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Effects of pre-lining methods on the convergence of a tunnel

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ABSTRACT

Recent tunnel construction methods in soft soils have introduced ground reinforcement techniques in front of the cutting face : the use of a jet-grouting arch, a steel pipe umbrella vault or precutting are typically considered as such. The implementation of these techniques allow to minimize and control the convergence of the excavation and the ground settlements, especially in bad grounds and sensitive urban areas.

These techniques have a major influence on the behavior of the ground around and even far in front of the cutting face. This is to modify the traditional design approaches presently used since these approaches do not take into account the influence of linings or pre-linings on the behavior of the face.

The aim of this paper is to give the main results that have been reached in works recently carried out to improve the design approaches in the case of the use of pre-reinforcement techniques. We will focus on :
- the description of the specific design problems generated by the use of pre-lining methods ;
- the method of study ;
- the key results that have been reached ;
- the possible adaptation of current design methods according to these results.

1. PRE-LINING TECHNIQUES AND TRADITIONAL DESIGN METHODS

1.1 The pre-lining techniques

All pre-lining techniques have common points since they contribute in reinforcing the ground around and in front of the cutting face. They therefore participate in a very efficient way into the global stabilization of the excavation. It is important to point out that they can reduce very consequently the convergence around as well as far behind the face.

However, these methods are not equivalent and distinctions can be made following different criteria :

- the extension of the zone affected by the pre-lining can vary a lot according to the technique : steel pipe umbrellas or jet grouting arches are usually implemented as far as 15 meters ahead of the face. On the other hand, precutting cannot be made more than 4 or 5 meters ahead of the face ;

- the pre-lining distance will therefore be considered as variable if several excavation phases can be performed between two consecutive implementations of the pre-lining (jet-grouting arch, steel pipe umbrella). In the other cases, it will be considered as constant.

1.2. Distribution of stresses during excavation

During excavation, initial stress σ_0 on the ground is distributed on several parts described figure 1 :

- a first part is dissipated by the convergence effect,
- a second part is supported by the ground behind the face (face effect),
- the last part is supported by the (pre-)lining.

