International Conference on Case Histories in Geotechnical Engineering

(2004) - Fifth International Conference on Case Histories in Geotechnical Engineering

16 Apr 2004, 8:00am - 9:30am

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Recommended Citation

Nasri, Verya; Winum, Christian; and Benslimane, Aomar, "Analysis of Tunnel Section Enlargement Through Cutting Masonry Liner (Paris-Marseilles Roches De Condrieu Railway Tunnel Case Study)" (2004). *International Conference on Case Histories in Geotechnical Engineering*. 1.
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Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

Analysis of Tunnel Section Enlargement through Cutting Masonry Liner (Paris-Marseilles Roches de Condrieu Railway Tunnel Case Study)

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ABSTRACT

With increase in the dynamic envelope of trains due to the increase of their cross section and speed, the need for widening tunnel cross section of existing tunnels is becoming a necessity. One of the solutions to this problem consists of cutting a fraction of the masonry liner thickness and replacing it with a higher strength, and therefore, a thinner material. In this paper, the case of the widening of the Roches de Condrieu tunnel on the Paris to Marseilles railway line is presented. A maximum of half of the thickness of the existing masonry liner should be removed somewhere between the tunnel crown and the springline. Three-dimensional finite element analysis was used to simulate the effect of this partial cutting of the liner over a limited specified length along the tunnel axis. This study allowed the determination of the maximum length of cutting along the tunnel axis without creating any stability problem for the tunnel section. Once the section cut is reinforced by a higher strength material such as steel fiber reinforced shotcrete, the work resumed with alternating panels.

INTRODUCTION

The Roches de Condrieu tunnel is located on the Paris to Marseilles railway line. This electrified line tunnel was built in 1854 through 1855, with a total length of 180 m, curved alignment of 700 m radius, and a gradient of 13mm/m towards Marseille. As illustrated on Fig. 1, a typical cross section of this tunnel shows a half circle arch section of 4.25 m radius sitting on vertical sidewalls. The height below crown is 5.8 m with the reference to track level and the tunnel opening is 8.40 m, which allows for a double track line. The sidewalls are 2.25 m high and approximately 0.5 m thick, and consist of gneissic masonry stones. The tunnel roof consists of bricks with an average thickness of 0.5 m. The maximum cover is 16 m.

Widening of this tunnel is required in order to allow for the B^+ car clearance. The natural and logical solution would require lowering the tracks. However, this was not possible as concluded based on feasibility studies conducted by the National French Railway Company (SNCF) tunneling department. In order to increase the tunnel cross section, one of the solutions consists of cutting a fraction of the masonry liner thickness between the crown and sidewalls, and replacing it with a higher strength, and therefore, thinner material. A minimum thickness reduction of 0.25m was needed (Fig. 2).

GEOLOGICAL SETTINGS

Based on the available geological survey, the tunnel crosses chrystalline rock that consist of dark anatexite with cordierite and/or sillimanite. These geological formations are metamorphic, heterogeneous, where the foliated schist zones, often folded, mixed with grained components of nebullitique texture. This type of rock is rich in biotite and is usually weathered. The rock is covered with glacial morraine of "Wurm" type. As illustrated on the geological profile shown on Fig. 3, at the portal on the Paris side, a fluvio-glacial deposit was found consisting of boulders encapsulated in a sandy matrix.

