

3D Numerical Study of Tunnel Advance Core Reinforcement: Application on Tunnel T4 from the Algerian East-West Highway

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ABSTRACT

The study of the balance and stability of tunnels is a matter of great importance. Movements resulting from excavation work on face and surface level of the tunnel are yet hard to apprehend. Lately, various methods and techniques of tunnel reinforcement have emerged, aiming firstly at controlling the deformations and settlements and on the other hand at maintaining the stability of tunnelling. The purpose of this work is to study the influence of strengthening the tunnel advance core on the behavior of the surrounding massif by comparing two methods of reinforcement, one called umbrella arch method and the other ADECO-RS method; which consist of strengthening the tunnel face with fiber glass bolts. These two methods have been used during the excavation work for the tunnel "T4" of the east-west Algerian highway. Numerical simulation results using the finite element program "Plaxis 3D Tunnel" have helped to demonstrate the potential efficiency of the ADECO-RS method compared to the umbrella arch method.

KEYWORDS: ADECO-RS method, Bolting, Numerical modeling, Reinforcement, Tunnel face, Umbrella arch method.

INTRODUCTION

During the excavation of tunnels, the most important problem is the stability of the tunnel face. The collapse of this one induces serious consequences on both human and financial plans. It is therefore necessary to limit the deformations in order to reduce settlements on the surface. Among the currently most used methods to stabilize the tunnel faces, there are "Umbrella Arch" and "ADECO-RS" (Controlled Analysis of Deformation in Rocks and Soils) methods.

Umbrella Arch Method (UAM) is commonly used for tunnel design in order to reinforce the ground around the tunnel and stabilize the tunnel face. It

consists of putting in place longitudinal bars or metal tubes at the periphery of the tunnel face, usually on the third or the quarter upper part of the circumference, resting on the last lining. This system is designed to limit decompressions and protect the excavation section from all surfaces of potential rupture.

The ADECO-RS method is a technique of pre-confinement, applied for the first time at the end of the 1980s in Italy (Lunardi, 1993). It consists of strengthening the tunnel face by bolting and using sealed tubular inclusions in the soil by an injection system to stabilize and to limit the extrusion of the tunnel face.

The two methods of reinforcement (ADECO-RS and Umbrella Arch) were used during the excavation of the tunnel T4 of the East-West

Highway in Algeria. In this paper, we present a comparison of measurements taken on-site relating to both reinforcement methods.

TUNNEL AND SITE SPECIFICATIONS

The T4 tunnel comes within the framework of the realization of the Maghrebine Unity Highway (MUH) which is about 7000 kilometers, crossing Algeria with a length of 1200 kilometers. The tunnel is part of the section 4 of this highway, it crosses mount Djebel El-Kantour north-east of the city of Constantine.

The highway tunnel comprises two substantially parallel tubes of a total length of 2500 meters (Figure

1). A distance of 22 meters separates the tubes. The dimension of the cross-section of each tube around the theoretical cut line is 17.9 m in width and 13 m in height. An access tunnel of 320 m in length was designed and connected to the main tube at 811 m from the northern portal; it aims to improve the excavation work progress by opening two tunnel faces in the middle of the tunnel, digging towards the southern portal. So, we come by having a total of six tunnel faces; two at northern portal (NL and NR), two in the middle of the tunnel towards the southern exit (MLS and MRS) and two at the (SL and SR) [L: Left, R: Right, N: North, S: South, M: Middle].

