Effect of the lay distance of a stiff support on the applicability of the Convergence-Confinement method

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Abstract. The use of the classical Convergence ConFinement (CV-CF) method which is a simplified tunnel design tool is very extended nowadays. A major limitation of this plane-strain approach is encountered when it is applied to the study of tunnels with a stiff lining near the tunnel face. Under this configuration, the pressure exerted by the ground over the lining can be underestimated. The reason stems from the fact that this method is not able to simulate the tridimensional arch effect taking place between the ground and the lining. To account for this ground-support interaction, some authors have proposed to enhance the classical CV-CF method by resorting the so-called implicit methods. However, these approaches still show some limits for very stiff lining. In this paper, the applicability domain of the existing CV-CF methods when applied to the design of full-face excavated circular tunnels with a stiff support system is discussed. The results of the ground-lining equilibrium state obtained with the plane-strain approaches are compared with the equilibrium state obtained with an axisymmetric numerical model which can properly capture the arch effect taking place at the vicinity of the tunnel face. A sensibility analysis with a focus on the support lay distance has been carried out. Finally, a simple chart that clarifies which CV-CF method is more adapted to each tunnel configuration is proposed.

1. Introduction

The Convergence-Confinement (CV-CF) method is a widely used tool for the preliminary design of underground support structures excavated in rock masses. The plane-strain analysis around a circular opening on which the CV-CF method is based allows for a simplified assessment of the 3D interaction between the tunnel support and the ground. However, under certain configurations and because of the inherent simplicity of the CV-CF approach, some limitations of the method have been highlighted (e.g., [1]).

In its origins, the CV-CF method was developed for full-face circular tunnels excavated in a homogeneous ground under isotropic stress conditions ($\sigma_0$) and where gravity effects can be disregarded. The tunnel excavation is simulated by a progressive reduction of a ‘fictitious’ internal support pressure $p_f$ applied at the tunnel wall by means of the deconfining rate ($\lambda$) (Equation 1).

The idea of simulating the loss of confinement by means of $\lambda$ was introduced by Panet and Guellec [2]. This parameter grows from a value of 0 at the initial state until the value of 1 when the tunnel is completely excavated.

$$p_f = (1 - \lambda)\sigma_0$$ (1)
The equilibrium state between the support and the ground is calculated by means of the combination of three different curves: the longitudinal displacement profile (LDP), the ground reaction curve (GRC) and the support confining curve (SCC) (see figure 1). The LDP is the relationship between the radial displacement of the tunnel wall $u(x)$ and the distance to the advancing face $x$, the GRC relates the progressive reduction of the fictitious pressure and the radial displacement of the tunnel boundary and the SCC describes the mechanical response of the support.

![Figure 1](image)

**Figure 1.** Schematic representation of the curves employed in the CV-CF method [3].

The classical CV-CF method assumes that the LDP and the GRC are intrinsic curves of the ground. However, when a stiff lining is placed close to the tunnel face these curves will be affected by the presence of the lining because of the so-called arch effect taking place between the tunnel face and the lining. In consequence, the results of the equilibrium state obtained with the classical CV-CF approach will differ from the 3D analysis [4].

The LDP allows for the assessment of the magnitude of radial displacement of the tunnel wall which have taken place when the lining is placed at a certain distance $d$ from the tunnel face. This parameter $u(d)$ is one of the main inputs of the classical CV-CF method. Therefore, to account for the lining stiffness in its evaluation $\bar{u}(d)$, the implicit methods where proposed [5-7].

However, the implicit CV-CF methods account for the influence of the arch effect through an appropriate modification of the LDP but not of the GRC which is kept the same as for unlined tunnels. The arch effect is stronger when large deformations take place. In consequence, due to these limitations, a range of application of the different approaches of the CV-CF method exists in terms of the geomechanical parameters of the ground, the mechanical parameters of the lining and the tunnel geometry. This applicability domain was discussed by De La Fuente et al. [3] for full-face excavated circular tunnels with a stiff lining system placed at one tunnel diameter from the tunnel face, which is a typical situation encountered for a single shield Tunnel Boring Machine (TBM). The authors have compared the equilibrium state between the support and the ground obtained from different CV-CF methods with the one obtained from a numerical axisymmetric model. Numerical simulations permit to capture the 3D effects at the vicinity of the tunnel face.

The objective of the present works is to extend the sensitivity analysis carried out by [3] to the effect of the support lay distance which is a key parameter.
2. Applicability of the CV-CF Methods

2.1. Numerical 3D Reference Model
Because of the axial symmetry of the problem, a simple axisymmetric numerical analysis has been performed with FLAC3D. The initial stress state is isotropic. The same numerical model used by [3] is used in the present study (see figure 2).

![Figure 2. Grid geometry. Axisymmetric model (FLAC3D) [3].](image)

The tunnel excavation is carried out step-by-step by incrementally removing the ground material and installing the elastic support at a given distance from the tunnel face. The step round length is small enough to simulate a continuous excavation. A Mohr-Coulomb elastoplastic model is used as constitutive behavior of the ground. The lay distance \( d \) can be expressed as follows:

\[
d = x_f + \frac{s}{2}
\]

(2)

Where \( s \) represents the step round length and \( x_f \) is the unsupported span (see figure 3).

