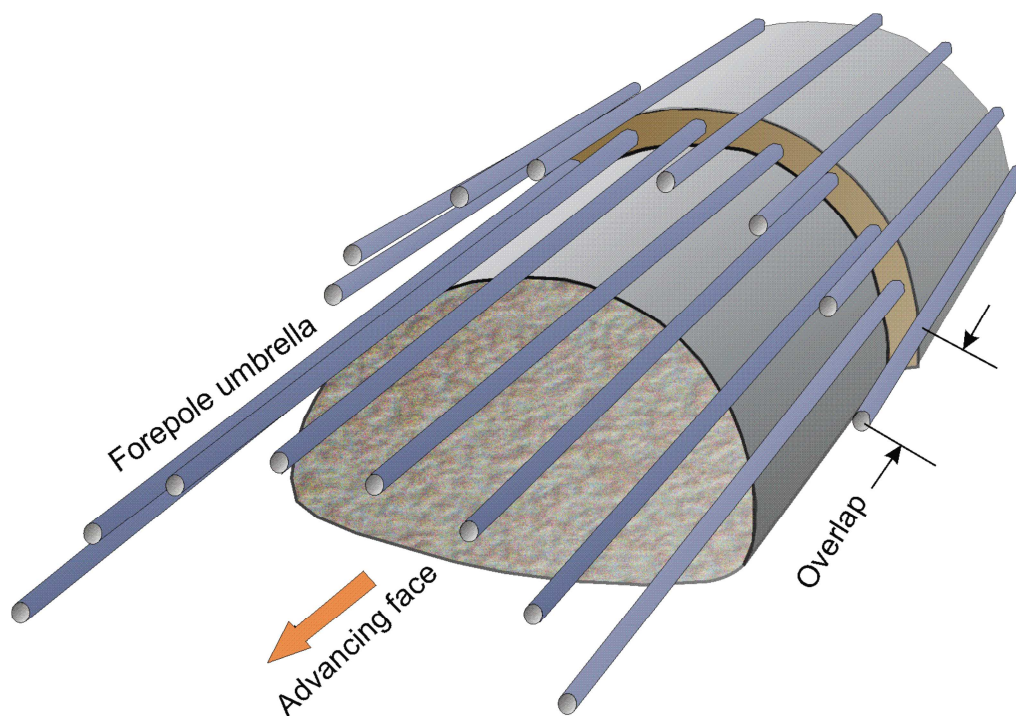


Figure 1. Tunnelling under the protection of an umbrella arch (after Hoek, 2004)

It is considered as an efficient way of improving the safety of tunneling operations and also of reducing the settlements induced at the surface and preventing building damages in urban areas (Leca and New, 2007, Ocak, 2008, Aksoy and Onargan, 2010). However, it remains difficult to assess quantitatively the role played by the umbrella arch in both respects.

The construction of a tunnel is fundamentally a three-dimensional process. The three-dimensional nature of the problem is even increased in the case of the umbrella arch: as shown by Figure 2 (corresponding to the case of a tunnel built in Toulon, south of France), the section of the tunnel varies along the direction of the excavation and the pipes of the umbrella, which lean partly on the lining already built, are not horizontal; the volume of soil excavated at each excavation step, the dimensions of the steel ribs and the length of pipes ahead of the tunnel face vary between two successive excavation steps.

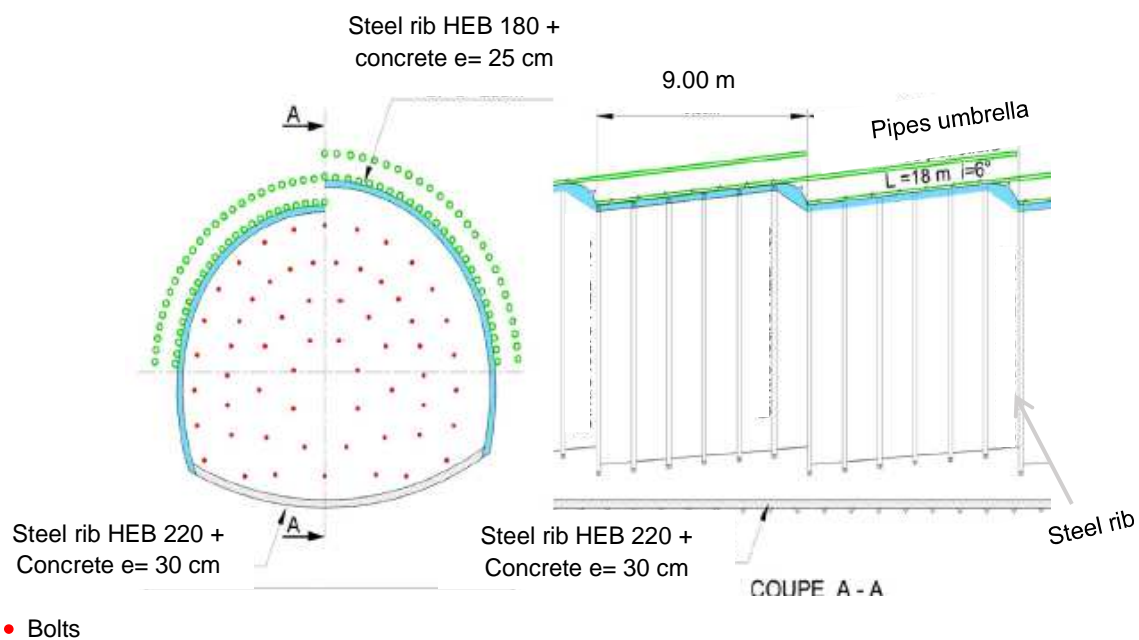


Figure 2. Profile of support of the south tunnel of Toulon (after Janin, 2012)

The umbrella arch has been the subject of numerous publications. Most of them deal with the mechanical load transfer between the ground and the pipes during the excavation process (Volkman and Schubert, 2010, Zhang et al, 2014, Oke et al, 2016), or with the increase in stability provided by the umbrella (Song et al, 2013).

The analysis of the umbrella arch being particularly difficult because of the complexity of the geometry, simplified approaches have been developed, in which the pipes are

modelled as beams resting on a set of springs (Volkman and Schubert, 2010, Song et al, 2013, Peila et al, 2017), or by means of a homogenization technique (Bae et al, 2005), and in some cases simplified approaches have been compared with more complete ones (Volkman et al, 2006).

Analyses focused on the loads transferred to the pipes are useful for the choice of the umbrella arch parameters (number and dimensions of pipes, length, overlapping between two arches, etc.), but do not convey much information regarding the displacements induced in the surrounding ground.

Regarding the influence of the umbrella arch on the settlements, it is worth recalling that, in engineering practice, the deformations induced in the ground are often analysed in plane strain, using the so-called convergence-confinement method (Panet and Guenet, 1982, Panet, 1995, AFTES, 2001). The generalization of this plane strain approach when an umbrella arch is installed, or when the tunnel face is reinforced by bolts, is a difficult problem (see for instance Janin, 2012). However, the complexity of the actual geometry makes the generation of a finite element mesh a complex task, and the corresponding numerical models are generally computationally very expensive. This is why there have been relatively few attempts to setup a detailed numerical model of the umbrella arch so far. Moreover, most of them deal only with the stability of the tunnel face. As a consequence, elements regarding the design of the arch with respect to objectives of settlement reduction are scarce in the literature: the main sources are the works by Oke et al (2014a), who have proposed a classification of the various types of umbrella arches and charts to predict the associated surface settlement reduction, based on field data. Other contributions provide useful elements regarding the settlement reduction obtained thanks to the umbrella arch (see for instance Aksoy and Onargan (2010), Shi et al (2014)).

