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Effect of the Umbrella Arch Technique Modelled as a Homogenized Area above a Cross Passage

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Abstract: The stability of tunnel cross passages excavated in soft soil has always been a major challenge. In recent years, new techniques based on the installation of pre-reinforcements before tunnel excavation have been developed to control excavation-induced deformation and surface settlements. In this paper, a finite element numerical simulation was conducted to study the reduction effect of an umbrella vault element modelled as a homogenized area on the deformations induced after the excavation of a cross passage. The results of this study show that the ground deformations can be controlled efficiently by using this type of pre-reinforcement. However, the findings showed that there is no effect of the umbrella arch length on the reduction of the ground deformations. This paper represents a very good demonstration of 3D modelling of tunnel junctions using pre-support techniques; it is the most advanced/appropriate research tool for studying the behaviour of cross passages and is useful as a paradigm for other researchers and practitioners.

Keywords: cross passage; numerical modelling; ground surface settlement; umbrella arch technique; homogenization technique

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1. Introduction

Cross passages are an important component of an underground structure: they are built at regular intervals for requirements such as safety, maintenance, emergency, passenger evacuation, and ventilation. These structures have a small cross-section, shorter length, and lower stiffness. Nevertheless, several studies have shown that the opening of these galleries frequently causes displacements and deformations in the main tunnel lining as well as in the ground surface.

Maintaining the stability of the cross passages is of paramount importance. Therefore, it is often necessary to reinforce the soil prior to excavation. Depending on the geological conditions, various soil reinforcement techniques can be incorporated. In particular, the use of pre-support methods, including the umbrella arch method (UAM), jet grouting, mechanical pre-cutting and sub-horizontal fibreglass face reinforcement could keep the tunnel face stable in soft grounds. This paper focuses only on the implementation of the Umbrella Arch Method (UAM) pre-support in cross-passages, and other reinforcement techniques are outside the scope of this research.

The umbrella arch technique or the pipe roof support system Figure 1 can be defined as an implementation of steel pipes or fibreglass pipes from the actual tunnel face to the front in an umbrella or canopy shape around the area to be excavated [1]; the pipes have an average length of 12 to 15 m, and an outer diameter varying from 70 to 200 mm. Steel pipes are typically installed at a 5 to 10 degree angle to create a sort of "umbrella" over the ground to be excavated [2]. The pipes will eventually be executed with advances that guarantee the necessary overlap for the stability of the tunnel face. The pipe umbrella method is installed in two different ways: predrilling and cased drilling [3].

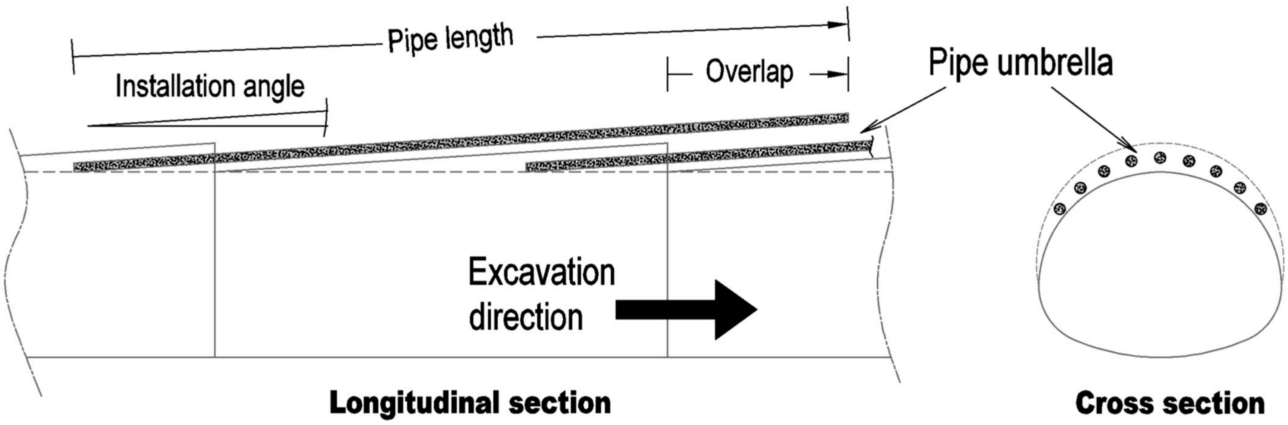


Figure 1. Cross section and longitudinal profil of an umbrella arch technique.