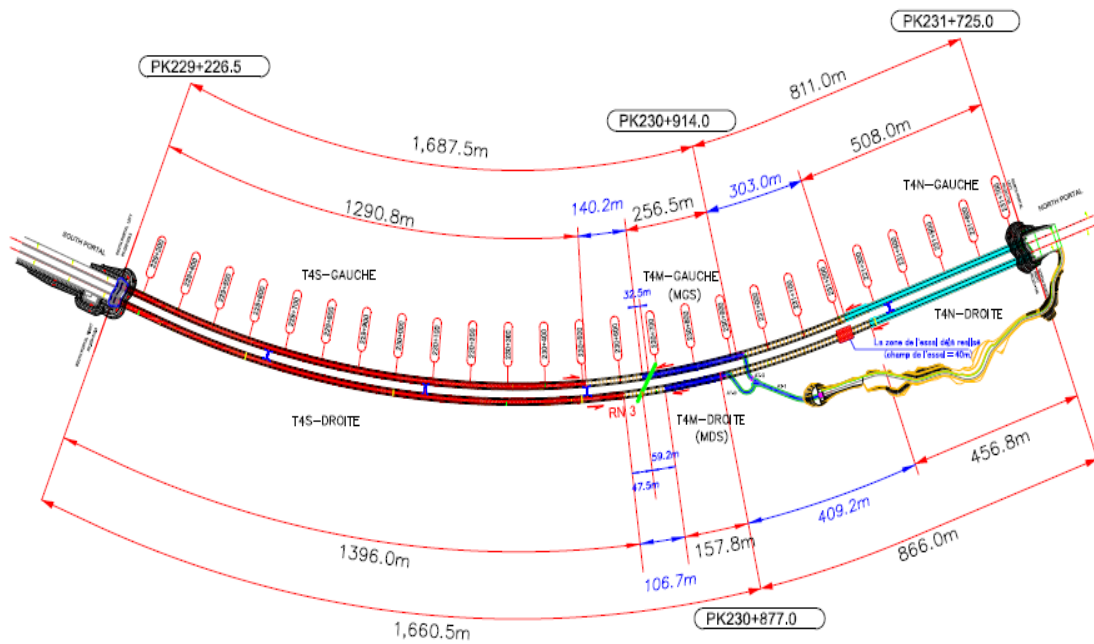


Figure (1): Plan view of tunnel T4

GEOLOGICAL AND GEOTECHNICAL CONDITIONS OF TUNNEL T4

According to the geotechnical and geological investigations, the team found that the geology of the mountain crossed by the tunnel is essentially from the

lower Cretaceous (Tellienne thrust sheets) consisting of marl and limestone in form of strongly folded and sheared blocks and altered argillite (Figure 2).

These are covered by deposits of quaternary, comprising clays, silts and conglomerates. The central part of tunnel T4 passes through the altered marl which

can be considered as laminated and grey in color. The maximum coverage of the tunnel is about 235 m and the most critical section corresponds to the lowest coverage which is about 17 m.

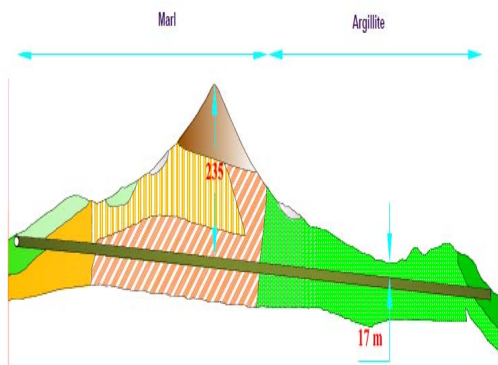


Figure (2): Geological cross-section

INSTRUMENTATION OF TUNNEL T4

The means currently being routinely employed for the monitoring of tunnels during their construction are auscultations. They aim first to control the risk of instability or settlements in the short term and ensure the sustainability of the tunnel in the long term. The most important parameters to be measured are (AFTES, 2005): geometric parameters (settlement and rotation at the surface, borehole displacement, convergence of the wall, extrusion), mechanical parameters (force, constraints of ground, support and concrete lining) and finally hydraulic parameters.

The auscultation system designed to track the behavior of tunnel during the excavation work and construction of temporary support is based upon the installation of: convergence stations inside the tunnel, positioned perpendicularly to the axis of the tunnel, to measure the convergence and settlement, borehole extensometers and strain gauges, extrusion measurement devices installed at the tunnel face, settlement benchmarks, inclinometers and piezometers on the surface.

Most of the instrumentation already used during

construction and connected to automatic data acquisition systems will continue to be employed for monitoring when the tunnel is in service.

PROCEDURE FOR NUMERICAL SIMULATION

The purpose of numerical studies conducted in this work is to best choose the most efficient methods of reinforcement to assure the stability of the excavation and thus anticipate constructive provisions to adopt.

Numerical simulations are performed by the finite element method with the calculation code PLAXIS 3D Tunnel and are produced based on the geotechnical and geometrical characteristics of the instrumented section [KP 231 +253].