This paper aims to study the influence of the umbrella arch and of face bolts on the settlements induced during the excavation of a shallow tunnel, excavated with the conventional method (i.e. without TBM). The approach relies on three-dimensional finite element simulations using the software CESAR-LCPC (Humbert et al, 2005).

The main objectives of the paper are:

- to demonstrate the feasibility of a finite element model that reproduces accurately the geometry of the umbrella arch and makes it possible to investigate the efficiency of umbrella arch to reduce the settlements,
- to provide quantitative elements regarding the settlement reduction that can be obtained using the umbrella arch, at least for a given geotechnical context,

- to discuss the consequences of simplifying the geometry of the tunnel in the numerical model on the predicted settlements.

In a first step (sections 2 to 5), we consider an ideal case, without referring to a real site: this allows considering the ground mass as homogeneous, which would not be representative in many situations. For brevity and clarity, we do not present a thorough parametric study: the results presented are limited to a given constitutive model, and to a specific type of umbrella arch, called “double forepole grouted umbrella arch” in the classification proposed by Oke et al (2014a). All simulations are carried out in drained condition, and do not take into account the influence of surface structures. Eventually, we compare our results with a case study and other elements taken from the literature.

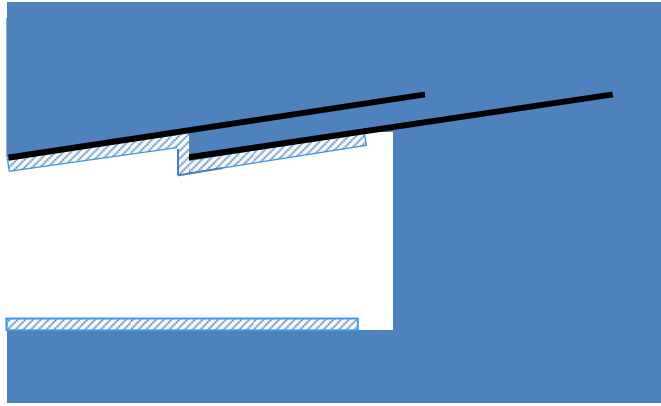
2 Position of the problem

Three-dimensional finite element simulations of the umbrella arch for shallow tunneling can be found in several references, generally for a specific tunnel project (Wang et al, 2018, Elyasi et al 2016). Only few of them (for instance Oke et al (2014b), Kitchah and Benmebarek (2016)) reproduce the actual geometry of the vault, while most studies adopt simplified geometries (Figure 3):

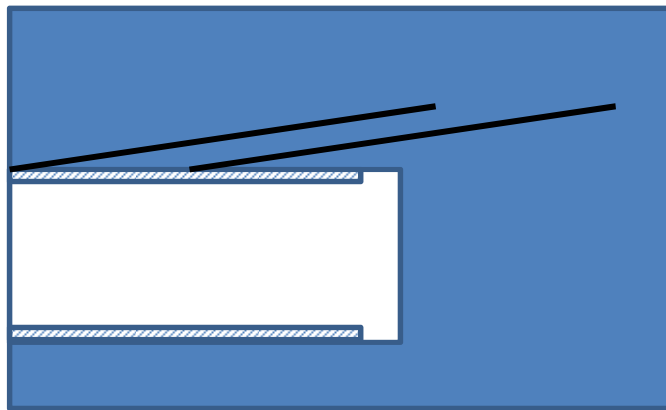
- some authors (Janin et al (2015), Monnet and Jahangir (2014)) have proposed models where the pipes are inclined, but rely on the concrete shell only at one end, which corresponds to what Leca and New (2007) call “basic forepoling” rather than to an umbrella arch (Figure 3b). One can wonder to what extent the influence of the pipes on the surface settlements may be reduced in that type of situation.

- other authors consider the pipes are horizontal and take into account a constant length ahead of the face (Gilleron (2016), Gilleron et al (2019)); pipes lean on the concrete shell already built behind the tunnel face (Figure 3c). This approach makes it difficult to take into account the cycle of renewal of the pipes, and the overlapping between two series of pipes, introducing a possible bias in the assessment of the settlements.

In what follows, we setup a numerical model reproducing the actual geometry, and discuss the influence of simplifying the geometry. We consider a tunnel with a circular vault, a curved sidewall and a curved invert. By symmetry, only half of the tunnel is represented in the simulations. The reinforcement of the tunnel face by horizontal fiberglass bolts is also taken into account.



(a) actual geometry



(b) inclined pipes resting on the concrete vault only at one end



(c) horizontal pipes leaning on the concrete lining already built

Figure 3. Geometry of the lining and of the umbrella arch : sectional view in a vertical plane

3 Modelling approach

The finite element method makes it possible to investigate the influence of the vault radius, the axis depth, the lining thickness, the inclination and the number of pipes, the angular opening of the vault, the length of each excavation step, etc. However, changing the geometrical parameters implies the generation of a new mesh; this is generally difficult with graphical preprocessors.

Moreover, the succession of excavation steps, with the activation and the deactivation of lining segments, bolts in the tunnel face and pipes of the umbrella arch also make the preparation of data with a graphical interface a difficult and error-prone task, unless a specific tool is developed to automate it. To facilitate the simulation of the excavation of a shallow tunnel with a variable section, we have developed:

- a script of commands for the three-dimensional finite element mesh generator GMSH (Geuzaine and Remacle, 2009),
- another script of commands, using a specific Python library dedicated to the finite element code CESAR, for the data relative to the material properties, boundary conditions and applied loads.

The process of construction is periodic, and constituted of cycles. Each cycle is divided in six excavation steps of 1.5 m. At the beginning of each cycle, a set of pipes are placed in the ground, forming an umbrella ahead of the face. The umbrella arch pipes are 18 m long. The next umbrella is installed at the beginning of the next cycle, 9 m further: two successive umbrellas overlap over 9 m. On the other hand, the area of the excavated section increases between two steps of a cycle of excavation. A 1.5 m section of the concrete vault is installed at each step. For practical reasons, the invert is built only after the excavation face has moved on over a certain distance. In the simulations presented hereafter, the invert is built by sections of 9 m (see section 4.1).

4 Hypotheses of simulation

This section summarizes the hypotheses and modelling techniques retained in this paper.

4.1 Geometry

The initial section, corresponding to the beginning of each of the cycles of the construction process, combines a vault of radius 4.5 m with an angular opening of 75 degrees on each side of the crown, associated with a sidewall of radius 13.5 m and a curved invert of radius

25 m, the total height being equal to 9.4 m. The depth of the tunnel axis is equal to 20 m and the thickness of the shotcrete lining and the raft is equal to 30 cm.

The mesh is 70 m wide and 36 m deep. The depth of soil below the tunnel invert is equal to 11 m. The total length of the mesh is equal to 91 m.

The umbrella arches are inclined of 6 degrees with respect to the axis of the tunnel. For a given umbrella, the first pipe and the last pipe are installed at 15 degrees and 75 degrees with respect to the crown. Each umbrella comprises 19 pipes for the half of the section taken into account in the mesh.

Figure 4 presents an example of tridimensional mesh that includes 310000 nodes and 230000 quadratic elements (10-node tetrahedra). The mesh generation takes around 5 minutes.