Regarding the design parameters associated with the umbrella arch elements, numerical simulations using 2D and 3D models, in addition to analytical models, were performed by some research studies to better understand the influence of design parameters on the forepole elements used in an umbrella arch system. Oke et al. [4] have contributed to the understanding of the influence of design parameters on umbrella vault elements. The authors used 2D finite element software using a homogeneous reinforced zone, and 3D finite difference software using structural elements to capture the behaviour of the tunnel front failure as a function of the following parameters: spacing, length, overlap, coverage angle, size, and angle of installation. Another study using an analytical approach was presented by Ranjbarnia et al. [5], the authors concluded that the diameter of a single umbrella element is more effective than the adjacent distance between elements to control tunnel displacement.

In reviewing the literature that covers the umbrella arch method (UAM), it is notable that the performance of this type of pre-support has been consistently discussed by many authors, many of whom agree that the UAM has an efficient effect on the stability of the tunnel face in difficult ground conditions. Volkmann and Schubert [3] proved that tunnel excavation under the umbrella support results in lower settlements, especially at the beginning of each pipe roof umbrella field.

In the same context, an interesting study was conducted by Hisatake and Ohno [6] by performing a series of centrifuge tests in unsaturated sands. The analysis of the results obtained showed that the application of the umbrella vault pre-support reduces the maximum settlement of excavated ground by full face to about a quarter of the non-pre-supported value under the same experimental conditions. Another study using the same type of analysis was conducted by Juneja et al. [7] and proved that the length of the forepole element has an influence on the tunnel stability. By comparing the numerical analysis with the results of real measurements, ref. [8,9] confirmed that the umbrella arch pipe was very effective at minimizing the soil surface settlement by more than 60%.

Certain reinforcement systems are usually applied in combination with the umbrella arch method; in the example of face bolting, the conjunction of these two types of pre-supports has proven to reduce the surface settlements as well as convergence values in the tunnel face [10–14].

Due to the complex geometry of a tunnel intersection with a cross passage, the numerical simulation of individual umbrella pipes over a cross-passage section is very complicated. Therefore, a simplified approach based on the homogenization method is implemented in a 3D numerical model to evaluate the effect of an umbrella arch on ground settlements caused by the excavation of a cross passage. The homogenization method consists of replacing the reinforced medium with an equivalent homogenized medium. The properties of the latter are obtained from those of the individual components (i.e., the rock and the bolts) using the theoretical tools of homogenization for periodic media [15]. The effectiveness of the homogenization method has already been evaluated and proven by several authors, including [15–17].

The tunnelling procedure using UAM, either independently or in combination with other pre-reinforcement techniques, is well explained in the literature by several authors [18–21]. However, its implementation in a tunnel junction area is seldom discussed. With the exception of [22], which assessed the effect of both deep soil-mixing and umbrella vault methods to stabilize the excavation of a cross passage, and [23] who studied the effect of the umbrella arch technique on a cross passage using a 2D homogenized numerical model, few studies have examined the effect of the umbrella arch technique solely on the stability of a cross passage excavation in a 3D simulation. To bridge this gap, this paper presents a finite element modelling (FEM) approach of an umbrella arch method modelled as a homogenized area using the theoretical tools of homogenization for periodic media applied to a cross passage excavated with the conventional method (NATM).

The approach relies on three-dimensional finite element simulations using the software CESAR-LCPC 3D V5. The novelty of this study lies in the fact that the sensitivities of a particular umbrella arch configuration are investigated in detail and with precision by means of a three-dimensional finite element analysis taking into account the staged excavation. Furthermore, with the description of the modelling and simulation process, the results provide a benchmark reference for similar numerical investigations that are rare in the scientific literature.