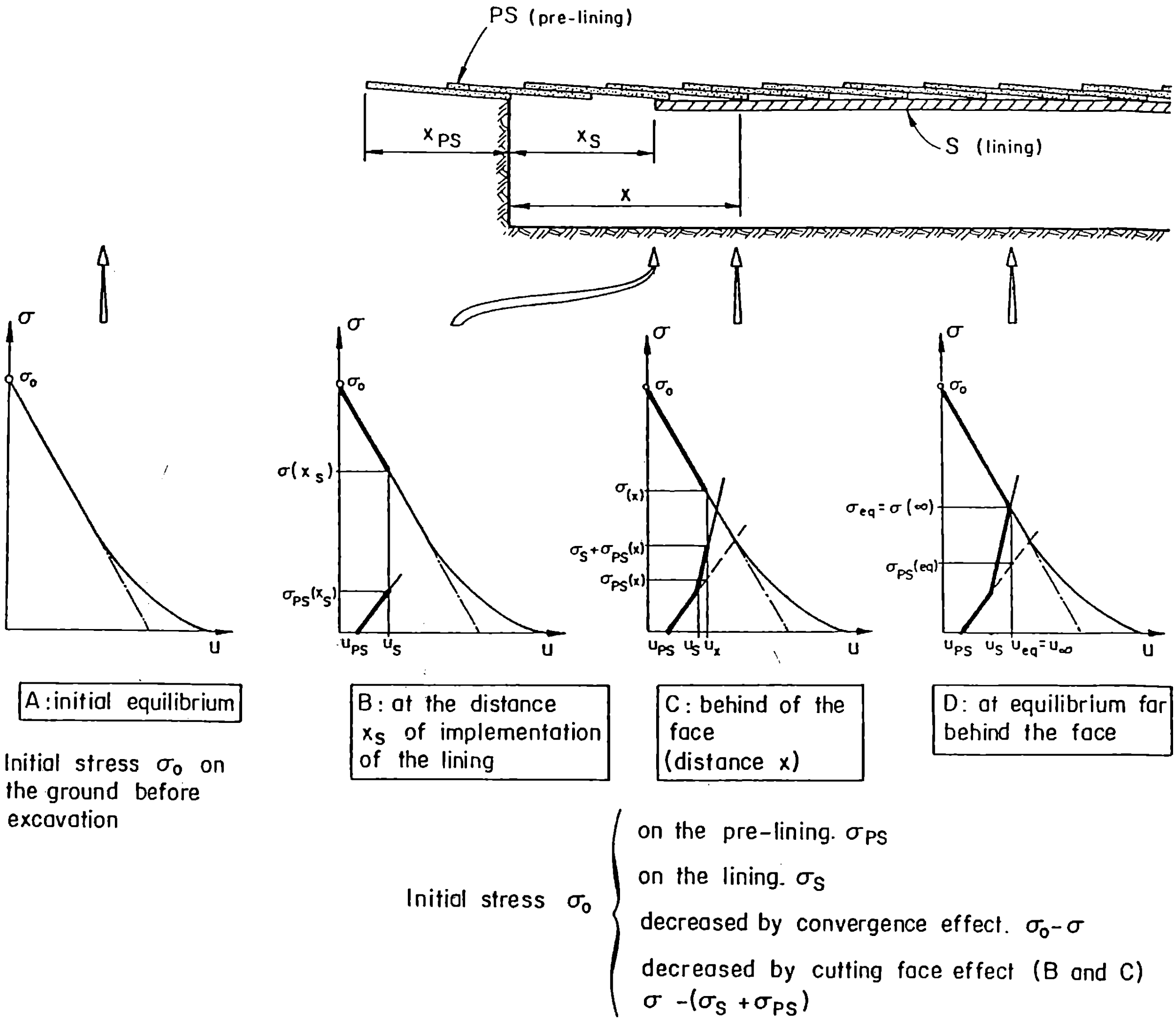

Figure 1 : Distribution of stresses during excavation

1.3. The traditional design methods

As regards the traditional tunnel design methods, at least in France, most of them are based on approaches using the " Convergence-Confinement " method. These approaches aim at determining jointly, in the case of a supported tunnel :

- the stress of the ground on the support,
- the convergence of the ground at the equilibrium.

These methods assume the case of an axisymetric problem which requires the assumptions of a circular excavation in an isotropic behavior. They require the estimation of a deconfinement ratio λ which is linked to the behavior of the excavation at a certain distance of the face (Ref: PANET-1995).

Recent improvements have been made to the traditional " Convergence-Confinement " method by taking into account with more accuracy the presence of traditional support behind the face. Basically, two assumptions have to be made to use any of these methods :

- the first one concerning the value of the convergence at the cutting face ;

- the other one concerning the behavior of the ground behind the face which is directly linked to the function a(x) :

$$a(x) = \frac{U(x) - U(0)}{U_\infty - U(0)} = 1 - \left(\frac{0{,}84}{\alpha X + 0{,}84}\right)^2$$

where U(x) is the convergence at a distance x from the cutting face (x > 0 behind the face), U(0) is the convergence at the face, U_∞ is the convergence far behind the face, and α a parameter depending upon the relative rigidity of the lining (Ref: BERNAUD-ROUSSET-1992).