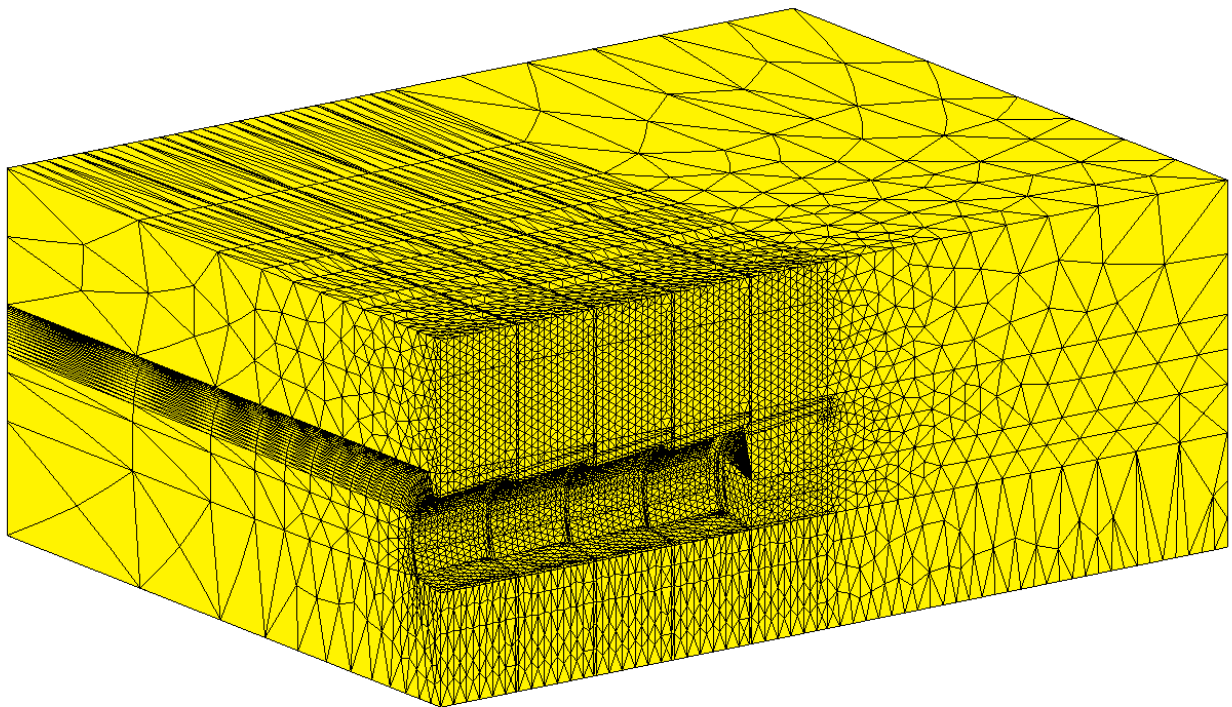


Figure 4. Tridimensional mesh (some elements are hidden to display the geometry after the final excavation step)

4.2 *Boundary conditions, constitutive models and mechanical parameters*

Boundary conditions

The nodes located on the lower boundary of the mesh are blocked in all three directions. On the vertical boundaries, the normal displacement and the tangential stresses are equal to zero.

Fiberglass bolts in the tunnel face

A simplified approach is adopted to simulate the tunnel face reinforcement by bolts: we adopt the “multiphase model” proposed by de Buhan and Sudret (2000), in its basic version where there is not relative slippage between the ground and the bolts. This model accounts for traction-compression forces in the bolts, their flexural stiffness being neglected. It has been used to model various reinforced ground structures, such as bolt-reinforcement of the tunnel face (Sudret and de Buhan (2001), de Buhan et al, 2007, 2008), piled rafts (Bourgeois et al, 2012a, 2012b) or mechanically stabilized earth walls (Bourgeois et al, 2012c, 2013). We adopted the following parameters:

Young’s modulus of the bolts $E_b = 40 \text{ GPa}$

area of a bolt cross-section 0.0008 m^2

volume fraction of bolts: $7.3 \cdot 10^{-4}$

The volume fraction of bolts is equal to the product of the number of bolts by the area of the bolt cross-section, divided by the area of the tunnel section. The value adopted here corresponds to 60 bolts in the entire tunnel face. In the numerical models presented here, the length of the bolts ahead of the tunnel face is constant and equal to 18 m.

Invert and vault

The invert modulus is taken equal to 20 GPa.

For the lining associating steel ribs and shotcrete, we follow the approach proposed by Janin et al (2015) for the Toulon tunnel: the modulus is determined by a homogenization process based on the characteristics of the ribs (HEB 220, $E_{\text{rib}} = 210 \text{ GPa}$), the thickness and stiffness of the shotcrete ($e = 30 \text{ cm}$, $E_{\text{shotcrete}} = 10 \text{ GPa}$) and the rib spacing (1.5 m in our study). One gets an equivalent homogenized modulus of 14 GPa.

Umbrella arch

The pipes are modelled by three-dimensional 3-node beam elements. A perfect bonding is assumed between the ground and the pipes; it is the same for the part of the pipes leaning on the tunnel lining.

The mechanical parameters of the pipes are taken from the literature (Gilleron, 2016):

Young’s modulus $E=210\,000 \text{ MPa}$, Poisson’s ratio $\nu=0.2$, section area 61.1 cm^2 , inertia 1860 cm^4 , external diameter 168 mm, thickness 12.5 mm.

Soil properties

The ground is assumed to be homogeneous. The constitutive model adopted here after is the Hardening Soil Model (Schanz et al, 1999, Plaxis, 2018). The interest of this model lies in the fact that it leads to a better evaluation of the vertical displacements below the invert than other (simpler) models (Hejazi et al, 2008).

The values of the different parameters are:

$$E_{50}^{\text{ref}} = 40 \text{ MPa} ; E_{\text{ur}}^{\text{ref}} = 120 \text{ MPa} ; \nu_{\text{ur}} = 0.3 ; p_{\text{ref}} = 100 \text{ kPa} ; m = 0.5 ; R_f = 0.9 ; \\ c' = 40 \text{ kPa} ; \varphi' = 25 \text{ degrees} ; \varphi = 0 \text{ degree.}$$

The initial stresses are geostatic with $\gamma = 20 \text{ kN/m}^3$ and $K_o = 1 - \sin \varphi = 0.577$.

4.3 Modelling the staged construction

As explained before, the construction process consists of a sequence of cycles. Each cycle is divided into six steps, each step corresponding to an advance of the tunnel face of 1.5 m, together with the activation of a segment of the lining. At the end of every cycle, a 9-m section of the invert is activated, and a new set of pipes is installed in the ground above the tunnel face. The process is illustrated in Figure 5, where the surrounding ground has been hidden for clarity.