2. Project Description and Geological Conditions

The Algiers metro project is a railway transport network serving the city of Algiers since 2011. The extension of line 1 of the Algiers metro from El-Harrach Centre station to Houari Boumediene airport is a major and vital project for the capital. The line extends over a distance of 9.5 km and includes 9 stations and 10 ventilation shafts. Cross passage 6 is located in an empty site in the Bab Ezzouar area as shown in Figure 2. The cross passage was excavated with the NATM method, while the main tunnel was excavated with an earth pressure TBM for the first time in Algeria. An extensive site investigation was carried out to determine the ground conditions. The subsurface soil was characterized by geotechnical drilling, in situ data and laboratory testing. According to geology and geotechnical investigations, the soil where the tunnels are laid out is quaternary deposits with lithological features consisting of silty-clayey sands occasionally mixed with stones with the presence of sandstone, superimposed on the formations of the recent Pliocene and ancient quaternary constituted, on the scale of the structure, by marl and marly clays known as El Harrach.

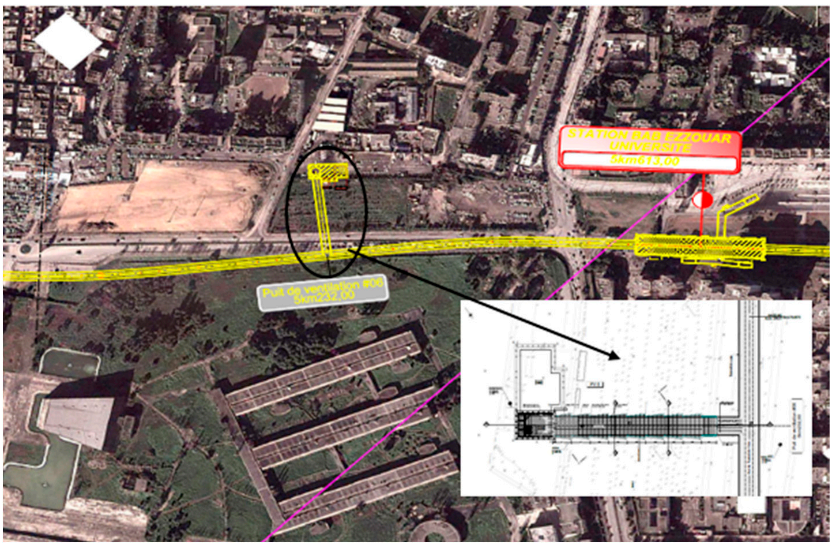
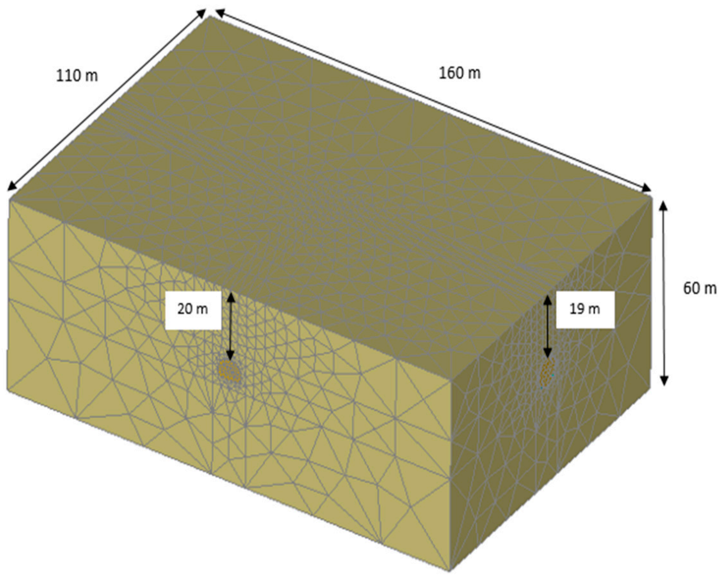


Figure 2. Location of the cross passage 6 in the Algiers metro project, Algeria.