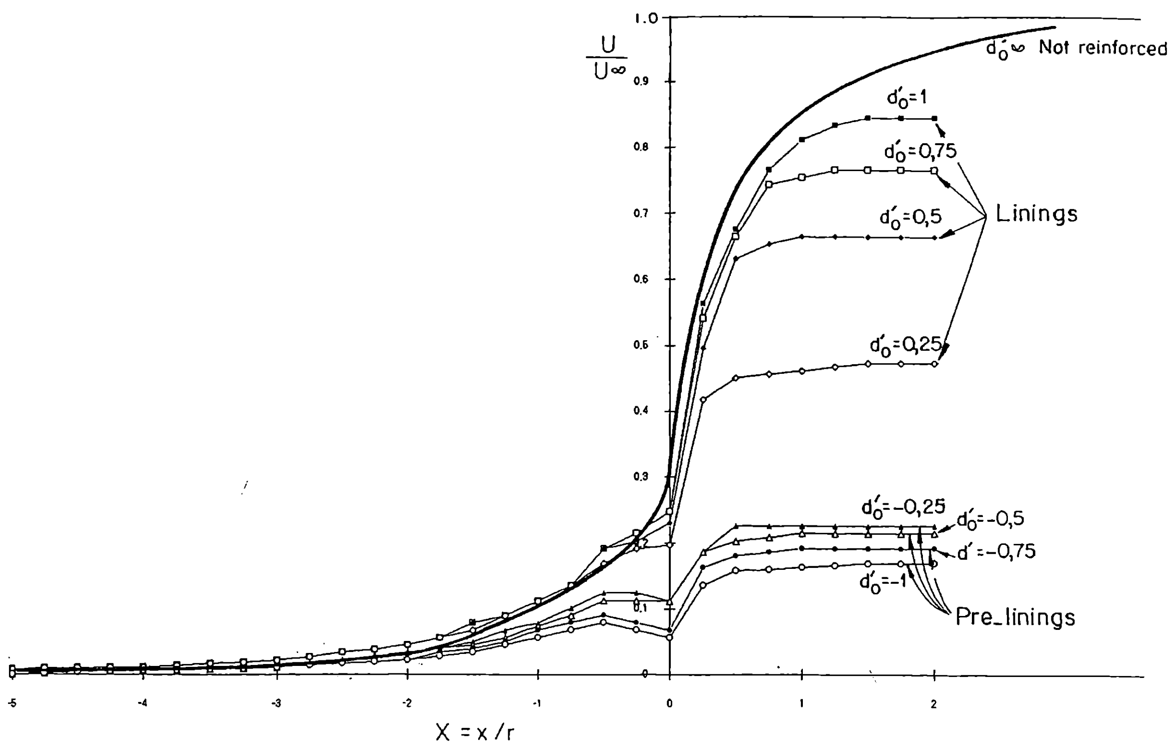

Figure 2 : Example of variation of the convergence profile according to the distance d'$_0$ of implementation of the (pre-) lining

1.4. A need for improvements in the calculation methods

These methods aim at determining the stress/strain conditions on the lining far from the face but they usually use basic assumptions to take into account the phenomena that occur in the vicinity of the cutting face. In any case, parameters such as the rigidity of the (pre-)lining or the location of its implementation affect the value of the convergence at the face and therefore the convergence profile all along the tunnel. This phenomenon is clearly shown on Figure 2, on which are plotted the convergence U(X), for different locations of the support $d'_0=d_0/R$ (d_0 distance of the support implementation from the face -negative for pre-lining-, R radius of the tunnel) for a given support rigidity. This is why further particular study has to be carried out in this zone in the case of pre-lining implementation, in order to appreciate properly the global convergence phenomenon.

2. METHODS OF STUDY

2.1. The FEM approach

The results presented here have been derived from several calculations that have been performed with a FEM axisymetric model. The FEM mesh used for the calculations is presented on Figure 3.