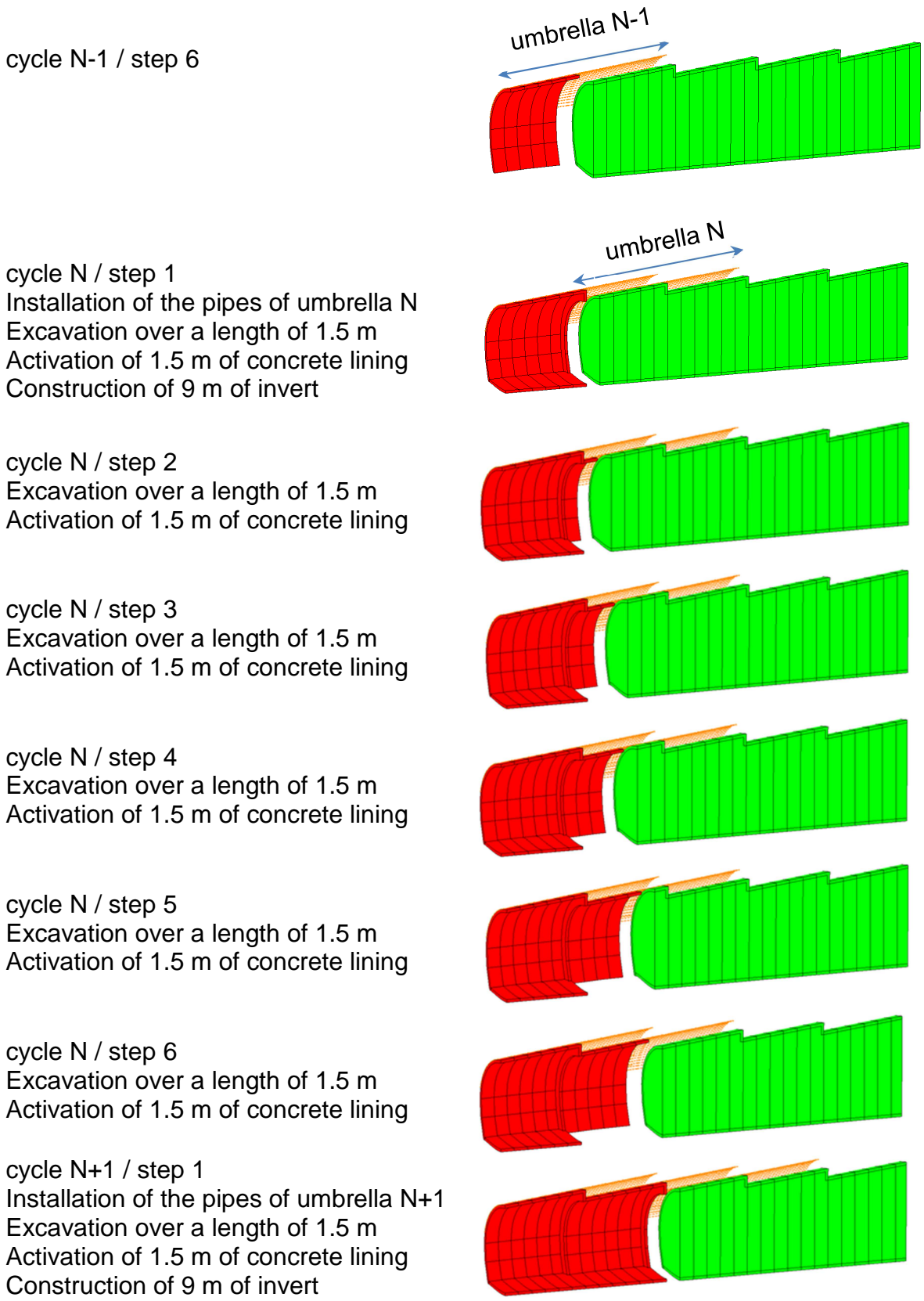


Figure 5. Description of the stages corresponding to a given cycle:
 in red : sprayed concrete lining and invert / in green: ground to be excavated
 In orange: pipes of the umbrella arch

5 Results

5.1 Analysis procedure

Because of the conical geometry of the section of tunnel, all calculation steps inside a given cycle are not equivalent and do not produce the same surface settlements. Besides, the settlements obtained numerically depend on the distance between the tunnel face and the left boundary of the mesh, at least for the first few cycles of construction. It was found necessary to perform the simulation of four entire cycles (i.e. to simulate 36 m of excavation) to obtain a “stabilized” solution. The total computation time with a PC with two Xeon processors amounts to approximately 15 hours. For the unreinforced case, the vertical displacements cumulated over the last cycle of 6 excavation steps, are shown in Figure 6.

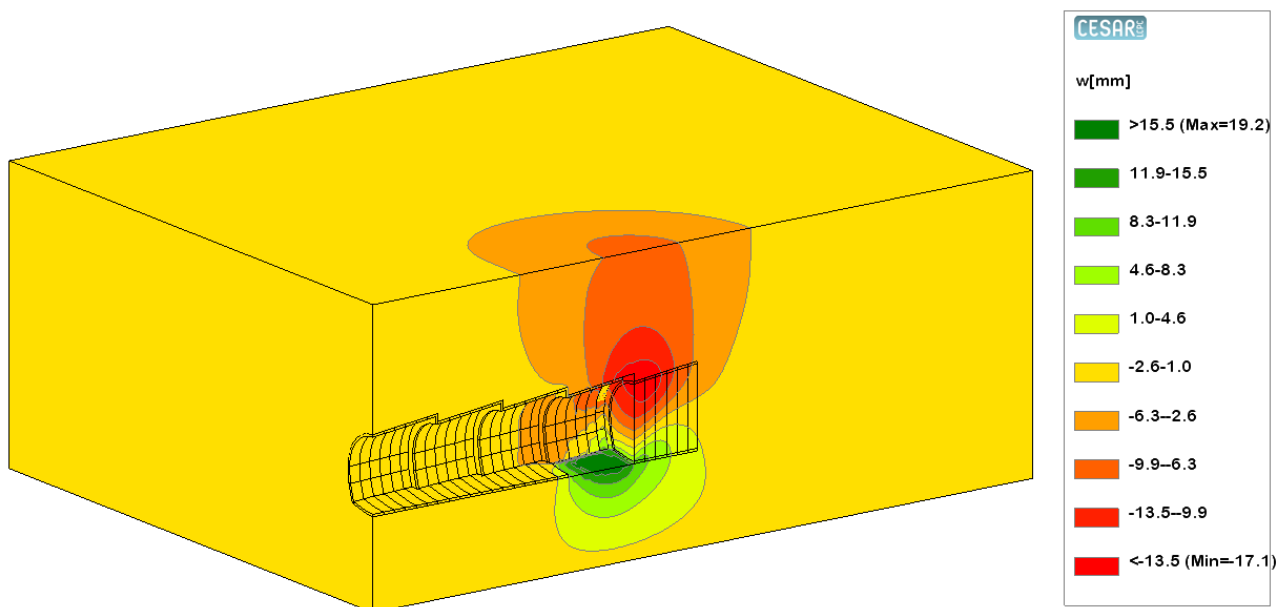


Figure 6. Contour lines of the vertical displacements generated by the 6 excavation steps of cycle #4

We reconstructed the final settlements as explained by Möller (2006): the settlements produced by the previous cycles are taken into account by translating the settlement trough obtained for the last cycle. The technique is illustrated by Figure 7 for the settlements obtained above the tunnel axis (in the simulation with no pre-support). It can also be used to obtain the final (transversal) settlement trough.

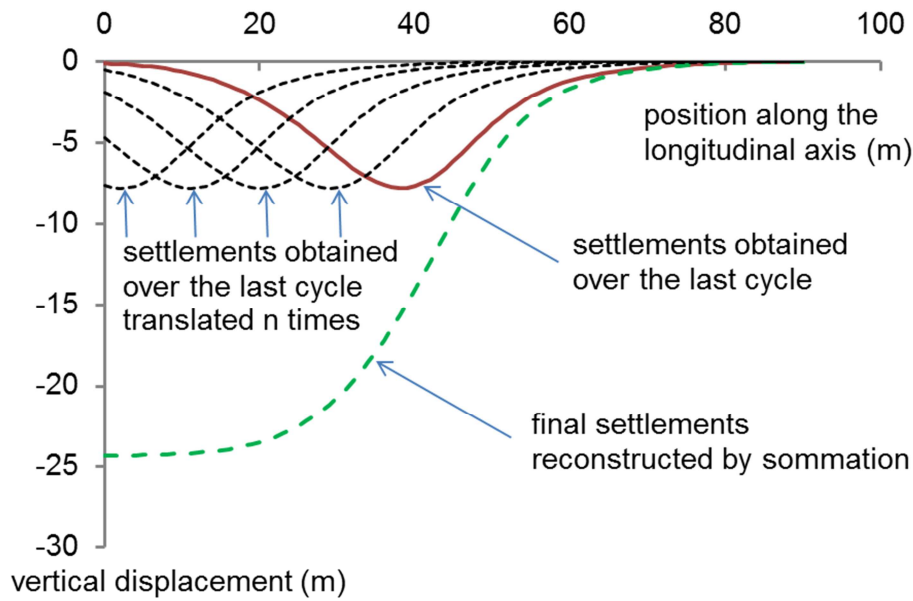


Figure 7. Reconstruction of the final longitudinal settlement profile on the basis of the settlements obtained for the last cycle

5.2 Settlement reduction provided by pre-supports

For the interpretation of the results, it is convenient to refer to the model proposed by Peck (1969), in which the surface settlement $S(x)$ at a distance x from the vertical plane of symmetry of the tunnel is described by a Gaussian function:

$$S(x) = S_{\max} \exp(-x^2/2i^2) \quad (1)$$

Where S_{\max} is the maximum settlement (above the tunnel axis, i.e. at $x=0$), and i is a parameter representing the lateral extent of the settlement trough. According to (1), $S(x)$ is equal to $0.6 S_{\max}$ for $x=i$.

