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# Recent progress in convergence confinement method

## Progrès récents dans la méthode convergence confinement

### Eine verbesserte Anwendung der Kennlinienmethode

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**ABSTRACT:** Convergence Confinement method is a plane strain approximation of supported tunnel analysis which is currently used in practice. However, efficiency of this method suffers from undetermination of the instant of support activation.

A new approach including three dimensional tunnel problems, is proposed to remove such drawback in a self governing way. The methodology has been set up from analyses on direct calculations on a simplified reference three dimensional tunnel problem.

**RESUME :** La méthode de convergence Confinement est une méthode courante d'analyse de tunnels, qui est une approximation en déformation plane. Toutefois, cette méthode souffre de l'indétermination sur le moment d'activation du soutènement.

On propose une nouvelle approche étendue au cas tridimensionnel, qui lève une telle indétermination de manière autonome. La procédure a été élaborée à partir d'une analyse direct d'un problème simplifié type de tunnel.

**ZUSAMMENFASSUNG :** Die Kennlinienmethode wird häufig bei der Auslegung von Tunnels angewandt. Hierbei wird näherungsweise ebene Deformation angenommen. Der Zeitpunkt zu dem sich der Tunnel verformt ist mit dieser Methode nicht bestimmbar. Wir schlagen ein neues dreidimensionales Model vor, anhand dessen bisher mit der erwähnten Methode nicht berechenbare Aufgaben lösbar sind. Dieses Verfahren wurde ausgehend von einem vereinfachten Rechenbeispiel entwickelt.

## 1 INTRODUCTION

In deep tunnels, support of the walls are fundamental elements which contribute to the stability of rockmass. This action, of three dimensional nature, involves an intricate interplay between the construction phases, rockmass and support behavior. In spite of constant progress achieved in three dimensional numerical analyses, approximate plane strain analyses of tunnel sections are very useful for engineers and currently used in practice. In order to reproduce the effects of tunnel face excavation and progress, these methods use either varying softening of elements inside tunnel section, or a variable fictitious stress state at the tunnel wall, as in convergence confinement method. However, efficiency of these approaches are impeded by a serious drawback which is concerned with the undetermination of the instant

for support activation. This factor appears as a very important interaction parameter between support and rockmass.

In this paper, a method is proposed to eliminate satisfactorily such indetermination, without modifying much the nature of calculations. This results in a new approach of the Convergence Confinement Method, which appears as self governing, independent of the particular behaviour of the rockmass and the support system.

## 2 A REFERENCE TUNNEL PROBLEM

In order to learn out general rules for deriving systematically the instant for support activation, we analyse a typical reference tunnelling problem (Figure 1) containing the main elements of actual deep tunnelling problem:

- constant advance rate (steady state hypothesis), which is implicitly supposed in CV-CF Method
- full face excavation.
- rotationnal symmetry of tunnel geometry.
- three-dimensional effects on support produced by tunnel face proximity (distance  $D_0$  to the leading edge of the tunnel), and anisotropic initial stress state defined by principal stresses  $\sigma_v$ , vertical, and  $\sigma_h$ ,  $\sigma_z$ , horizontal, with the latter parallel to tunnel axis.

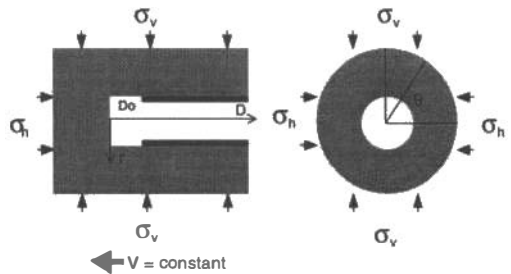


Figure 1 The reference tunnel problem

The methodology is based on comparing direct calculations performed on that reference problem, to those of the approximate plane strain analysis.

For direct calculations (excavation, support placement), a specific numerical tool has been built up, taking advantage of the peculiar hypotheses of the problem. There results in a very interesting and versatile Finite Element program, based on the steady state algorithm (Nguyen Q.S & al. 1981, Maitournam 1989), which allows to treat the sequential problem on a fixed geometry; and a Fourier's development of solutions in the angular direction  $\theta$  (Zienkiewick 1977, Winnicki & Zienkiewick 1979, Hanafy & Emery 1980), which replaces the three dimensional problem by a succession of two dimensional problems.