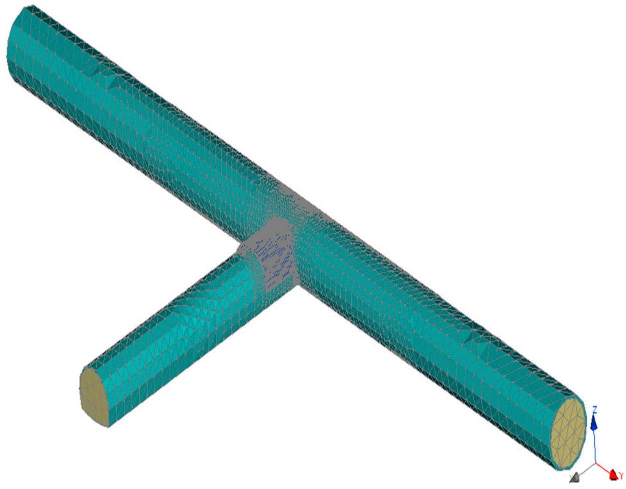
3. Modelling Approach

3.1. Geometric Description and Constitutive Model

The geometric model of the intersection considered in this study is shown in Figure 3 with an aspect ratio of d/D = 0.8. The main tunnel has a circular shape with a diameter of D = 10 m, while the cross passage has a horseshoe shape with a diameter of d = 8 m. The umbrella arch elements are modelled as a homogenized medium; the elements are assumed to behave as a linear elastic material with the properties shown in Table 1. The FE model with improved soil is shown in Figure 4, where the surrounding soil has been masked for more clarity.



(**a**)



(**b**)

Figure 3. Three-dimensional numerical model: (**a**) isometric view; (**b**) relative positions of the main tunnel and the cross passage.

Table 1. Parameters chosen for the modelling of the umbrella vault.

Parameter	Elasticity Modulus (MPa)	Thickness (m)	Poisson's Ratio
Value	9981	0.5	0.3

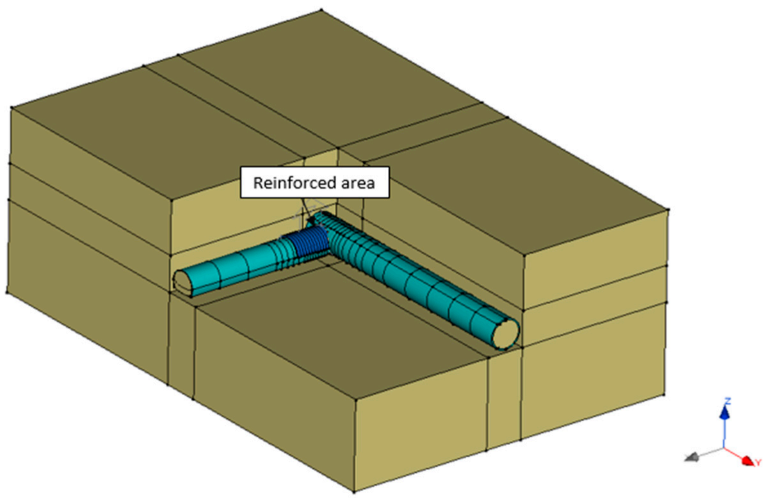


Figure 4. Geometry adopted for the improved region above the cross passage.

The behaviour of the soil mass was assumed to be governed by an elastoplastic constitutive model based on the Mohr–Coulomb failure criterion with a non-associative flow rule. The support elements were modelled as a linear elastic material. For the Mohr–Coulomb model, the stress limit states are described through the friction angle (ϕ), cohesion (c), and expansion angle (ψ). The parameters of the constitutive model were selected on the basis of geotechnical study of the project area, and are summarized in Table 2.

Table 2. Geomechanical characteristics retained in the 3D modelling.

Parameter	Marl	Support of the Main Tunnel	Support of the Cross Passage
Density $\left(Kn/m^3\right)$	21	/	/
Elasticity modulus (MPa)	111	35,000	25,000
Poisson's ratio	0.3	0.2	0.2
Cohesion (KPa)	56	/	/
Friction angle (°)	21	/	/
Expansion angle (°)	10	/	/

3.2. Boundary Conditions

In order to neglect the influence of the borders, the mesh size is set to 160 m in the longitudinal direction Y (direction of excavation), and transverse X is 110 m and 60 m in depth. The coverage above the tunnel is 20 m. The mesh is refined around the intersection. In the end, the number of zones in the mesh is about 130,714 and it has 22,045 nodes.