The tunnel has a diameter of 16 m and the thickness of its support is 40 cm. For reasons of symmetry, half of the geometry is modeled. To take into account the evolution of displacement with depth and minimize the influence of the condition at boundaries, the boundaries of the model according to (X and Z) must be located at 4 or 5D of the tunnel. The ground was modeled by triangular prism elements at 15 nodes and has about 5300 elements (Figure 3).

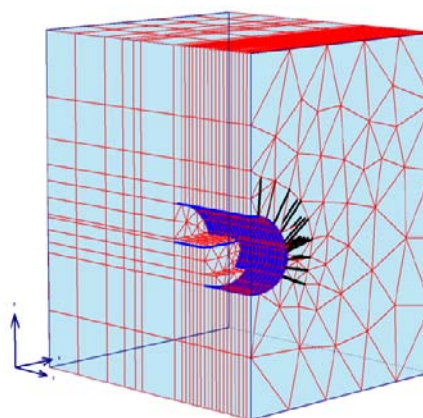


Figure (3): 3-D numerical model

Soil behavior was represented by the elastic-plastic non-linear model HSM (Hardening Soil Model);

AFTES (2003) considers that the cyclic tests (loading/unloading) remain the most appropriate for assessing the deformation modules. Hejazi (2008) showed that in the study of underground excavations, this model allows obtaining surface displacements which snap better on the *in situ* results.

The parameters of the Hardening Soil Model (HSM) were taken as: $E_{50}^{ref} = 4\text{Mpa}$, $E_{oed}^{ref} = 4\text{Mpa}$, $E_{ur}^{ref} = 13\text{MPa}$, $C' = 10\text{kPa}$, $\phi' = 15$, $\psi = 0$, $\nu = 0,3$ and the coefficient of lateral pressure $K_0 = 1 - \sin\phi'$.

The cover over the tunnel is of the order of 27m, and the simulation of the excavation phasing was designed according to real excavation work steps, where digging was accomplished by divided sections.

The tunnel lining elements consist of 8 node quadrilateral plates. These plates are elements of structure used to model slender elements placed in the ground and having a flexural rigidity E_I and a significant normal stiffness E_A . Given that there are two elements (arches and shotcrete), it is appropriate to use a flexional rigidity and a normal equivalent one. Regarding the strengthening of the core or the tunnel face by bolting, we find several methods in literature simplifying modeling. We can mention the simplified approaches, the method of homogenization and full terrain modeling, inclusions and their interaction.

UMBRELLA ARCH METHOD (UAM) MODELING

The Umbrella Arch Method is a technique of pre-reinforcing which consists of putting longitudinal steep pipes with an inclination of 10° at the periphery of the tunnel face.

To analyze the reinforcement effect of UAM, a series of arrangement has been made as for the steel pipe (diameter: 114 mm, thickness:

6 mm, length: 12.25 m) 0.5 m of distance in transverse direction and 9 m of distance in longitudinal direction. The injection of material that has been used is the silicate resin gives a strong internal

bond between the soils. Homogenization of a reinforced soil massif consists of replacing (bolts and soil) by an equivalent homogeneous material whose behavior results from the individual behavior of each element and the interaction thereof (Figure 4).

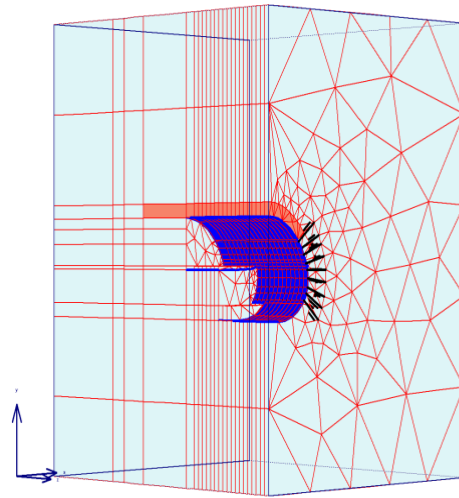


Figure (4): Mesh adopted for umbrella arch method

To replace the soil by a homogeneous material, an equivalent deformation modulus is used, but we will first define the basic cell; this term represents the elementary structure of the composite soil/bolts, it is the smallest volume containing the constituent materials of reinforced soil.