O'Reilly and New (1982) have shown that the parameter i is well correlated with the tunnel axis depth H :

$$i = K H \quad (2)$$

where K is a parameter depending mainly on the type of ground. It is generally accepted that K does not depend much on the construction technique. A mean value of 0.43 is often considered as a good a priori estimate of K .

In the model proposed by Peck, the volume of the settlement trough is equal to:

$$V_L = 2.5 i S_{\max} \quad (3)$$

It is usual to compute the "volume loss", defined as the ratio of the settlement trough volume to the volume of the excavation.

In the case of open face tunneling, the values of volume loss reported from actual sites are in the range 0.5%-2% (Mair (1996)). We adopt here as a reference value a volume loss of 1%, but it must be kept in mind that, contrary to K , this value depends on the construction techniques. For the simulation presented above, $H = 20$ m and $V_L = 0.7$ m³/m . The above formula lead to $i = 8.6$ m and $S_{max} = 33$ mm.

Figure 8 shows the final longitudinal settlement profile obtained for the non-reinforced simulation and the simulation with the bolts and the umbrellas, and Figure 9 shows the final transversal settlement troughs.

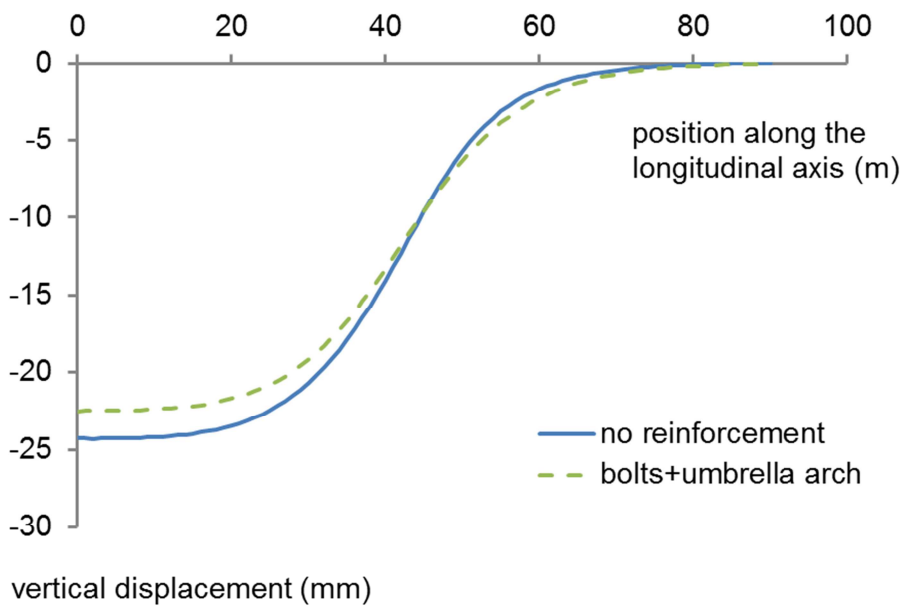


Figure 8. Final longitudinal settlement profiles

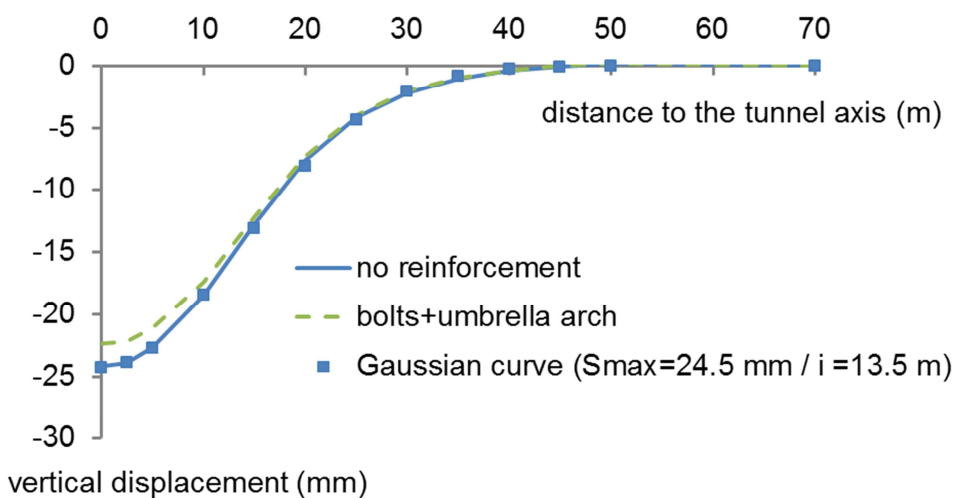


Figure 9. Final transversal settlement troughs

The values of the maximum settlement are given in Table 1.

Table 1. Maximum final settlements for each simulation of calculation

Support type	Maximum final settlement (mm)
none	24.5
bolts	24.3
umbrella arch	22.5
umbrella arch + face bolts	22.5

In the first place, the volume loss obtained in the simulation is equal of 0.8%. This means that the numerical simulation is representative of a realistic situation.

The maximum settlements obtained in the simulation are in the same order as the value anticipated using the empirical correlations. By contrast, the width of the settlement trough obtained numerically is close to 13 m (with or without pre-supports), thus much larger than the empirical value of 8.6 m. This poor performance of numerical models, as regards the settlement trough width, has been reported previously by many authors (for instance Addenbrooke et al, 1997), and generally attributed to a lack of representativeness of the constitutive models for the ground.

The reinforcement of the tunnel face by bolts has practically no influence on the computed maximum final settlement. The umbrella arch alone or associated with bolts decreases the maximum final settlement by 7.4% with respect to the unreinforced case. In other words, the numerical simulation does not seem to indicate that the pre-supports are able to effectively reduce the settlements, at least for the range of values considered here, i.e. in situations where maximum settlements are in the order of 25 mm.

We have performed a second series of simulation for lower ground properties, namely $E_{50}^{ref} = 30$ MPa, $E_{ur}^{ref} = 90$ MPa and $c' = 30$ kPa instead of the reference values (40 MPa, 120 MPa and 40 kPa respectively), all other parameters being unchanged. The maximum settlement in the simulation without pre-supports was increased up to 38 mm (which corresponds to an increase by 56%) and the decrease in maximum settlement obtained with the umbrella arch was equal to 9.3%.

5.3 Influence of the geometry

In the simulations above, the mesh reproduces the geometry of the concrete lining. We discuss here the error made if the mesh takes into account a constant section instead of a conical shape, and the influence of this simplification on the conclusions regarding the influence of the pre-reinforcements on the settlements.

We have built a new mesh, using the software C-Newton, developed by Itech (2018) in the framework of the French research project Newton. This software generates automatically the tridimensional mesh and the data files. The pipes are horizontal and lean on the lining previously built; the simulation takes into account the umbrella arch with a constant length ahead of the tunnel face. Bolts in the tunnel face are represented by bar elements (instead of the homogenized approach presented in section 4.2), with a constant length ahead of the tunnel face. The length of the excavation steps, the position where the invert is built, and many other parameters are variable. The finite element simulation itself is performed using the same solver as in the previous simulations. Figure 10 presents the tridimensional mesh obtained. It is composed of 380000 nodes and 145000 quadratic elements (20-node hexahedra and 15-node pentahedra). The simulations are carried out with the same material properties, boundary conditions and initial stresses as before, with the reference values of the ground properties.