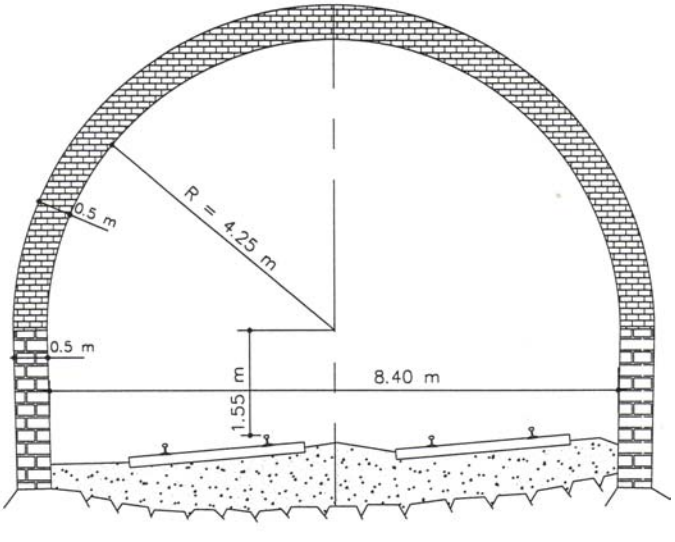

Fig. 1. Typical tunnel section

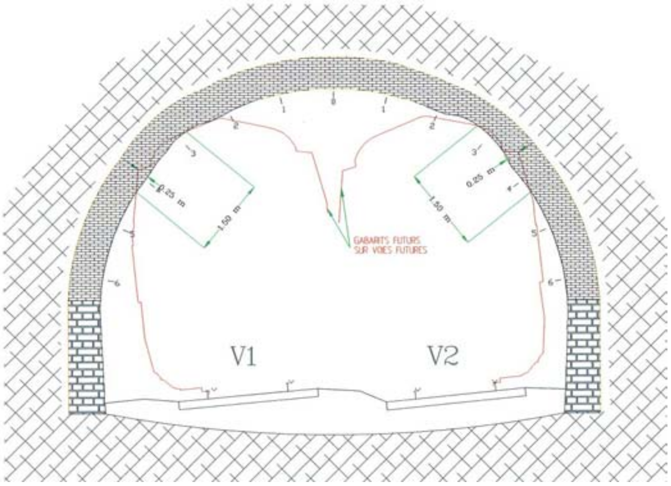

Fig. 2. Car clearance required

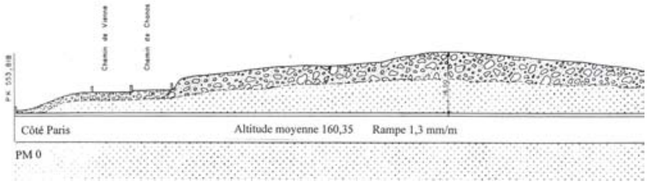

Fig. 3. Longitudinal geological profile

MATERIAL PROPERTIES

Based on the geotechnical investigations conducted by the geotechnical consulting French firm Simecsol (1982), the mechanical properties used in the analysis are summarized in Table 1. These values resulted directly from laboratory testing or were derived using available literature.

Table 1. Mechanical properties of the rock and the liner

Parameter	Rock (anatexite)	Brick	Stone masonry
Young's modulus (Mpa)	25000	6200	25000
Poisson ratio	0.2	0.2	0.2
Compressive strength (Mpa)	20	10	20
Tensile strength (Mpa)	2	1	2
Unit weight (kN/m^3)	24	22	25
Lateral earth pressure coefficient	0.5	-	-

The purpose of this analysis is to assess the most feasible and cost effective procedure for the tunnel widening through cutting the masonry liner either continuously, or alternately, without compromising the global tunnel stability. One of the main analysis objectives was to define the extent of the reinforcement needed in the section cut to preserve the tunnel integrity. The interesting aspect of the current study is to assess the effect of cutting a fraction of the masonry liner thickness on the global tunnel stability and the induced redistribution of the stresses in the rock/structure system.

EXCAVATION METHOD

Due to the lack of construction records, it was assumed that the entire tunnel section was excavated in one stage, and then the liner was installed. This approximation has a limited effect on the long-term analysis results, which is considered as the initial step for the widening process.

Analysis Steps

The problem is analyzed using the Convergence-Confinement method (Panet, 1995). The finite element program CESAR (Humbert, 1989), developed by the French laboratory of the National School of Bridges and Roads (Laboratoire Central des Ponts et Chaussees) was used. This code takes into account the construction staging, and allows the use of the elastic and elasto-plastic constitutive material laws.

The analysis was conducted following four basic Steps: (i) excavation, (ii) liner installation, (iii) long-term creep effect, and (iv) liner cutting.

Step (i): Modeling of the tunnel excavation. The relaxation coefficient was assumed to be 0.5. The parabolic criterion was used to simulate the elasto-plastic behavior of the rock.

Step (ii): Modeling of the tunnel liner installation. The remaining part of the released rock forces was applied to the extrados of the liner. The parabolic criterion was also used to simulate the elasto-plastic behavior of the brick and stone masonry.