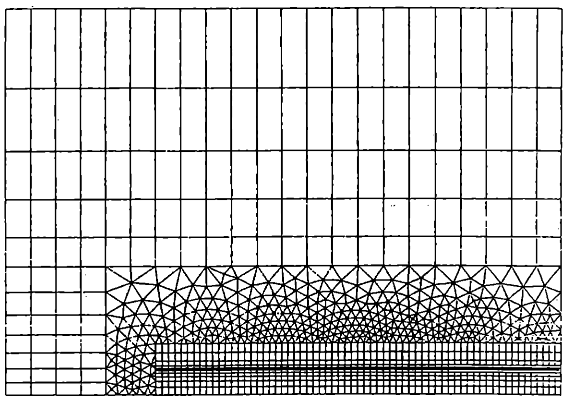

Figure 3 : FEM mesh used for the calculations

2.2. Pre-lining modelisation

The particularity of pre-lining techniques such as the use of a jet-grouting arch or steel pipe umbrella is to modify the characteristics of the ground cylinder located around the excavation. In the cylinder co-exist different types of material (ground, steel pipes, grout,...). Taking into account the exact geometry of all these elements would lead to an unrealistically complicated model (the precision of which would not fit with the assumption of an axisymetric model). The assumption has thus been made that the structure {ground + pre-lining} would behave like a homogenized cylinder with equivalent characteristics.

2.3. Dimensionless parameters

With such assumptions (axisymetry, homogenization) the behavior of any (pre-) lining can be fully described by one dimensionless parameter K_s', ratio between the rigidity of the lining and the Young Modulus of the ground.

Practically, a parametric study can be carried out in order to estimate the value of the relative convergence of the tunnel U = u/r (ratio between the convergence and the tunnel radius).

Four dimensionless parameters are necessary to fully describe the conditions of the problem in the case of an elastic behavior of the ground, five in case of an elasto-plastic behavior :

- $\sigma_0' = \sigma_0/E$, ratio between the initial stress in the ground and the Young Modulus of the ground ;

- ν, Poisson's ratio of the ground ;

- K_s' as described before ;

- $d_0' = d_0/r$, ratio between the distance to the face at which the (pre-)lining is implemented ($d_0 > 0$ in the case of a traditional reinforcement, $d_0 < 0$ in the case of a pre-lining) and the tunnel radius.

In the case of an elasto-plastic behavior, we must consider an additional ratio N_s, called stability coefficient. For Tresca behavior, $N_s = \sigma_0/c$ where c is the cohesion of the ground.

3. CONVERGENCE AT THE CUTTING FACE

This convergence has been estimated in various cases by varying on the dimensionless parameters described in § 2.3.

3.1. Case of the tunnel excavated without any (pre) lining

If we call U_e (resp. U_{pl}) the relative convergence of the tunnel far behind the face for an elastic (resp. elasto-plastic) behavior of the ground in the case where the tunnel is not supported ($U_e = (1+\nu).\sigma_0'$), we can establish the following relationships :

$U(0,\nu,\sigma_0') = (0{,}4.\nu + 0{,}095).U_e$ for the elastic case,

$U(0,\nu,\sigma_0',N_s) = (0{,}4\nu + 0{,}5).(0{,}413 - 0{,}0623.N_s).U_{pl}$ for a Tresca behavior.

3.2. Case of the tunnel excavated with the implementation of a (pre-)lining

3.2.1. Elastic behavior of the ground

Two particular cases can be distinguished :

- the case where the lining is implemented far behind the cutting face ($d_0' = +\infty$) ; the results of § 3.1. are then valid. The notation adopted in this case will be : $U(0) = U(0, +\infty)$

- the case where the pre-lining is implemented far in front of the cutting face ($d_0' = -\infty$) ; the notation adopted in this case will be : $U(0) = U(0, -\infty)$.