3.3. Modelling the Staged Construction

The initial step was implemented to generate the effects of geostatic stress. The main tunnel was then excavated using the full-face technique. A face pressure P_f = 0.252 MPa was applied at the front face of the excavation, and its value was calculated using the formula mentioned by [24,25]. The excavation is modelled by successive deactivation of the tunnel volume elements; during this phase a certain percentage of stress relaxation λ is applied, while the lining is activated and deconfinement is completed after each excavation step. Subsequently, the homogenized medium representing the umbrella arch pipes is activated and the excavation of the cross passage is done in semi-section. The excavation length of the main tunnel was set at 1.5 m, which is the same length as the segments used in situ. For the cross passage, the excavation length was 1 m, which is also the length used in the project when excavating the cross passage. Steps 1–62 were performed to simulate the construction of the main tunnel and steps 63–116 were performed to model the activation of the umbrella arch and the construction of the lateral opening and the cross passage. The percentage of relaxation λ was calculated using the C-Lambda software. For simplification reasons, only one soil layer was considered in the 3D modelling, namely the marl layer.

To assess the settlement reduction provided by the umbrella arch technique, three models with different pre-support lengths were performed; the lengths of the umbrella arch elements will be as follows: L = 8 m, L = 10 m, L = 12 m.

4. Results and Discussions

In order to evaluate the effect of reinforcing by umbrella vault, the following quantities were compared:

(1) Transverse settlement trough
(2) Extrusion at the front face along the vertical axis of the cross passage
(3) Plastic zones

4.1. Transverse Settlement Trough

Looking at Figure 5, which represents the distribution of the transverse settlement as a function of the different lengths of the umbrella arch before and after the excavation of the cross passage, it can be seen first of all that the excavation of the cross passage generated an increase in the value of the maximum settlement as well as a displacement of its position of almost 11 m with respect to the centerline of the main tunnel. Furthermore, the application of the reinforcement before the excavation of the cross passage decreases the values of the settlement in the ground by almost 30%; however, there is no significant influence of the length of the umbrella arch according to the results. The effect of reinforcement by the umbrella arch technique on the reduction of ground settlements has already been reported by [26–28].

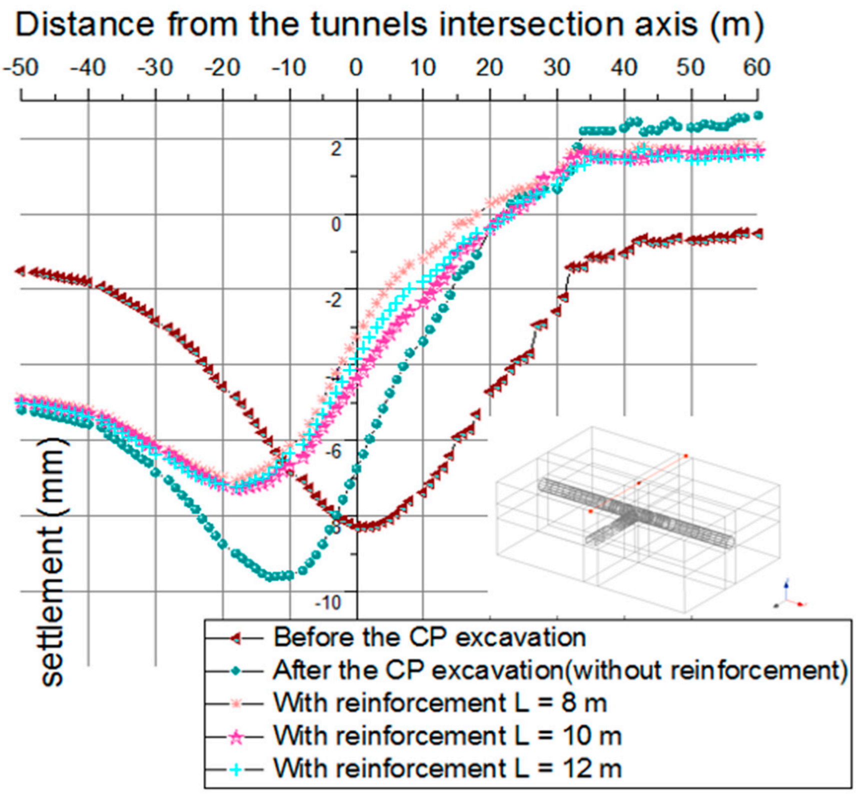


Figure 5. Effect of the umbrella arch technique on the transverse settlement trough.