Step (iii): Long term behavior of the tunnel. A simplified approach is used to simulate the long-term behavior of the tunnel. However, this approach is applicable only in the case of linear visco-elastic materials. In this step, the mechanical characteristics of materials are modified in order to simulate their long-term behavior.

Step (iv): Modeling of the tunnel liner cutting. At this stage, the released stresses are applied on the cut section surface, and the impact of this loading on the tunnel stability is analyzed. In this 2D analysis, all the cutting induced loading is applied to simulate a continuous cutting of the liner along the tunnel.

Figures 4a and 4b show the mesh used in the analysis. Due to the symmetry of the geometry, the applied loading and the boundary conditions, only half of the system was modeled. Also, the boundary conditions were fixed to prevent any horizontal movement along the axis of symmetry. In order to eliminate the boundary effect, the rock is modeled along a distance of 4 times the tunnel width in the horizontal direction, and 4 times the height under the tunnel invert. For a better accuracy, the finite element mesh was refined in both directions. The elements in the cut zone were deactivated in the final analysis step.

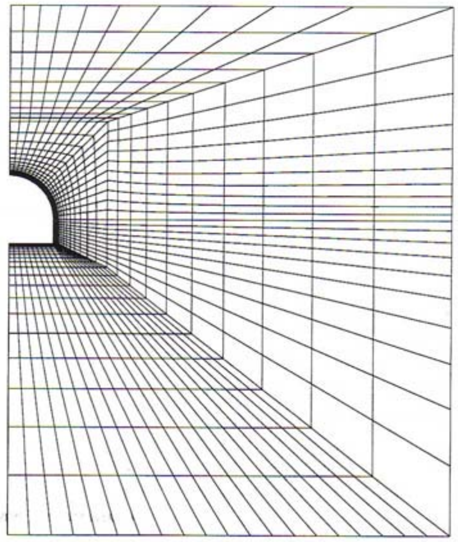

Fig. 4a. Analysis model

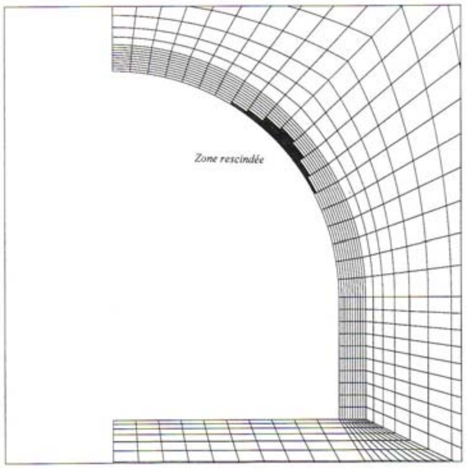

Fig. 4b. Cut zone

ANALYSIS RESULTS AND INTERPRETATION

The comparison of the deformed shapes of the liner intrados from step (iii) and step (iv) illustrates that the additional deformation due to the liner cutting can be neglected. Figure 5 shows the order of magnitude and direction of the principal stresses at the nodes of the rock and liner elements. Figures 6a and 6b illustrate the isovalues (shown in kPa) of the normal stresses σ_{xx} and σ_{yy} respectively, at the rock and tunnel liner. As it can be observed, the generated stresses are well below the masonry compressive strength. The analysis results show that the rock liner system remains elastic.

Due to the fact that the rock strength is higher than the liner strength, the major part of the excavation induced short and long-term loadings is supported by the rock itself. In this particular case, the liner basically supports its own weight. In addition, as illustrated by the stress distribution, the liner cutting does not affect the global stability of the tunnel; therefore, reinforcing the cut zone is not required.

To assess the impact of the mechanical characteristics of the rock on the rock/liner interaction, the cutting method and the reinforcement type required, similar analysis was conducted using a softer type of ground such as medium to stiff clay. The mechanical properties of this clay are summarized in Table 2.