![Figure 3. Sequence of calculation in the step-step method. 1. Installation of the lining. 2. Excavation and calculation [3].](image)

2.2. Plane-Strain Reference Approaches
A summary of the plane-strain methods studied in this work can be found in table 1. Different expressions of the LDP [8-10] are combined with the classical and with the implicit CV-CF methods.
Table 1. Plane-strain approach: Combination of different LDP curves for various CV-CF methods for the comparison with 3D numerical results.

| Classical CV-CF Method - LDP Panet [9] | Classical CV-CF Method - LDP Vlachopoulos and Diederichs (V & D) [10] | Guo and Minh Method (M & G) - LDP Panet [9] | Guo and Minh Method (M & G) - LDP Vlachopoulos and Diederichs (V & D) [10] | Bernaud and Rousset Method (B & R) – LDP Panet and Guénot (P & G) [8] |

2.3. Sensitivity analysis on the stiff support lay distance

Dimensionless variables and parameters are used to perform the sensitivity analysis. They are noted with the superscript (’) and they allow for the normalization of the problem of a tunnel excavation [3].

\[
R^* = \frac{R}{e}; \quad d^* = \frac{d}{2R}; \quad E^* = \frac{E}{E_t}; \quad \tilde{u}^*(\infty) = \frac{\bar{u}(\infty)2G}{\sigma_0 R}; \quad \sigma_{max}^* = \frac{\sigma_{max}}{\sigma_0} \tag{3}
\]

where \( R \) is the tunnel radius, \( \sigma_0 \) is the initial stress state, \( e \) is the thickness of the support/lining, \( E \) and G respectively represent the Young’s modulus and the shear modulus of the ground, \( E_t \) is the Young’s modulus of the lining and \( \tilde{u}^*(\infty) \) and \( \sigma_{max}^* \) are the normalized radial displacement of the ground and the maximal hoop stress developed in the lining at the equilibrium state.

The list of the previously defined parameters needs to be supplemented with the load factor \( N \) defined as the ratio \( 2\sigma_0/\sigma_c \), where \( \sigma_c \) is the uniaxial compression stress of the rock mass. Furthermore, the friction angle \( \varnothing \) and the dilation angle \( \Psi \) need to be considered as independent parameters for the sensitivity analysis to obtain a complete description of the mechanical problem. Other parameters such as the Poisson’s ratio of the ground \( \nu \) and the Poisson’s ratio of the lining \( \nu_l \) have a limited impact on the equilibrium state between the ground and the lining.

A trade-off was carried out to reduce the number of calculations of the sensibility analysis by grouping some representative values of parameters \( N, \varnothing, \Psi \) in three families depending on the expected convergences of the ground: small convergences \((N = 1, \varnothing = 35^\circ, \Psi = 0^\circ)\), moderate convergences \((N = 2, \varnothing = 25^\circ, \Psi = \varnothing/3)\) and large convergences \((N = 5, \varnothing = 20^\circ, \Psi = 0^\circ)\). These three families of parameters are combined with different values of \( d^*, E^* \) and \( R^* \).

In the analysis, we consider values between 0 and 2 for parameter \( d^* \): 0.5, 1, 1.5 and 2. \( d^* = 0 \) represents a support installed right at the tunnel face, \( d^* = 1 \) is the typical configuration of a tunnel excavated with a single shield TBM and \( d^* = 2 \) could represent a tunnel excavated with a double shield TBM. \( E^* \) is varied between 0.05 and 1. Parameter \( R^* \) takes values of 10, 12.5 and 15. Finally, the Poisson’s ratio of the ground is kept unchanged and equal to \( \nu = 0.25 \). The Poisson’s ratio of the lining is also kept constant and equal to \( \nu_l = 0.2 \). A total of 225 combinations are possible (see figure 4).

Figure 4. Combination of parameters for the sensitivity analysis.
2.4. Results and discussion

The equilibrium states obtained from 225 axisymmetric simulations resulting from the combination of the mechanical parameters are compared with the different CV-CF approaches cited in Table 1. The maximum hoop stress developed in the support at the state of equilibrium, obtained from the axisymmetric models, is compared with the one obtained from the different approaches of the CV-CF method.

Figures 5, 6 and 7 show the comparison between the CV-CF approaches and the results of the axisymmetric simulations in terms of $\sigma_{max}$ only for a representative set of values. The total set of results is given in the online resource [11].

When parameter $E^*$ is smaller than 0.6 and the lining is installed close to the tunnel face the classical CV-CF approach tends to underestimate the stress state in the lining. This conclusion agrees with the results of [4]. When $d^*$ is smaller than 1, the implicit method of M&G combined with the LDP of V&D appears to be the most suitable. When $1 \leq d^* \leq 2$, the M&G method combined with the LDP of Panet is the most accurate choice. However, there exists a limit for applying the CV-CF methods when the relative stiffness of the support with respect to the ground is very high where none
of the CV-CF methods provide an accurate result. Figure 7 shows a chart that clarifies the applicability limits of the CV-CF implicit methods in function of parameters $d^*$, $E^*$ and for $R^*$ between 10 and 15 and $N$ between 1 and 4.