4.2. Extrusion at the Front Face along the Vertical Axis of the Cross Passage

Figure 6 compares the numerical results in terms of the extrusion of the front face at the vertical axis of the cross passage. It is evident that the umbrella vault reinforcement plays a dominant role in the extrusion of the front face: it effectively decreased the maximum surface settlement by approximately 20% from 75 to 60 mm. In contrast to these results, several authors have argued the effectiveness of the umbrella arch on the face extrusion and many have concluded that it has little or no influence on the movements of the front face, as in the example of [29].

4.3. Plastic Zones

Regarding the evolution of the plastic zone after the excavation of the cross passage, we can notice that the implementation of the umbrella arch had a significant influence on the distribution of the plastic zone both on the main tunnel and on the cross passage: this is particularly apparent in Figure 7. The extent of the plastic zone was notably reduced in the area where the umbrella arch was installed. These results are consistent with the findings of [30] who have confirmed that the use of fore-poling leads to a significant decrease in plastic zones.

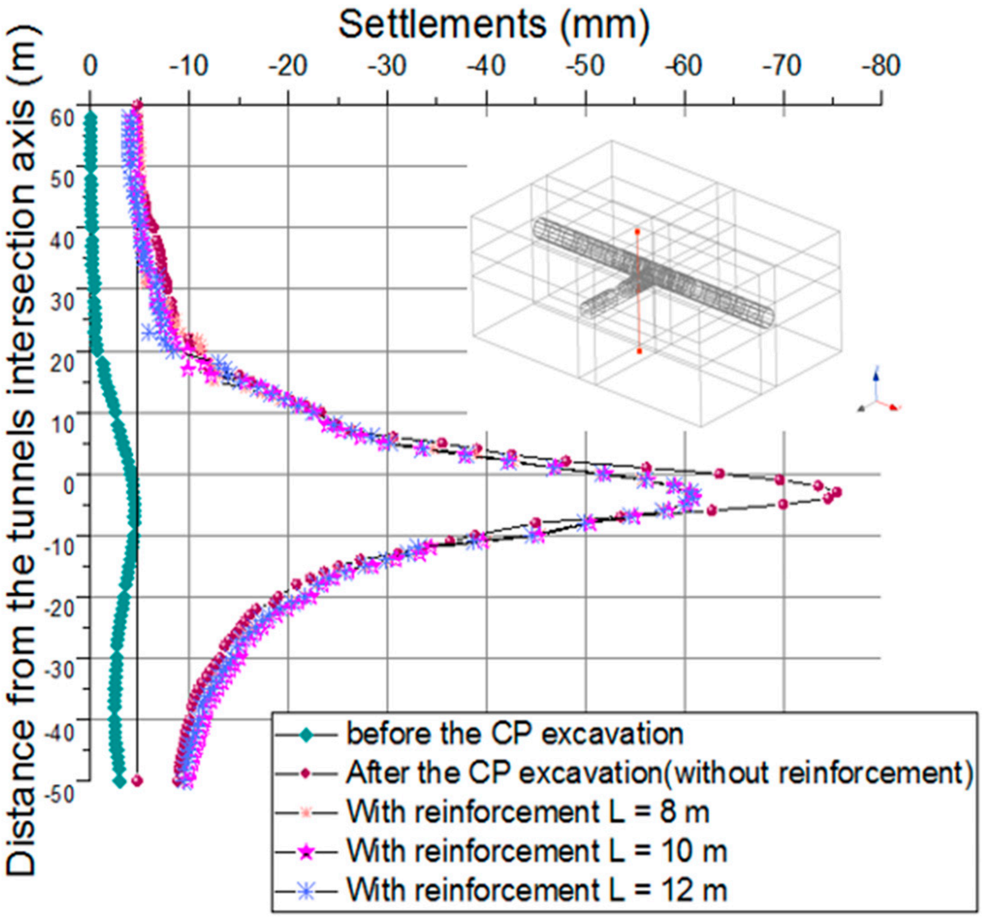


Figure 6. Effect of umbrella arch technique on face extrusion.