In this case :

$U(\infty) = Ue/[(1+\nu).Ks' + 1]$
(convergence far behind the face at the equilibrium),
and $U(0, -\infty) = \xi(Ks',\sigma 0',\nu).U(\infty)$

with :

$$\xi(K's,\sigma'0,\nu) = \left(0{,}74 - \frac{1}{(K_s' + 3)^{0{,}7}}\right)\frac{0{,}4.\nu + 0{,}095}{0{,}287}$$

In the case of a (pre-)lining implemented at a finite distance from the cutting face, the value of the convergence at the level of the cutting face can be estimated between the values of $U(0, +\infty)$ and $U(0, -\infty)$. We propose the following formula which can be used in the case of a (pre-)lining implemented close to the cutting face (pre-cutting or NATM for instance) :

$$U(0,d_0') = \frac{U(0,+\infty)-U(0,-\infty)}{\pi}.Arctan\left(2{,}8.d_0' - 0{,}3\right) + \frac{U(0,+\infty) + U(0,-\infty)}{2}$$

This formula gives accurate results for several calculations that have been carried out. One example is presented on Figure 4.

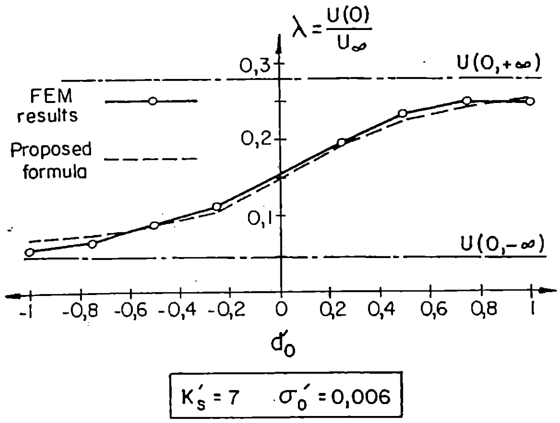

Figure 4 : Variation of the convergence at the cutting face with d'_o.

In the case of pre-lining implemented far in front of the cutting face (jet-grouting arch, steel pipe umbrella vault for instance), it is convenient to consider U(0) = U(0, - ∞).

3.2.2. Elasto-plastic behavior of the ground

No very general law could yet be determined in that case, according to the problem becomes rapidly very complicated. In any case, it is interesting to notice that two plastified areas are likely to appear :

* one in the vicinity of the cutting face, even if the value of Ns is below 1 ;

* another one, remaining all along the tunnel behind the cutting face ; its presence is directly linked to the fact that Ns is more than 1.

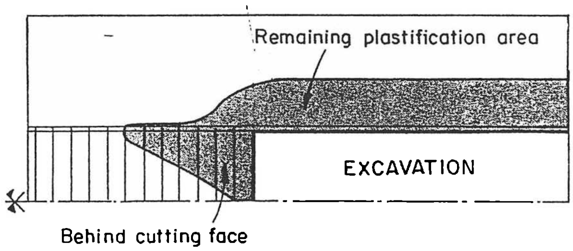

Figure 5 : location of different plastic zones.

It is interesting to notice that for Ks' < (Ns - 1)/(1 + ν) both plastified areas will appear, whatever the position of the (pre-)lining. This can be an indication for the designer in order to know if the problem has to be considered like an elasto-plastic situation or if it can be treated in elasticity. More detailed results are presented on Figure 6.