Table 2. Mechanical properties of the clay

Parameter	Soil
Young's modulus (Mpa)	50
Poisson ratio	0.2
Cohesion (Mpa)	20
Friction angle (degrees)	20
Dilatancy angle (degrees)	20
Unit weight (kN/m^3)	24
Lateral earth pressure coefficient.	0.5

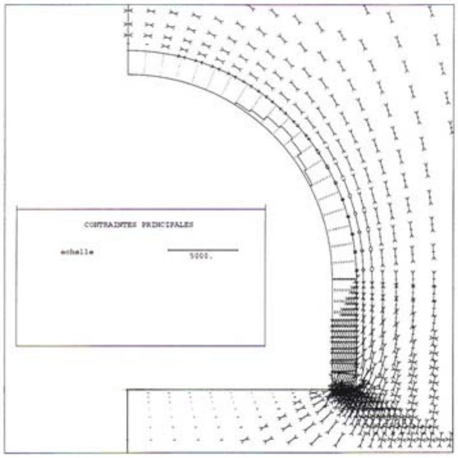

Fig. 5a. Principal stresses in rock and liner before the cut, for the case in which rock is stiffer than liner

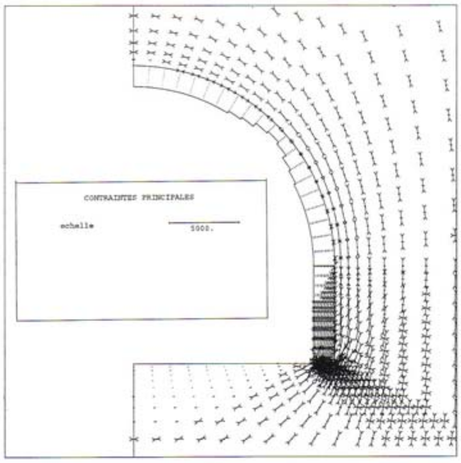

Fig. 5b. Principal stresses in rock and liner after the cut, for the case in which rock is stiffer than liner

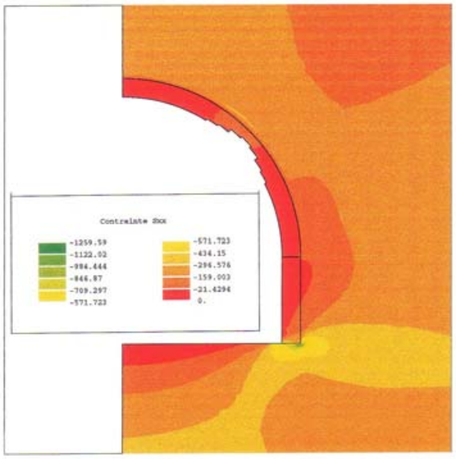

Fig. 6a. Isovalues of horizontal normal stress σ_{xx} *(kPa)*

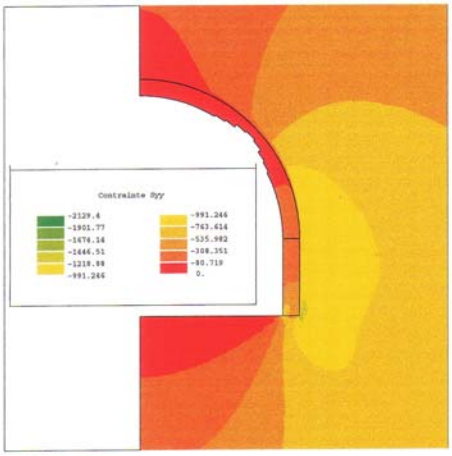

Fig. 6b. Isovalues of vertical normal stress σ_{yy} *(kPa)*

Figures 7a and 7b illustrate the deformed shapes of the liner during the analysis steps of the long-term behavior and the cutting process respectively. As it can be seen, a settlement of 5.4 mm took place at the tunnel crown level.

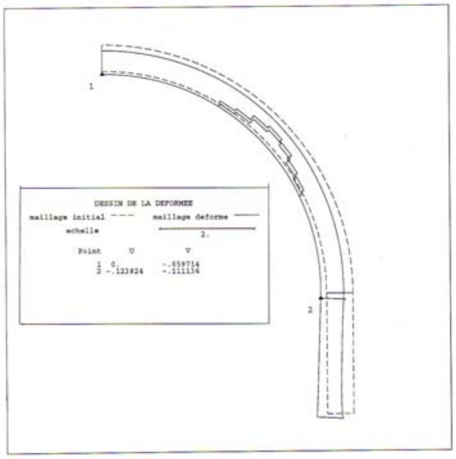

Fig. 7a. Liner deformed shape resulting from long-term analysis step (Clay soil)