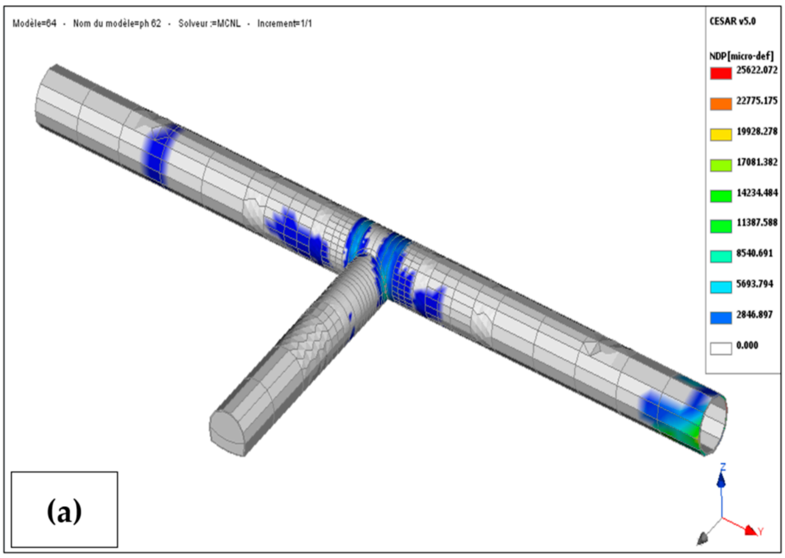


Figure 7. *Cont*.