To determine E_{eq} , we can use the homogenized stress tensor, which comes from the sum of the contribution of each of the two materials, or the following formula is used directly:

$$E_{eq} = \frac{E_s A_s + E_{mc} A_{mc} + E_b A_b}{b * h} \quad (1)$$

$b * h$: Surface of the basic cell.

A : Surface material.

E_{mc} : Mortar cement.

ADECO-RS MODELING METHOD

ADECO-RS method consists of strengthening the tunnel face by polymer injection tubes reinforced by fiber glass in order to improve the strength characteristics of deformability of the advancing core, prevent premature extrusion of the front and minimize the occurrence of plastic deformation zones and their spread behind the front by the phenomenon of convergence.

Generally, there are several types of bolts on the market, depending on their shape; some are made of ribbed fiberglass tubes also serving as sealing mortar injection tubes for sealing, while others are constituted by triangular or rectangular elements of fiberglass associated with an injection tube of PVC. In order to understand and use fiber-glass reinforcement technology properly, it is important to keep in mind two concepts that lie at the base of the ADECO-RS approach of which it forms part:

The centrality of the deformation response of the ground to the action of excavation. The design engineer must give maximum attention to this, firstly to analyze it and then to control it (Lunardi, 2008).

The use of the advance core of the tunnel (stiffened with fiberglass reinforcement or protected with advance rings of improved ground or of fibre reinforced mortar) as the key to interpretation (for analysis) and as a structural stabilization element (for control) of the deformation response mentioned above during excavation and construction.

The parameters that characterize this intervention are the length, frequency, overlap, cross-section and geometrical distribution of the reinforcement.

The bolts used in tunnel T4 are tubular inclusions GFRP (Injection tube reinforced in polymer fiberglass) sealed in the ground by an injection system (cement slurry), with a total length of 19.5 m.

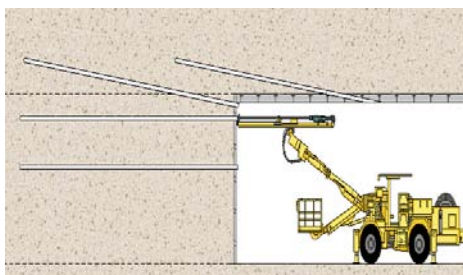


Figure (5): Insertion of GFRP tubes

To model the tunnel face reinforcement, we used the simplified approaches such as the application of a pressure gauge (PEILA, 1994) or an enhanced cohesion in the massif (Grasso et al., 1991, 1993).

These approaches do not take openly the bolting into account, but attempt to simplify the provision of the bolting reinforcement by the use of an equivalent parameter.

First Case: (Peila Approach)

This approach is proposed by (PEILA, 1994). It consists of taking into consideration the contribution of the reinforcement by application of an equivalent face pressure (Figure 6). This pressure is equal to the sum of the forces in the bolts applied to the tunnel face:

$$P_{reinf} = \min \left\{ \frac{NA\sigma_{adm}}{S}, \frac{NS_l\tau_{adm}}{S} \right\} \quad (2)$$

where:

N is the number of bolts;

A is the cross-sectional area of the bolt;

σ_{adm} is the yielding strength of the bolt; material;

S is the tunnel face surface;

S_l is the lateral surface of the bolt;

τ_{adm} is the soil-bar limit skin friction.

Table 1. Pressures applied to the face

	n	S (m ²)	A σ_{adm} (kN)	P _{reinf} (kN)
Case A	55	126.3	600	261.28
Case B	45			213.7
Case C	35			166.2

Second Case: (Grasoo et al. Approach)

This approach is proposed by (Grasso et

al., 1993) who have proposed to simulate the effect of longitudinal reinforcement of the tunnel face by an increase of the soil properties and in particular by influencing on the value of cohesion (Figure 6).

They arrived at the following formula:

$$c_{\text{reinf}} = c + \frac{\Delta\sigma_3}{2} * \tan\left(\frac{\pi}{2} + \frac{\varphi}{2}\right) \quad (3)$$

where $\Delta\sigma_3 = \frac{N * T_b}{S}$

C: soil cohesion;

φ : soil friction angle;

$\Delta\sigma_3$: increment of minor stress due to bolts.