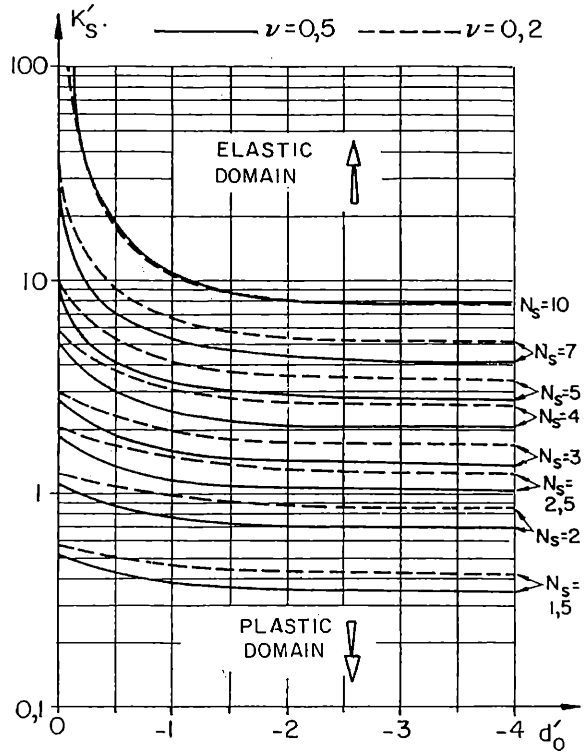

Figure 6 : limits of the elastic behaviour of the ground.

4. DETERMINATION OF THE CONVERGENCE IN FRONT AND BEHIND THE CUTTING FACE

The traditional design methods can be adapted according to these results. A more accurate value of the convergence *at the level of the face* can be introduced in the calculations.

As regards the convergence profile *behind the cutting face*, it can be deduced using a classical a(x) function (cf § 1.2.).

The convergence *in front of the cutting face* can be determined very generally as follows :

$U(x) = U(0).b(x)$ with $b(x) = 1/(1 - \beta.x + x^2)$, β depending on d_0', K_s' and ν.

The calculations have shown here that the value of β varies between 0,6 and - 1.

A convergence profile can then be determined in many cases (even by combination of these results in the case of the implementation of various (pre-) linings). Further details are given in the corresponding reference (GUILLOUX et al -1996).

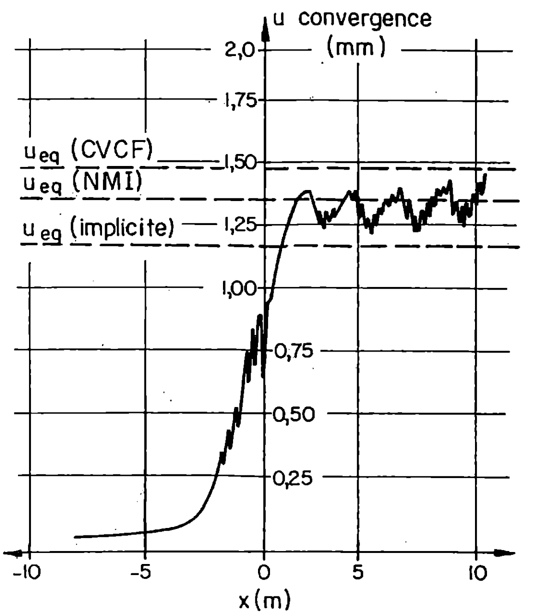

Figure 7 : convergence curve for pre-lining (FEM)

A typical result of finite element analysis is presented figure 7.

CONCLUSION

This study enables to give, in many cases, a much more accurate value of the convergence at the level of the cutting face, behind it and in front of it. This leads to an accurate determination of the convergence at the level of implementation of the lining which gives useful information in order to carry out :

- a " Convergence-Confinement " calculation (or a similar calculation using derived methods) ;

- a 2D Finite Element calculation on a precise cross-section ; such a calculation (which allows to take into account the geometry of the excavation with a much better precision) requires the determination of a deconfinement ratio λ which is directly linked to the convergence at the level of the cross-section considered. This ratio can therefore be estimated with much more accuracy in the case of the implementation of pre-linings according to the results presented in this paper.

BIBLIOGRAPHY

PANET (1995) Le calcul des tunnels par la méthode Convergence-Confinement.
Presses de l'École Nationale des Ponts et Chaussées.

BERNAUD-ROUSSET (1992) La "nouvelle méthode implicite" pour l'étude du dimensionnement des tunnels.
Revue Française de Géotechnique n° 60.

GUILLOUX-BRETELLE-BIENVENUE (1996) Prise en compte des pré-soutènements dans le dimensionnement des tunnels.
Revue Francaise de Géotechnique (to be published)