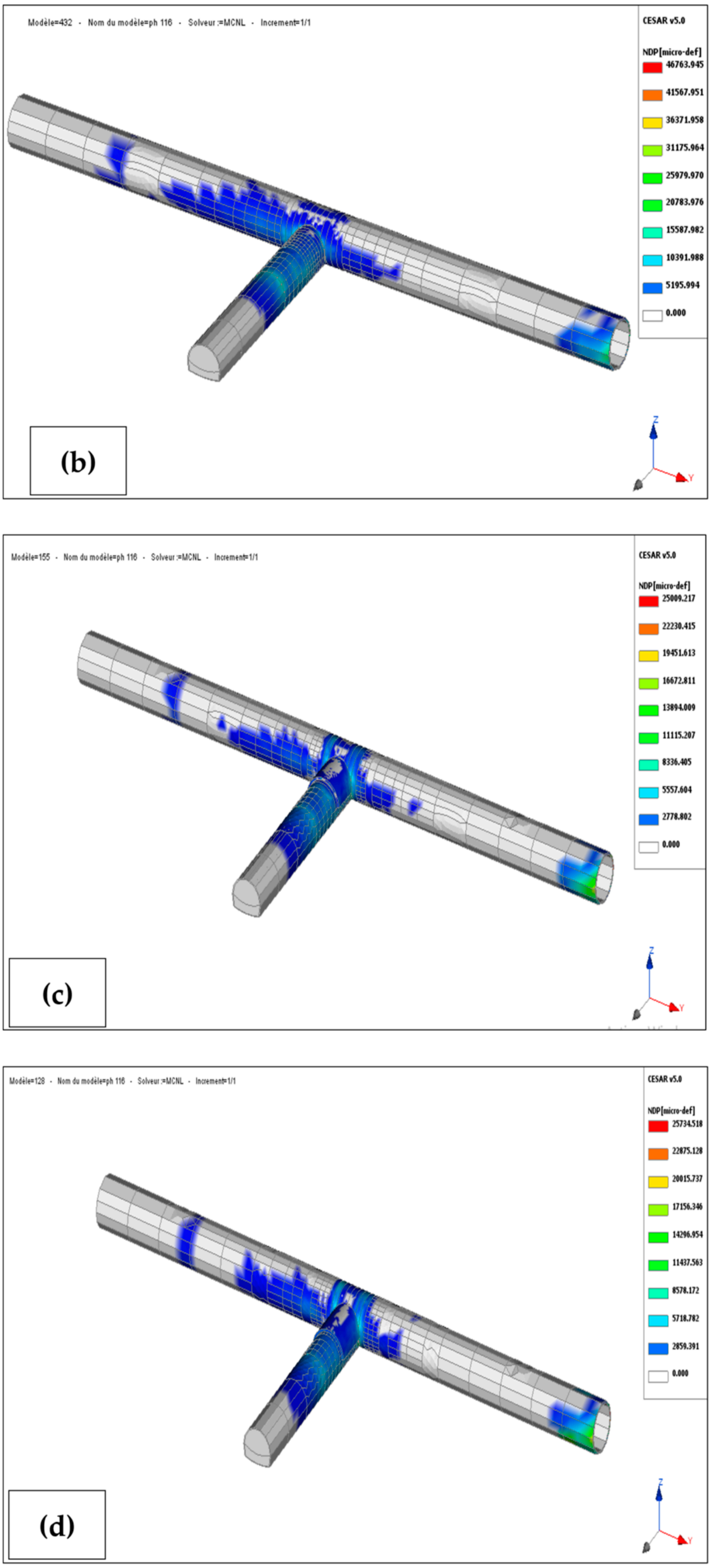


Figure 7. *Cont*.

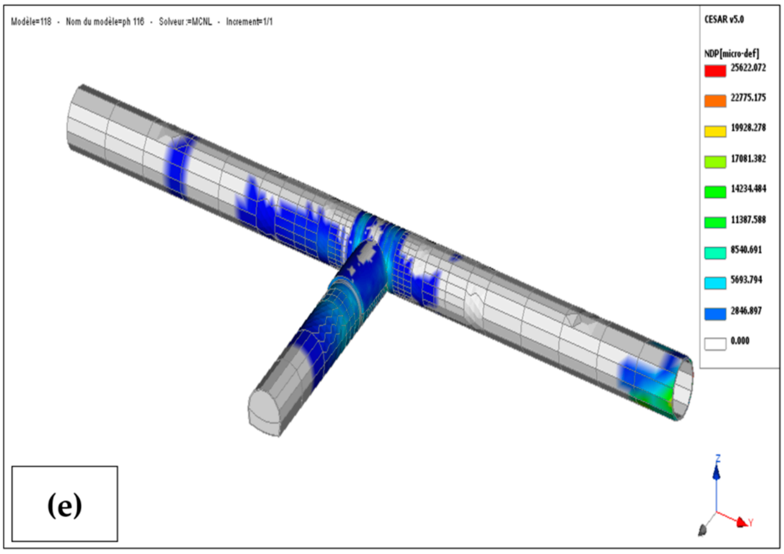


Figure 7. Effect of umbrella arch technique on the distribution of the plastic zone at the final construction step. (**a**) Before the cross-passage excavation, (**b**) After the cross-passage excavation (without reinforcement), (**c**) with reinforcement L = 8 m, (**d**) with reinforcement L = 10 m, (**e**) with reinforcement L = 12 m.

5. Conclusions

In this study, a 3D finite element simulation using the CESAR LCPC V5 finite element software was performed to investigate the effect of implementing the Umbrella Arch Method (UAM) in the intersection area between a tunnel and a cross-passage. The umbrella arch method was modelled as an equivalent homogenized medium using the theoretical homogenization tools for periodic media. The results showed that the use of this type of reinforcement effectively reduced the extent of surface settlement by nearly 30%; in addition, the extrusion at the front face along the vertical axis of the cross passage was decreased by about 20%. Furthermore, the extent of the plastic zone was significantly reduced in the area where the umbrella arch was installed. However, the results showed that the length of the umbrella arch elements had no significant influence on the extent of the ground deformation.

The present investigation confirmed that the 3D staged excavation proves to be a useful tool for assessing induced movements in tunnel junctions. The homogenization method, on the other hand, can be smoothly integrated into the modelling process, as it has been proven by literature and numerical results to have many practical advantages, including ease and accuracy of modelling, as well as the elimination of the convergence problems encountered when modelling with bar elements. This paper also provides a paradigm for the evaluation of tunnel-induced settlements and their mitigation based on a realistic design situation for metro tunnels. It thus also serves as a guide for future design exercises and is one of the few references in the international literature on finite element modelling of tunnel junctions with pre-supports.

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