The same limitation as described above about the traction estimation in bolts is valid: traction is either evaluated from strength properties or from a calculation of the really mobilized traction.

The mechanical characteristics used for the modeling are presented in Table (2).

Table 2. Mechanical characteristics used for reinforced cohesion

Cases	n	S (m ²)	Tb (kN)	$\Delta\sigma_3$ (kN/m ²)	C (kPa)	C _{reinf} (kPa)
Case A	55	126.3	600	261.28	10	180.25
Case B	45			213.77		149.3
Case C	35			166.27		118.34

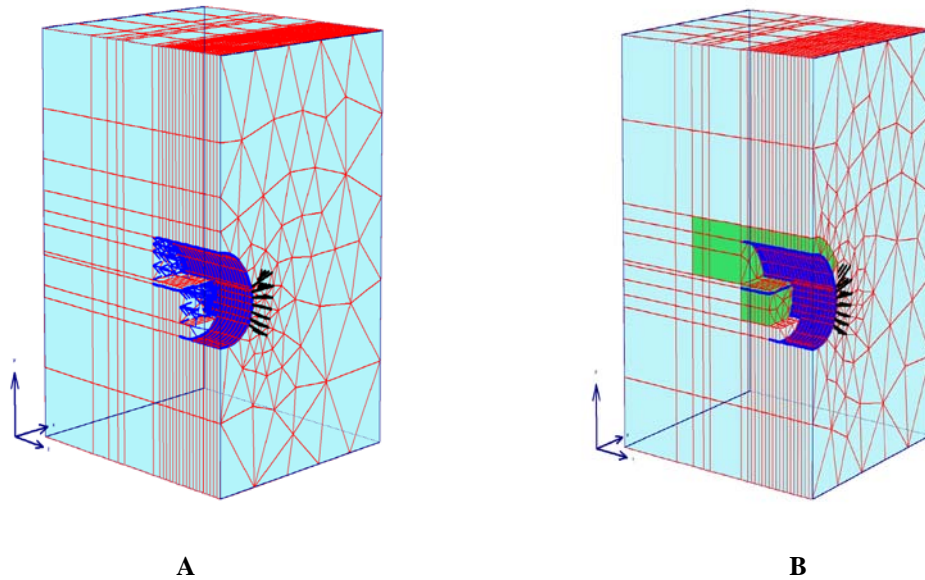


Figure (6): 3D numerical model for ADECO-RS method (A: equivalent face pressure. B: reinforced cohesion)

RESULTS OF CALCULATIONS AND DISCUSSION

The results of 3D simulations are compared with experimental data collected from section

[KP 231 +253] during tunneling; these data include settlements and convergence. First and foremost, it seems necessary to specify that the relationship between the surface settlements and the work depth is neither simple nor linear (Leblais, 1991).

Actually, settlements depend on geological, hydrogeological and geotechnical conditions, on the work geometry and underground position as well as on methods of excavation. However, it is clear that a shallow project is often more harmful and requires special monitoring. Tunneling disrupts the initial stress field as the hydrogeological conditions.

Generally, this stress modification is accompanied by instantaneous displacement of the face towards excavation as well as convergence of the tunnel walls (AFTES, 2005).

To date, theoretical determination of the displacement field around the underground work remains a delicate issue. It is particularly difficult to give a mathematical representation of the phenomena observed during tunneling as many factors must be taken into account as well as the three-dimensional pattern of the displacements spreading in the soil mass.

The solution to such a mechanical problem

requires, in particular, determining at the very best the equations representing the intrinsic behavior of materials (rheological law of the soil condition, lining and possibly grouting products).

For the evaluation of surface settlements, many researches conducted in the United States and in the UK (Peck, 1969; Attewell, 1986) have shown that the shape of transverse settlement trough is generally fairly well represented by a Gaussian curve. In this case, the settlement S at the distance y is given by:

$$S(y) = S_{max} \exp\left(-\frac{x^2}{2i^2}\right). \quad (4)$$

The measurements made at this section show that the settlement is stabilized at 21cm in the tunnel crown after 20 m of tunneling. Table (3) shows the displacement in tunnel crown (S_{cr}) and surface settlement (S_{max}) corresponding to the vertical axis of the tunnel of the two methods.