![Figure 7: Chart showing applicability limits for CV-CF methods](image)

**Figure 7.** Chart showing applicability limits for CV-CF methods.

From Figure 8 we can observe that the arch effect is amplified for a lay distance of 1 diameter corresponding to the configuration of a tunnel excavated with a single shield TBM. When the ground deformation is blocked with the installation of a stiff lining close to the tunnel face, the problem is well addressed using M&G implicit method with a correction of the LDP for the effect of the stiffness.

Cantieni and Anagnostou [4] explained the impossibility of plane strain methods to reproduce the stress path of the points at the tunnel wall as they are completely unloaded when they are excavated and then recompressed once the lining is placed. They show that this limitation of the plane strain models is the main source of discrepancy with the 3D numerical models. When $d^*=0$ the tunnel wall is never unloaded to zero and when $d^*=2$ the tunnel wall doesn’t undergo a big recompression as the lining is installed far away from the tunnel face. Under these two configurations ($d^*=0$ and $d^*=2$), the CV-CF methods show a better performance than when $d^*=1$ where the unloading and recompression path of the tunnel wall is the most pronounced.

It is important to note that for $N=5$, no method is actually suitable. To establish the threshold of $N$ for which the previous guidelines are satisfied, a set of numerical simulations with values for $N$ of 3 and 4 have been carried out (Figure 9 and Figure 10). To study the worst-case scenario $d^*=1$ and $\theta = 20^\circ$ have been chosen. The obtained results show that the applicability domain of the CV-CF implicit methods proposed when $N$ is equal to 1 and 2 can be extrapolated to values of $N$ equal to 4.

Results concerning convergences at the equilibrium state have also been studied and they can be found in the online resource 2 [12]. We can conclude that convergences at equilibrium can be properly obtained with the M&G implicit approach in combination with the LDP of V&D for any ground behavior, support lay distance and support stiffness. However, when $1 \leq d^* \leq 2$ the classical CV-CF method combined with the LDP of V&D better suits the numerical results. It is important to note that the dilation angle is a source of discrepancy in terms of tunnel wall convergences between a plane-strain model and a 3D numerical approach [3]. For this reason, convergence results obtained for $N = 5$...
could be affected by this effect as an associate flow rule has been considered for this combination of parameters.

\[ d^* = 1 ; R^* = 12.5 ; \phi = 20.0^\circ ; \psi = 6.7^\circ ; N = 3 \]

**Figure 9.** Comparison of \( \sigma_{\text{max}}^* \) obtained with different approaches when \( N = 3 \).

\[ d^* = 1 ; R^* = 12.5 ; \phi = 20.0^\circ ; \psi = 6.7^\circ ; N = 4 \]

**Figure 10.** Comparison of \( \sigma_{\text{max}}^* \) obtained with different approaches when \( N = 4 \).

3. Conclusion

In the presence of a stiff support/lining system in a tunnel, especial attention needs to be paid during the preliminary design stage with the CV-CF methods. The 3D arch effect which takes place between the tunnel face and the support/lining system cannot be properly simulated by means of plane-strain methods. This effect leads to an almost systematical underestimation of the stresses developed in the lining when a classical CV-CF method is used. Larger ground convergences and stiffer linings will result in a greater underestimation of the stresses in the lining. Some CV-CF approaches called implicit methods have partially solved this problem by adapting the longitudinal displacements profile to account for the arc effect. However, some limitations are still present as plane-strain methods consider that the ground reaction curve is intrinsic to the ground.

In the present work, we have compared different CV-CF methods with a numerical axisymmetric model which captures the 3D effects at the vicinity of the tunnel face with a focus on the effect of the lay distance of the support. It has been shown that a lay distance of one tunnel diameter corresponding to a tunnel excavated with a single shield TBM corresponds to the configuration where the arch effect is amplified.

It can be concluded that for a reliable evaluation of the stress state at equilibrium in the lining, an implicit CV-CF approach such as the one proposed by Minh and Guo is necessary in the presence of a stiff support system. This method should be combined with the LDP of [10] for stability numbers \( N \) going from 1 to 4 and for a lay distance \( d \) smaller than one tunnel diameter. Similar results are obtained when the lining lay distance varies between one and two tunnel diameters which could represent a tunnel excavated with a double shield TBM. The difference is that the best results are obtained in this case with the Minh and Guo (1996) approach combined with the LDP of Panet.

However, when the relative stiffness of the support with respect to the ground is very high, none of the CV-CF methods provide an accurate result. To clarify the applicability limits of the CV-CF implicit methods, a simple chart has been provided in this study. By entering the relative stiffness of
the lining respect to the ground stiffness and the normalized lay distance of the lining in the chart, a direct assessment of the applicability of the CV-CF methods can be obtained.

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