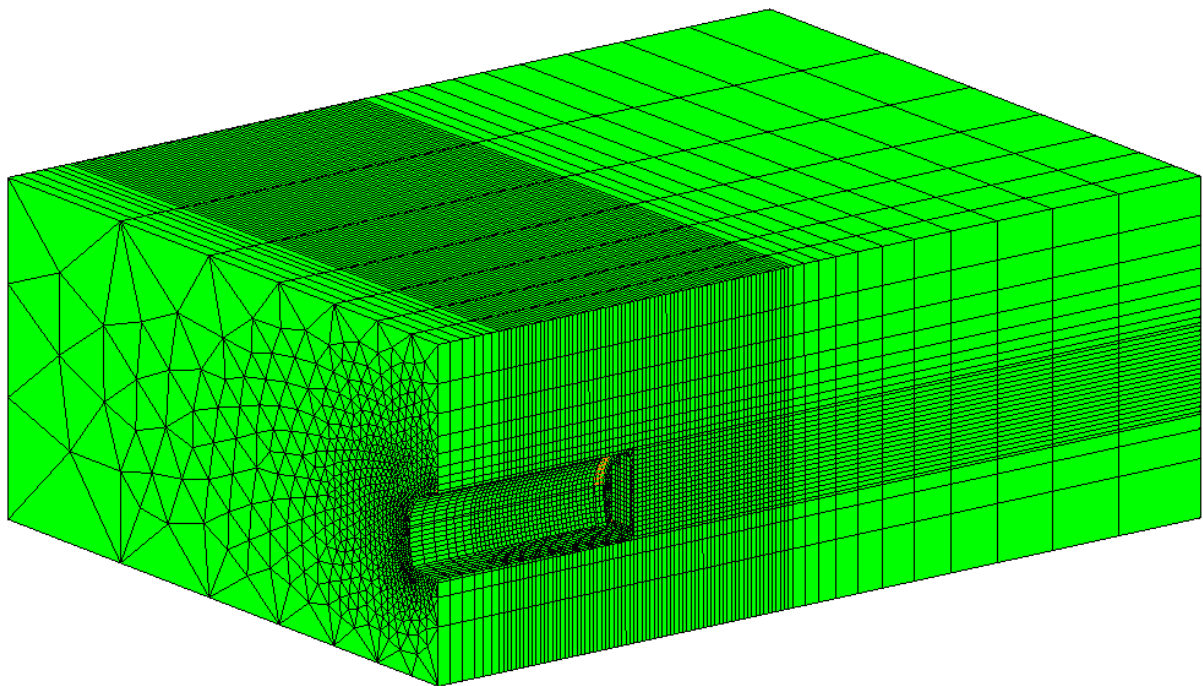


Figure 10. View of the tridimensional mesh generated using C-Newton

The maximum final settlements obtained for the non-reinforced case and the case reinforced by the combination of bolts in the tunnel face and 20-pipes umbrella arches are equal to 23.9 and 21.7 mm respectively.

On the one hand, the absolute values of settlements are in good agreement with those obtained with the more complex mesh.

On the other hand, the reduction in maximum final settlement obtained thanks to the umbrella arch is of 9% with respect to the calculation without pre-reinforcement. This is also very close to the conclusions obtained with a conical geometry. This shows that the proposed geometrical simplification is largely validated (at least for the parameters taken into account here).

6 Application to a case study

In this section, the proposed approach is applied to the case study reported by Janin et al (2015), in Toulon. The southern Toulon tunnel is an urban shallow tunnel, with an average section of 120 m², with a height of 11.2 m and a width of 12.7 m. The mean section is presented in Figure 11. The thickness of the sprayed concrete lining is 25 cm; the invert is 30 cm thick.

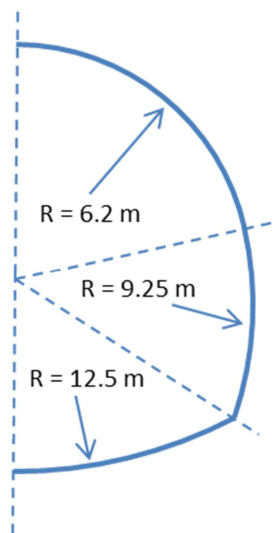


Figure 11. Geometry of the average section considered in the model

The tunnel was built without resorting to a TBM, and the ground was reinforced by face bolts and an umbrella arch, composed of 13 steel autodrilling pipes (51/33 mm, 18 m long) installed every 9 m, with an angle of 6 degrees between the pipes and the direction of the tunnel axis. Again, the tunnel is dug by steps of 1.5 m. In the simulation, the invert is built

by sections of 9 m when the distance between the tunnel face and the existing invert is equal to 10.5 m.

The geological profile shows three layers: a 3.5 m superficial layer of fill, a layer of colluviums between 3.5 m and 5.9 m deep, and a bedrock at depths larger than 5.9 m. The tunnel axis depth is 30 m. The mechanical properties adopted hereafter (Table 2) are taken from Janin et al (2015) without any modification.

Table 2. Mechanical properties

	volume weight (kn/m ³)	K _o	E ₅₀ ^{ref} (MPa)	v _{ur} (-)	c' (kPa)	φ' (deg)	ψ (deg)
Fill	19	1	1.6	0.2	2	20	0
Colluvium	20.8	1	40	0.2	10	30	0
Bedrock	24.2	1	240	0.2	40	25	0

For the other parameters of the Hardening Soil Model, we adopted $E_{ur}^{ref} = 3 E_{50}^{ref}$ and $R_f = 0.9$.

For the lining and the invert, we adopted the same values as Janin et al (2015): $E = 13.5$ GPa for the lining and 14 GPa for the invert.

A new mesh was generated for this case study. Since the tunnel is deeper than in the previous case, it was necessary to increase the dimensions of the mesh: it is 120 m wide, 168 m long and 70 m high, and the final excavation length is 72 m. The numerical results are presented in Figure 12 and Figure 13, and compared with the measures reported by Janin et al (2015). They show a good agreement between the finite element model and the observations.

In the numerical simulations, the influence of the umbrella arch on the settlements is even less than in the simulations presented above: the relative difference is equal to 3%. This can be explained by the fact that the ground is significantly stiffer than in the simulations considered before.

In a general way, our results are consistent with the conclusions drawn by Janin et al (2015).

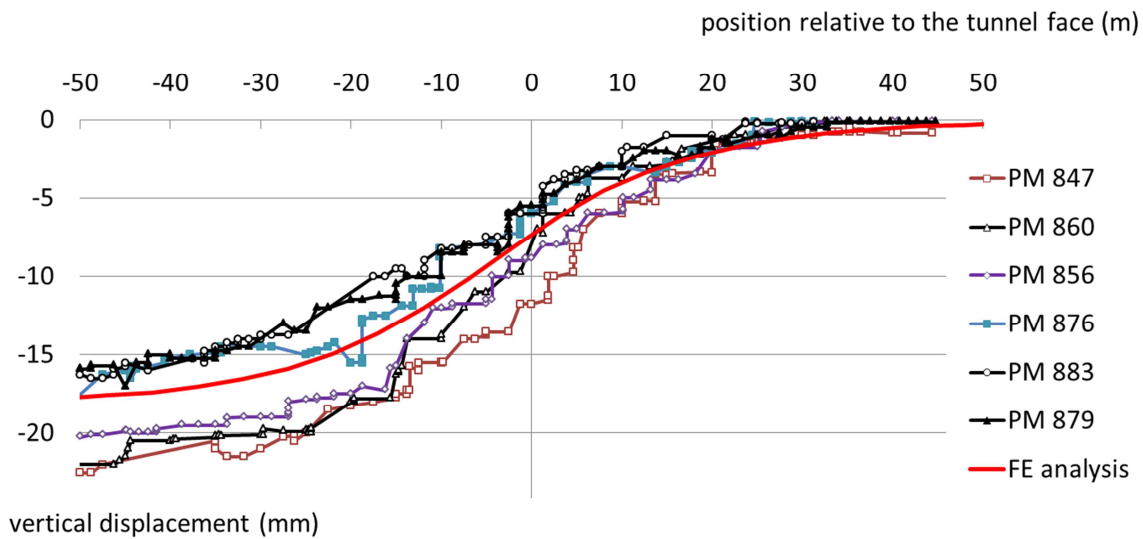


Figure 12. Longitudinal settlement profiles: comparison of numerical simulations with measurements reported by Janin et al (2015)