Table 3. Displacements in tunnel crown and surface settlement corresponding to the vertical axis

Methods	Umbrella Arch Method	ADECO-RS Method					
		Case 1 : PEILA Approach			Case 2 : Grasso et al. Approach		
		A : 55 bolts	B : 45 bolts	C : 35 bolts	A : 55 bolts	B : 45 bolts	C : 35 bolts
S_{cr} (m)	0.246	0.183	0.186	0.204	0.204	0.21	0.216
S_{max} (m)	0.15	0.094	0.1	0.11	0.096	0.101	0.11
S_{max}/S_{cr}	61%	51%	53%	54%	47%	48%	50%

The vertical displacement is maximum at the vertical axis of the tunnel (Y) in the two methods. It is possible to observe that the largest displacements occur just above the tunnel crown, with the displacement "damping" from the tunnel crown until the surface where the displacements are smaller.

Regarding the ADECO-RS method, the results are almost identical for both cases, and it is noted that it is better in that the number of fiberglass elements is higher than 45 bolts, for the results should

be in good agreement with reality unlike the umbrella arch method. These results were also confirmed by (Barisone and Pelizza, 1982; Lunardi, 2008, 1993; Wang et al., 2009) who have carried out *in situ* measurements to study the effectiveness of reinforcement of the advance core using fiberglass elements and arch umbrella method, especially Al-Hallak (1999) during studying in a centrifuge the effect of bolting, which has highlighted that the establishment of bolts at the advance core of a

tunnel significantly improves the stability of the tunnel face.

Figure 7 shows the surface settlements at the end of the last stage of calculation. The first observation we can make is that the settlements obtained by the ADECO-RS method may have substantially the same form; this superposition confirms visually that the curves obtained are very similar. The second remark is that the reinforcement of the advance core using fiberglass elements has contributed to reduce the vertical settlement by about 40% compared to the umbrella arch method.

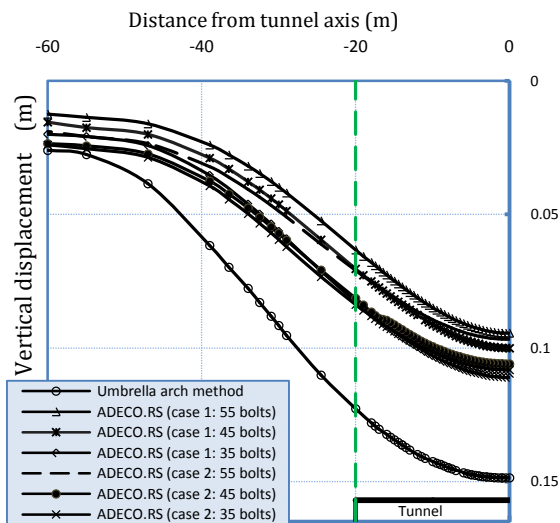


Figure (7): Vertical displacement at the soil surface

The contribution of the umbrella arch method on the reduction of surface settlement appears so limited. This result is consistent with the findings of Eclaircy-Caudron (2006) and Juneja (2010).

Figure 8 represents the horizontal movement in the soil mass in the vertical section, far from the tunnel by 1m. The displacements are negative ($U_x < 0$) if they are heading to the tunnel (compression), and they are positive if management has a sign opposite (contraction).

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. When we move away from the tunnel, the horizontal displacements diminish. These results are confirmed by Dolzhenko (2002) and Galli (2004).