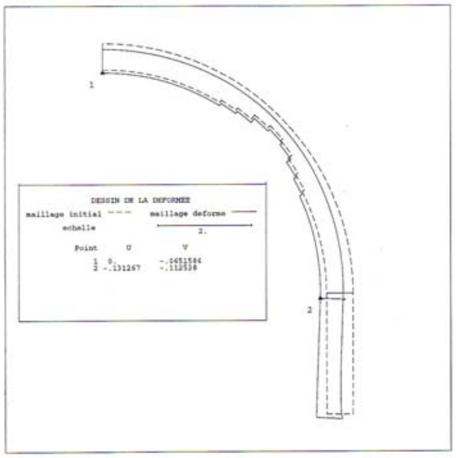

Fig. 7b. Liner deformed shape resulting from cutting analysis step (Clay soil)

Figure 8 shows the order of magnitude and direction of the principal stresses at the soil and liner element nodes. Figures 9a and 9b illustrate the isovalues of the normal stresses σ_{xx} and σ_{yy} respectively, at the soil and liner. As opposed to the previous case, the liner material is much more rigid than the surrounding soil, therefore, a large part of the load is supported by the liner. The generated stresses are higher than the liner elastic limit in most of the cut zone. As shown on Fig. 10, the plastic zone is well developed behind the cut area, which results in the cut zone failure.

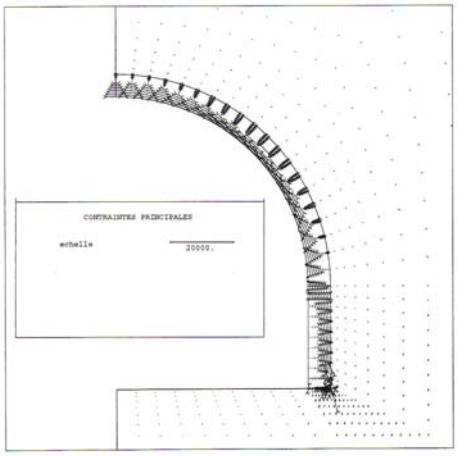

Fig. 8a. Principal stresses in soil and liner before the cut, for the case in which soil is less stiff than liner

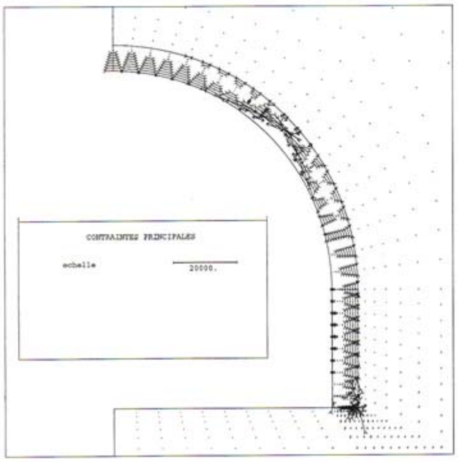

Fig. 8b. Principal stresses in soil and liner after the cut, for the case in which soil is less stiff than liner