As intrinsic rules are expected to be found out, details of constitutive laws appear as less important, so that a simple elastoplastic Mises model was used. Four adimensional parameters define the reference problem:

- Stress anisotropy factor .....  $K_0 = \sigma_h / \sigma_v$
- Loading factor .....  $N_s = 2P_0 / R_c$
- Support laying distance to the face normalised by tunnel radius .....  $D_0$
- Relative support stiffness .....  $K^* = K_c / K_m$
- where,
- $P_0 = (\sigma_h + \sigma_v) / 2$ : mean geostatic pressure
- $R_c$ : rock mass uniaxial strength
- $K_m$ : elastic stiffness of the ground
- $K_c$ : support normal stiffness
- $K_f$ : support bending stiffness

### 3 THE CIRCULAR SYMMETRIC CASE (ISOTROPIC INITIAL STRESS STATE)

This is the traditional reference problem of the CV-CF Method. In this case, an equivalent "plane strain" closure of tunnel section is produced by a fictitious pressure  $P_i$ , applied at the wall of the tunnel, which simulates deconfining effect due to excavation process. This fictitious pressure, which decreases from its initial geostatic value  $P_0$  until zero, can be expressed linearly in terms of a deconfining ratio  $\lambda$  :

$$P_i = (1 - \lambda)P_0 \quad 0 \leq \lambda \leq 1 \quad (3.1)$$

A serious drawback of this method is the undetermination of the support activation instant.

The supported tunnel problem appears then as uncoupled, and can be expressed graphically, in a  $P_i$  vs closure  $U_i$  diagram (Figure 2). Equilibrium of the supported tunnel is obtained, in this diagram, as the intersection between the ground response and the support one. The unknown support activation instant at support laying distance  $D_0$  to the excavation face is represented by the wall convergence  $U_0$  or by the deconfining ratio  $\lambda_0$ , (Figure 2).

The CV-CF problematics can also be described by the following set of equations:

$$\begin{cases} P_\infty = M(U_i) & \text{ground} \\ P_\infty = K^*(U_i - U_0) & \text{sup port} \\ U_0 = ? \end{cases} \quad (3.2)$$

Uncertainty on determination of  $U_0$  is testified by the AFTES guidelines (1983). Since years 1990s, a renewed effort has resulted in more precise and

satisfactory methods for determining  $U_0$ , (Corbetta 1990, Nguyen-Minh & Corbetta 1991, Bernaud & Rousset 1992, Nguyen-Minh & Guo 1993).

The similarity ratio (i.e. the final free convergence  $U_\infty^f$ ), is given by the plane strain analysis.

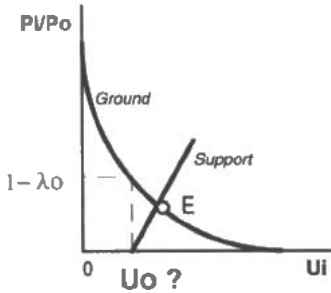


Figure 2 Convergence Confinement Problematic

The basis of our approach rely on two "universal" principles learned from analyses on direct axisymmetrical numerical models: the Self Similarity principle and the Interaction Principle,

### 3.1 The Self Similarity Principle

This principle allows us to derive the free elastoplastic convergence  $U_0^f$  at  $D_0$  from the normalized elastic one  $F(D)$ , with  $F(\infty) = 1$  (Figure 3).

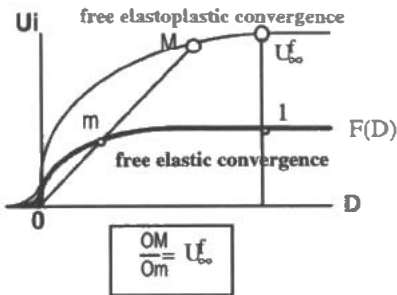


Figure 3. Schematic diagram of self similarity principle

The self similarity expresses then as (Corbetta 1990, Corbetta & Nguyen-Minh 1991):

$$U_0^f = U_\infty^f F(D_0 / U_\infty^f) \quad (3.3)$$

$$F(D) = 0.29 + 0.71(1 - \exp(-1.5D^{0.7}))$$

### 3.2 The Interaction Principle

The face-support interaction effect has been studied through extensive parametric analyses carried out on the direct numerical model.

The results lend a definite trend expressed by a universal curve when  $U_0$  and the stabilised convergence  $U_\infty$  are divided by their respective values  $U_0^f$  and  $U_\infty^f$  when tunnel is unsupported (Figure 4). This interaction principle expresses support action which transforms convergence at support leading edge into the final convergence :

$$U_0^* = \Phi(U_\infty^*) \quad (3.4)$$

$$\Phi(x) = 0.55 + 0.45x - 0.42(1-x)^3$$

where

$$U_0^* = U_0 / U_0^f \quad U_\infty^* = U_\infty / U_\infty^f$$

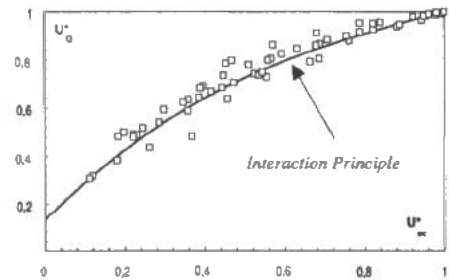


Figure 4. Interaction Principle

### 3.3 Determination of $U_0$

The missing equation for  $U_0$  is finally obtained by combining the Interaction Principle (3.4) to the free convergence obtained by the Self Similarity Principle (3.3). The problem of supported tunnel is then resolved by the completed system of equations (3.2).