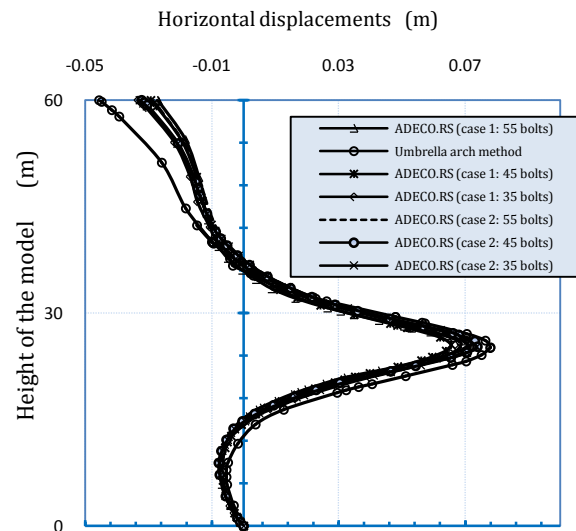


Figure (8): Horizontal displacement

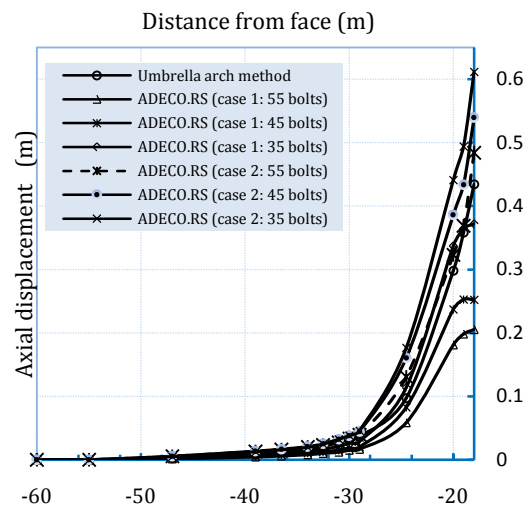


Figure (9): Axial displacement

The umbrella arch method gives a maximum value U_x of 8 cm, with a difference of 25% compared to the

ADECO-RS method. The concentration of displacement in this section obliges the geotechnical engineer to be careful with the design of lining.

The final result which can be represented concerns the extrusion; it is the longitudinal deformation of the tunnel face.

Figures 9 and 10 represents an example of measurement results of the axial displacement and extrusion plotted vs. bolt density (number of bolts at the tunnel face).

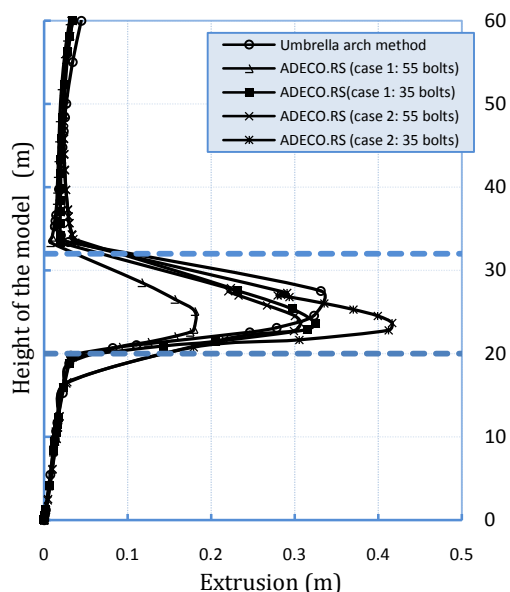


Figure (10): Extrusion of tunnel face

At the outset, we note that the best performing method to maintain the front size is ADECO-RS. Reinforcement with 55 bolts reduces the extrusion by 70% compared to the arch umbrella method. This result conforms to the different studies available in literature,

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such as that of Dias and Kastner (2005) who concluded that tunnel face bolting has an important influence on the extrusion with a reduction of 60% of the movements in the case of high density.

CONCLUSIONS

Auscultation and observations carried out on site have demonstrated the effectiveness of the ADECO-RS method compared to the umbrella arch method in reducing deformations inside the tunnel and putting an end to rockfall phenomenon at the level of tunnel face and pre-convergence in advance core tunnel. It was proved by the confrontation between auscultation and simulation that the use of ADECO-RS method allows to obtain results in good agreement with the phenomena really observed during the excavation of the tunnel.

We can say that the calculations carried out by the ADECO-RS method showed good concordance of displacements evaluated numerically with those measured during excavation.

Finally, numerical modeling in general is regarded as a prediction method (to limit the damage and reduce the cost of production), but one should firstly obtain reliable and complete parameters (physical and mechanical) in order to discuss the various approaches. We hope that this method will bring a complement to the existing methods for tunnel face analysis and provide a help to the engineer faced with these problems.

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