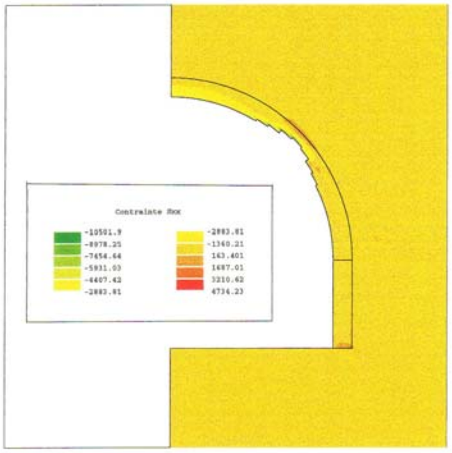

Fig. 9a. Isovalues of horizontal normal stress σ_{xx} *(clay, kPa)*

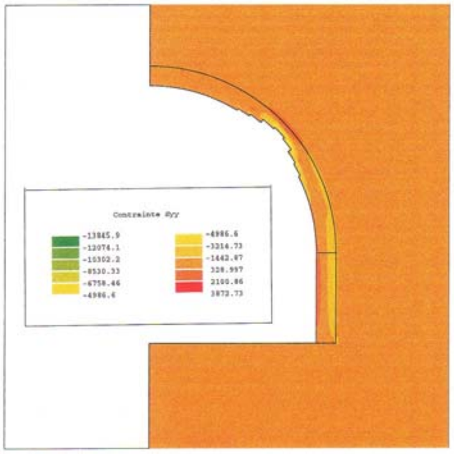

Fig. 9b. Isovalues of vertical normal stress σ_{yy} *(clay, kPa)*

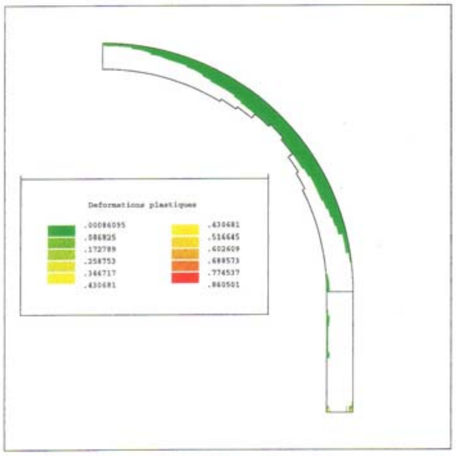

Fig. 10.Isovalues of total plastic strain (clay soil)

The results clearly indicate that the cutting process cannot be performed continuously along the tunnel axis. The following solutions were considered:

- Longitudinal alternate cutting.
- Ground improvement around the tunnel liner.
- Reinforcement of the tunnel liner by bolting.

In order to evaluate the global stability of the soil/structure system in the first suggested solution, and to optimize the number and the width of the cut zones, it was necessary to use a 3D model to take into account the excavation stages along the tunnel axis. A 2D model can also be used with a coefficient of relaxation ($0 \leq \lambda \leq 1$) to simulate the 3D effect of the alternate cutting. Similarly to the Convergence-Confinement method, this second solution is approximate. The relaxation coefficient, which depends on the geometry of the cut zone, can be determined by a simplified 3D analysis.

In order to simulate the effect of ground improvement around the tunnel liner, it was necessary to increase the mechanical characteristics of the ground (Young's modulus, compressive strength) in the area affected by the ground improvement operation. The extent of this increase can be assessed and quantified by laboratory and in situ testing.

In the third solution, the bolts can be modeled by truss elements and their length and spacing can be defined by corresponding analysis.

3D ANALYSIS FOR CUT WIDTH DETERMINATION (LONGITUDINAL ALTERNATE CUTTING OPTION)

The following example illustrates the methodology to determine the cut width in the longitudinal alternate cutting option using a 3D simulation. The depth of the cutting is set at 0.2 m; the length in the transverse section is set at 2.8 m (in practice, these values are dictated by the required widening to allow for larger trains); and for the first trial, the width selected is 1m. In decreasing the cut width, the increase in the cut zone stresses can be limited. A very small width can result in a higher cost. The objective of the analysis is to determine the optimal width in order to minimize the rehabilitation cost and time, and control the extent of the additional stresses induced by the liner cutting operation.

Figures 11a and 11b display the 3D mesh used in the analysis conducted for the longitudinal alternate cutting option. Due to the symmetry, only half of the system was modeled. Similarly, the boundary conditions were fixed to prevent any horizontal movement along the axis of symmetry. In order to eliminate the boundary effect, the ground/liner system is modeled along a distance of 5 times the width of the cut zone in the tunnel axis direction. The analysis was conducted following similar steps as for the previous case (excavation, liner installation, long-term effect, and cutting).