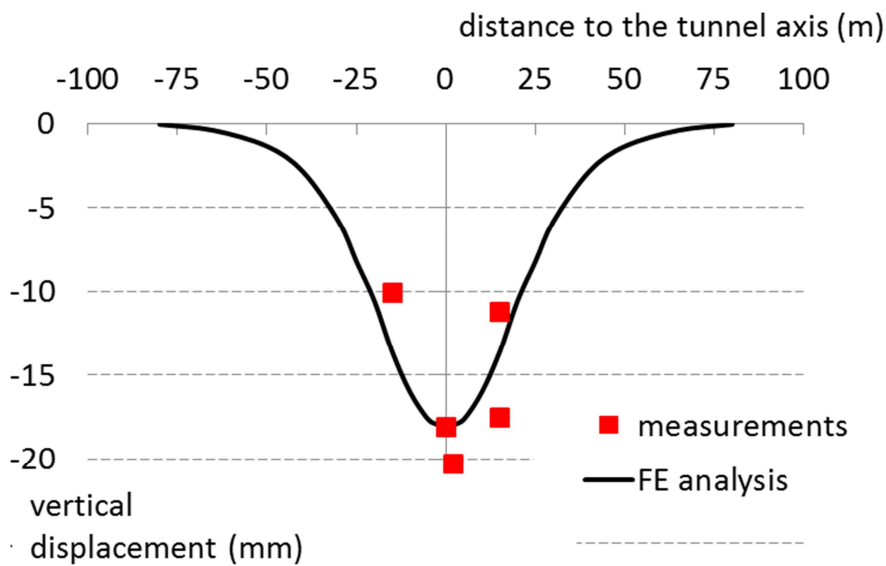


Figure 13. Final settlement transversal profiles: comparison of numerical simulations with measurements reported by Janin et al (2015)

7 Discussion

The influence of face bolts and of the umbrella arch on the settlements induced by tunneling is difficult to quantify. Numerical simulations provide a way of investigating the problem. However, relatively few works have provided so far quantitative results regarding the reduction of settlements obtained with these techniques:

Bae et al (2005) have presented simulations in which the ground settlements are reduced by up to 52%, using a homogenized framework to account for the role of the umbrella arch. It is worth recalling that Volkmann et al (2006) have concluded that the umbrella arch cannot be correctly simulated with that type of approach, if settlements are to be predicted. On the other hand, Ocak (2008) reports, in the specific case of a tunnel of the Istanbul metro, that the surface settlements obtained with the umbrella arch are about three times less than the ones observed in the same area without it.

Aksoy and Onargan (2010) presented three dimensional finite element simulations in which the umbrella arch made it possible to reduce the maximum settlement from 23 mm to 7 mm, which corresponds to a reduction by 70%.

Janin (2012) has obtained a reduction in final settlement (with respect to the case without pre-reinforcement) of 7% with the umbrella arch alone. Monnet and Jahangir (2014) have proposed similar simulations and obtained a settlement reduction due to the umbrella arch of 5%. These authors tend to reach conclusions very similar to those obtained in the present study, even if Janin (2012) obtained a reduction up to 44% if the umbrella arch is combined with steel (not fiberglass) bolts.

Gilleron (2016) and Gilleron et al (2019) have proposed another three dimensional analysis, based on an original constitutive model that combines an anisotropic nonlinear elastic model with the Mohr-Coulomb criterion. The umbrella arch provides a reduction of the settlements by 20 % with respect to the case without pre-reinforcement, and up to 31% in combination with bolts. Again the umbrella arch seems to provide only a limited reduction in settlements.

From these results, it can be observed that the computed efficiency of the umbrella arch to reduce the settlement varies greatly according to the case under discussion; no author seems to have presented a direct correlation between, on the one hand, the properties of the umbrella and of the ground, and, on the other hand, the reduction settlement that can be obtained. Yet, Oke et al (2014a) have carried out a literature review of data of tunnelling projects and provided an abacus that can be used to predict the order of magnitude of the reduction of surface settlement that can be achieved, for a given type of umbrella arch, as a function of the ratio of the overburden to the height of excavation. The diagram does not include the influence of the ground, but can serve as a reference. For the type of tunnel under consideration above, the diagram leads to expect a reduction in the order of 27 to 55 %, while, in the present study, the umbrella arch reduces the settlement by less than 10% with respect to the case without pre-reinforcement. Arguably, the relative increase of stiffness provided by the umbrella arch depends on the ground

properties and on the absolute values of the surface settlements: it is likely that the settlement reduction provided by the umbrella arch is larger in a softer ground; or, alternatively, it is likely that the umbrella arch is an efficient solution to reduce settlements above a certain value (in the order of 100 mm or more for instance), but not if the settlements are small. In the literature review by Oke et al (2014a), the order of magnitude of the settlements is generally three to ten times larger than those obtained in our simulations, which may explain at least a part of the difference in the settlement reduction obtained.

8 Conclusion

Quantifying the influence of pre-supporting systems on the settlements induced by tunneling is a difficult problem. This paper demonstrates that three dimensional finite element codes make it possible to investigate various aspects of the problem by performing all kinds of parametric studies in a relatively routine manner, once tools specifically dedicated to this application have been developed.

In this paper, we have proposed a three dimensional simulation with a mesh that reproduces precisely the geometry of the lining of a tunnel built under an umbrella arch. For the parameters adopted here, the reduction in settlement provided by the umbrella arch is in the order of 7 to 9% with respect to the non reinforced case. The results show that the use of a simplified geometry for the lining has little influence on the results.

Our simulations also tend to show that the pre-supports do not always make it possible to reduce the magnitude of the maximum settlements by more than a few percents, depending on the geotechnical context. The cost and constraints of the umbrella arch technique justify to keep on refining the tools to anticipate the settlement reduction that can be achieved in the context of a given project. Also, if the umbrella arch does not reduce the settlement to acceptable values, it is certainly worth considering compensation injections, which remain to be taken into account in the simulations.

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10 References

- 1- Addenbrooke TI, Potts DM, Puzrin AM (1997) The influence of pre-failure stiffness on the numerical analysis of tunnel construction, *Géotechnique*, 47(3), 693-712.
- 2- AFTES (2001). Recommendations on the convergence-confinement method. http://www.aftes.asso.fr/publications_recommandations.html
- 3- Aksoy CO, Onargan T (2010). The role of umbrella arch and face bolt as deformation preventing support system in preventing building damages, *Tunnelling and Underground Space Technology*, 25, 553-559.
- 4- Bae GJ, Shin HS, Sicilia C, Choi YG, Lim JJ (2005). Homogenization framework for three-dimensional elastoplastic finite element analysis of a grouted pipe-roofing reinforcement method for tunnelling, *Int J Numer Anal Methods in Geomechanics*, 29: 1-24.
- 5- Bourgeois E, Hassen G, de Buhan P (2012a). Settlement analysis of piled-raft foundations by means of a multiphase model accounting for soil-pile interactions, *Computers and Geotechnics*, 46 ; 26–38. doi : 10.1016/j.compgeo.2012.05.015
- 6- Bourgeois E, Hassen G, de Buhan P (2012b). Finite element simulations of the behavior of piled-raft foundations using a multiphase model, *Int. J. Numer. Anal. Meth. Geomech.* 2012. DOI: 10.1002/nag.2077