A validation of this method is obtained by comparing the results of the direct axisymmetrical calculations to the previsions of the new plane strain approach. The generality of this approach has

been assessed not only by such an internal validation, but also by external validations, using other constitutive laws, and comparing the predictions to direct axisymmetrical calculations and to other existing approximate methods. The universality of the interaction principle is also demonstrated by its validity extended to viscoplastic behavior (Guo 1995).

#### 4 EXTENSION TO THREE DIMENSIONAL CASE (ANISOTROPIC STRESS FIELD)

In engineering practice, two dimensional approaches are applied to more realistic tunnel cases, either by means of the softening modulus method, or by the extended CV-CF method.

But the validity of a fundamental hypothesis assumed in the extended CV-CF Method, e.g. the deconfining ratio  $\lambda$  concept, has not been proved as yet, and must be previously checked :

$$\underline{\sigma}_i = (1-\lambda)\underline{\sigma}_0 \quad 0 \leq \lambda \leq 1 \quad (4.1)$$

where  $\underline{\sigma}_i$  is a fictitious stress state in the nucleus inside tunnel section, and  $\underline{\sigma}_0$  is the initial geostatic stress.

Next remains the determination of the instant for activating the support elements, which is connected to the determination of a deconfining ratio  $\lambda = \lambda_0$ .

Concerning the reference problem, some analytical solutions for determining the ground reaction curves are available in limited cases, e.g. in elastic case (Kirsch 1898, Muir Wood 1975, Curtis & al. 1976, Panet (1986)). In plasticity, some analytical solutions have been proposed for unsupported tunnels in a perfect plastic Coulomb material, provided some assumptions be made on the shape of the plastic zone (Detournay 1983).

However, a general plane strain approach needs a systematical numerical treatment, e.g. by finite elements. Following a similar methodology used in rotational symmetry case, direct and plane strain approaches are considered simultaneously.

##### 4.1 Validation of the deconfining ratio concept

Answering this question is equivalent to check if any deformed section in the plane strain calculation for a given deconfining ratio  $\lambda$ , corresponds to any definite deformed tunnel section, in the three dimensional calculation. For this purpose, let us consider for any given longitudinal section  $\theta$ , the  $\lambda$

vs.  $D$  relationship obtained by comparing the convergence curve in the three dimensional calculation  $U_i(D)$  with the plane strain convergence  $U_i(\lambda)$  (Figure 5). If a unique  $\lambda(D)$  relationship exists, then the fictitious stress concept is valid. This is practically true, as shown by the close fit by less than 10% between  $\lambda(D)$  for two meridional sections ( $\theta=0^\circ$  and  $\theta=90^\circ$ ) (Figure 6).

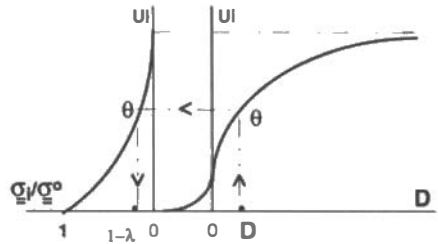


Figure 5 Scheme for determining  $\lambda(D)$

Thus, for an unsupported tunnel, parameter  $\lambda$  is univocally attached to a definite section during the face advance. As a consequence, this parameter is also attached to the mean convergence of that section in function of the distance  $D$ .

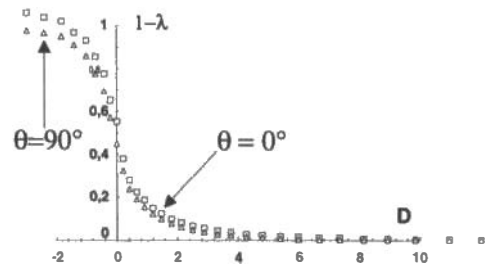


Figure 6 Relationship  $\lambda(D)$  for two meridional sections

##### 4.2 Validation of using $\lambda$ as a support activation instant

According to the fact that the convergence curve depends on support characteristics (Bernaud, 1991), it must be remarked however, if ever  $\lambda$  could stand for a time, that the instant of support activation could not be readily derived from the  $\lambda$  vs.  $D$  relationship. Indeed, as shown in case of

rotational symmetry, such a determination should be indirect.