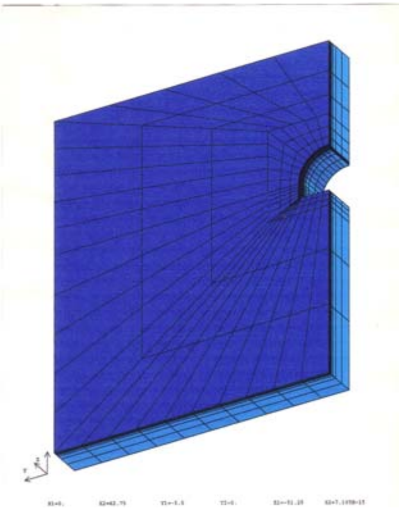

Fig. 11a. Model used for alternate cut analysis

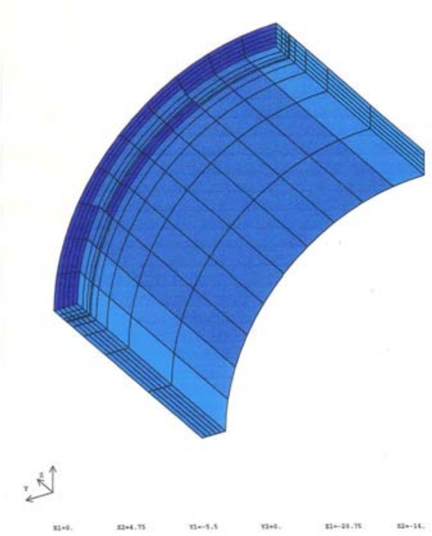

Fig. 11b. Mesh for liner cut alternately

Figure 12 represents the isovalues of the normal stress σ_{zz} in the liner and its redistribution due to a single cutting operation. The variation of horizontal displacement in the tunnel cross section and the minor principal stress in the middle of the cut zone between the 3rd and 4th analysis steps are summarized in Table 3. These variations, resulting from the cutting performed on masonry liner, were computed for 2 different types of cutting (continuous cutting along the tunnel axis, and longitudinal alternate cutting with a fixed width of 1 m).

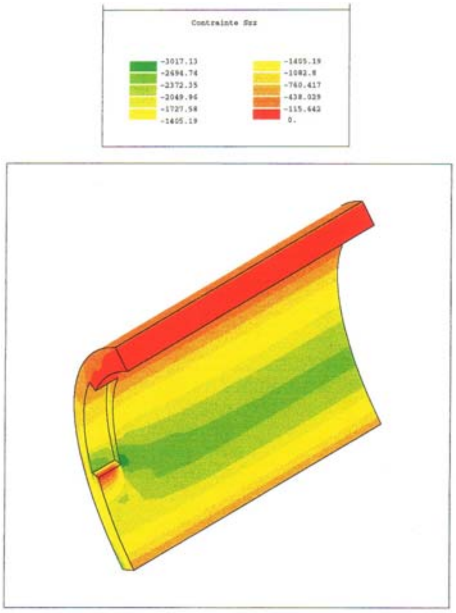

Fig. 12. Isovalues of the normal stress σ_{zz} in the liner

Table 3. Variation of the horizontal displacement and the minor principal stress in the middle of the cut zone

Cutting type	Variation of the horizontal displacement (mm)	Variation of the minor principal stress (kPa)
Continuous cutting	0.66	1488
Longitudinal alternate cutting	0.04	212

CONCLUSION

This example illustrates the efficiency of the longitudinal alternate cutting in limiting the increase in the values of the critical components of the displacement and stress in the cutting zone. In order to optimize the width of the cut zone, a parametric study should be conducted with different values for the cut width provided that the global stability of the tunnel is not compromised. A constant cut width can be used throughout the tunnel length and the cut zone can be reinforced by shotcrete to achieve similar liner strength before and after the cutting operation. it is necessary to reinforce the cut zone with shotcrete. In this case, it can be assumed that the variations of the displacements and stresses resulting from consecutive longitudinal alternate cutting are approximately similar to those obtained by the previous analysis.

REFERENCES

Humbert, P. [1989], “*CESAR-LCPC : Un code général de calcul par éléments finis*”, Bulletins de liaison des Laboratoires des Ponts et Chaussées, Vol. 160, pp. 112-114.

Nasri, V., P. Ramondenc and J.P. Magnan [1998], “*Conception d’un système de renforcement pour le tunnel ferroviaire de la Nerthe"*, Bulletin des laboratoires des Ponts et Chaussées Vol. 217 pp. 53-59.

Panet, M. [1995], “*Le calcul des tunnels par la méthode convergence-confinement*”, Presses de l'ENPC, Paris, p 177.