- 7- Bourgeois E, Le Kouby A, Soyez L (2012c). Influence of the strip–backfill interaction model in the analysis of the behavior of a mechanically stabilized earth wall, *Soils and Foundations*, 52(3):550–561. doi : 10.1016/j.sandf.2012.05.012
- 8- Bourgeois E, Corfdir A, Chau TL (2013). Analysis of long-term deformations of MSE walls based on various corrosion scenarios, *Soils and Foundations*, 53(2):259-271.
- 9- De Buhan P, Sudret B (2000) Micropolar multiphase model for materials reinforced by linear inclusions, *Eur. J. Mech. A/Solids* 19 (4), 669-687.
- 10- De Buhan P, Hassen G, Bourgeois E (2007). Multiphase model as an improved homogenization procedure for the design of bolt-supported tunnels, *EURO:TUN 2007, ECCOMAS Conference on Computational Methods in Tunnelling*.
- 11- De Buhan P, Bourgeois E, Hassen G (2008). Numerical simulation of bolt-supported tunnels by means of a multiphase model conceived as an improved homogenization procedure, *Int. J. Numer. Anal. Meth. Geomech.* 2008; 32:1597–1615
- 12- Elyasi A, Jawadi M, Moradi T, Moharrami J, Parnian S, Amrac M (2016). Numerical modeling of an umbrella arch as a pre-support system in difficult geological conditions: a case study, *Bull Eng Geol Environ* 75:211-221.
- 13- Geuzaine C, Remacle JF (2009). Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities. *International Journal for Numerical Methods in Engineering* 79(11), 1309-1331.
- 14- Gilleron N (2016). Méthode de prévision des tassements provoqués par le creusement des tunnels urbains et influence des présoutènements, thèse de doctorat, Université Paris-Est, 238 p.
- 15- Gilleron N, Bourgeois E, Chatellier P, Saïtta A (2019). An anisotropic stiffness model for the prediction of the evaluation of the settlements induced by tunneling in the Paris area, in preparation.
- 15- Hejazi Y, Dias D, Kastner R (2008). Impact of constitutive models on the numerical analysis of underground constructions. *Acta Geotech.* 3 (4), 251–258.
- 16- Hoek E (2004). Numerical modelling for shallow tunnels in weak rock; Discussion paper #3 (geotecnica.dicea.unifi.it/hoek_shallow.pdf).
- 17- Humbert P, Fezans G, Dubouchet A, Remaud D (2005). CESAR-LCPC: a computation software package dedicated to civil engineering uses, *Bull. des Laboratoires des Ponts et Chaussées* 256-257.
- 18- Itech (2018). <http://www.itech-soft.com>

- 19- Janin JP (2012). Tunnels en milieu urbain : prévisions des tassements avec prise en compte des effets des présoutènements (renforcement du front de taille et voûte parapluie), PhD thesis, Institut National des Sciences Appliquées de Lyon, 267 p.
- 20- Janin JP, Dias D, Emeriault F, Kastner R, Le Bissonnais H, Guilloux A (2015). Numerical back-analysis of the southern Toulon tunnel measurements: A comparison of 3D and 2D approaches, *Engineering Geology*, 195, 42-52.
- 21- Kitchah F, Benmebarek S (2016). Finite difference analysis of an advance core pre-reinforcement system for Toulon's south tube, *Journal of Rock Mechanics and Geotechnical Engineering*, 8, 703-713.
- 22- Leca E, New B (2007). Settlements induced by tunneling in Soft Ground, *Tunnelling and Underground Space Technology*, 22, 119-149.
- 23- Mair RJ (1996). Settlement effects of bored tunnels. In: Proc. Int. Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, London, Balkema, pp. 43–53.
- 24- Möller SC (2006). Tunnel induced settlements and structural forces in linings. Doctoral thesis, Institute of Geotechnical Engineering, University of Stuttgart.
- 25- Monnet A, Jahangir E (2014). Preliminary 3D Modelling of Structural behaviour of Face Bolting and Umbrella Arch in Tunneling, *Plaxis Bulletin Autumn 2014*.
- 26- Ocak, I (2008). Control of surface settlements with umbrella arch method in second stage excavations of Istanbul Metro, *Tunnelling and Underground Space Technology*, 23, 674-681.
- 28- Oke J, Vlachopoulos N, Marinos V (2014a). Umbrella arch nomenclature and selection methodology for temporary support systems for the design and construction of tunnels, *Geotechnical and Geological Engineering*, 32, 97-130.
- 29- Oke J, Vlachopoulos N, Diederichs MS (2014b) Numerical analyses in the design of umbrella arch systems, *Journal of Rock Mechanics and Geotechnical Engineering*, 6, 546-564.
- 30- Oke J, Vlachopoulos N, Diederichs MS (2016). Semi-analytical model for umbrella arch systems employed in squeezing ground conditions, *Tunnelling and Underground Space Technology* 56, 136–156.
- 31- O'Reilly M, New B (1982). Settlements above tunnels in the United Kingdom. *Tunnelling*, 82, pp. 173-181.
- 32- Panet M, Guenot A (1982). Analysis of convergence behind the face of a tunnel. *Proceeding of the International Symposium Tunnelling, (IST'82)*, The Institution of Mining and Metallurgy, London, pp: 197-204.

- 33- Panet M (1995). Le calcul des tunnels par la méthode convergence-confinement. Presses de l'école nationale des Ponts et chaussées, Paris. ISBN: 2859782303, pp : 177.
- 34- Peck R (1969). Deep excavations and tunnelling in soft ground. 7e International Conference Soil Mechanics and Foundation Engineering.
- 35- Peila D, Marchino C, Todaro C, Luciani A (2017) Comparison of the results of analytical and numerical models of pre-reinforcement in shallow tunnels, Archives of Civil Engineering, vol LXIII, 4, 135-147, doi : 10.1515/ace-2017-0045.
- 36- Plaxis (2018). Plaxis 2D Material Models Manual 2018.
- 37- Schanz T, Vermeer PA, Bonnier PG (1999). The hardening soil model: formulation and verification, Beyond 2000 in Computational Geotechnics, Balkema, Rotterdam, 281-290.
- 38- Shi Y, Yang J, Wang S (2014) Sub-horizontal reinforcement of weathered granite before tunneling beneath a spillway, Int J Rock Mechanics and Mining Sciences, 283-293.
- 39- Song KI, Cho GC, Chang SB, Lee IM (2013). Beam–spring structural analysis for the design of a tunnel pre-reinforcement support system, Int J Rock Mechanics and Mining Sciences, 59, 139-150.
- 40- Sudret B, de Buhan P (2001). Multiphase model for inclusion reinforced geostructures. Application to rockbolted tunnels and piled raft foundations Int. J. Num. An. Meth. Geotech. 25 (2001), pp. 155-182
- 41- Volkmann GM, Button EA, Schubert W (2006). A contribution to the design of tunnels supported by a pipe roof, Proc 41st US Rock Mechanics Symp, American Rock Mechanics Assoc, Golden (CO).
- 42- Volkmann GM, Schubert W (2010). A load and load transfer model for pipe umbrella support, in Rock Mechanics in Civil and Environmental Engineering, Zhao, Labiouse, Dudt & Mathier (eds), 379-382.
- 43- Wang Z, Li W, Li S, Qiu W, Ding W (2018). Development of an Optimum Forepole Spacing (OFS) determination method for tunnelling in silty clay with a case study, Tunnelling and Underground Space Technology 74, 20-32.
- 44- Zhang Z, Li H, Liu H, Li G, Shi X (2014). Load transferring mechanism of pipe umbrella support in shallow-buried tunnels, Tunnelling and Underground Space Technology, 43, 213–221.