Anyway, it is not evident that  $\lambda$  could stand for support activation instant in plane strain approach. To check this, we determine first from the direct three dimensional analysis the likely instant  $\lambda_0$ , corresponding to the leading edge of support at distance  $D=D_0$ , from a diagram similar to Figure 5, but concerned with the mean convergence  $\tilde{U}_i$ . This activation instant is then used in the plane strain approach and the final convergence is compared to the direct calculation. The good agreement thus obtained justify the use of  $\lambda$  for activation instant. It must be checked now if,  $\lambda = \lambda_0$  can effectively represent any definite instant for support activation (Figure 7).

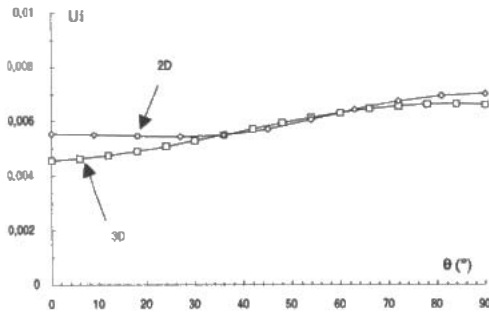


Figure 7 Comparison between stabilised convergences

#### 4.3 Determination of $\lambda_0$ in the three dimensional case

As shown hereabove, parameter  $\lambda$  can be effectively related to the mean convergences  $\tilde{U}_i$ , as well as to initial stress state as a deconfining ratio. A "mean rock mass convergence curve"  $(1 - \lambda)$  vs  $\tilde{U}_i$  can then be defined from the plane strain calculations. It can be postulated now that  $\lambda_0$  (or equivalent  $U_0$ ) be obtained by the same system of equations as Eq. (3.2), but concerning the mean convergence values  $\tilde{U}_i$ .

To check this conjecture, it is necessary that the two principles still work on the mean convergences:

self similarity principle and interaction principle.

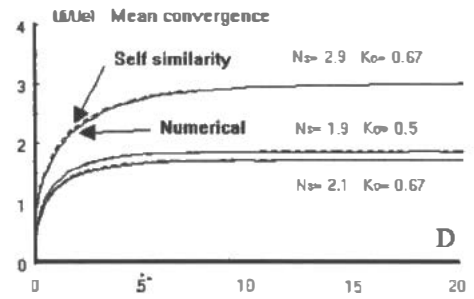


Figure 8 Extension of self similarity Principle

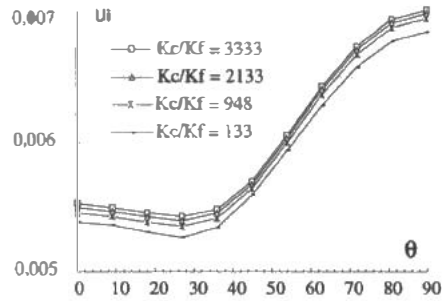


Figure 9. Small influence of bending stiffness  $K_f$

It has been checked that self similarity principle effectively extends to mean convergences (Figure 8). As interaction principle only depends on the normal stiffness parameter  $K_c$ , a preliminary condition is that bending support stiffness has little weight on the angular distribution of convergence, which can be indeed verified (Figure 9).

Then, a system of equations analogous Eq. (3.2), but concerning the mean convergences, allows us to determine an activation instant  $\lambda_0$  which shows satisfactory results when compared to direct three dimensional calculations (Guo 1995)

It must be noticed here that the mean convergence curve is different from the curve obtained for the circular symmetrical case with isotropic initial stresses equal to the mean stress.

## 5 CONCLUSIONS

The constant rate advancing supported circular tunnel under anisotropic geostatic loading stress state has been chosen as a reference three

dimensional tunnelling problem. This problem was thoroughly analysed, using an efficient and versatile numerical tool taking advantage of the specific hypotheses of this problem, in order to find out general rules for determining the instant for support activation in plane strain approaches.

The methodology proposed herein is based on the resolution of an equivalent mean convergence problem and good accuracy have been obtained so far. For more general problems, the mean convergence value concept can be reasonably extended on the same bases, provided the steady state concept be satisfied : this include different other tunnel geometries, including shallow tunnels, non homogeneous rockmasses, exhibiting various constitutive laws, including anisotropy, various support reaction curves.

In case of any doubts, when the problem is far different from the reference case studied herein, it is worth verifying the approximate plane strain prediction with some direct three dimensional analysis.

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