Convergence-Confinement method in shallow tunnels

Méthode de Convergence-Confinement pour tunnels peu profonds

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SYNOPSIS The applicability of the Convergence-Confinement method (C.-C. method) to design of shallow tunnels is investigated by comparing results of the method with field measurements for two tunnels in stiff clay in Edmonton, Canada. Both tunnels were excavated under very similar conditions. The only important difference between them was the depth to diameter ratio. Because of this ratio the two tunnels exhibited different responses to analyses by the C.-C. method. The deep tunnel showed a good agreement between the analysis and field data, while the shallow tunnel did not. This discrepancy was attributed to the non-axisymmetric mode of deformation developed around the shallow tunnel.

INTRODUCTION

A number of methods are currently used for design and analysis of tunnels. Among them the convergence-confinement method (C.-C. method) has played an important role in providing an insight into the interaction between lining support and the surrounding ground mass. The method is relatively simple, easy to use and can readily indicate the sensitivity of the chosen solution through a range of possible ground parameters, support characteristics and modes of installation.

However, to maintain simplicity, a number of simplifying assumptions is employed in its derivation. These assumptions make the method applicable only to deep tunnels in a hydrostatic stress field, therefore, the use of the C.-C. method in shallow tunnels is open to question. The main purpose of this paper is to discuss this problem. The discussion is based on field data obtained from two tunnels constructed in Edmonton, Alberta, Canada.

THE CONVERGENCE-CONFINEMENT METHOD (C.-C. METHOD)

The C.-C. method is based on a concept in which the ground structure interaction is analysed by an independent study of the behaviour of the ground and of the tunnel support. The ground behaviour is represented by a ground reaction curve (GRC) and the lining by a support reaction curve (SRC). The former describes the ground convergence in terms of the applied confining pressure while the latter relates the confining pressure acting on the lining to its deformation. The solution for the ground support interaction is then given by the intersection of these two curves, as illustrated in Figure 1.

In the past a number of approaches to the determination of GRC has been published. Brown et al. (1983) presented a summary of the characteristic features of each of the main formulations derived in the past 40 years.

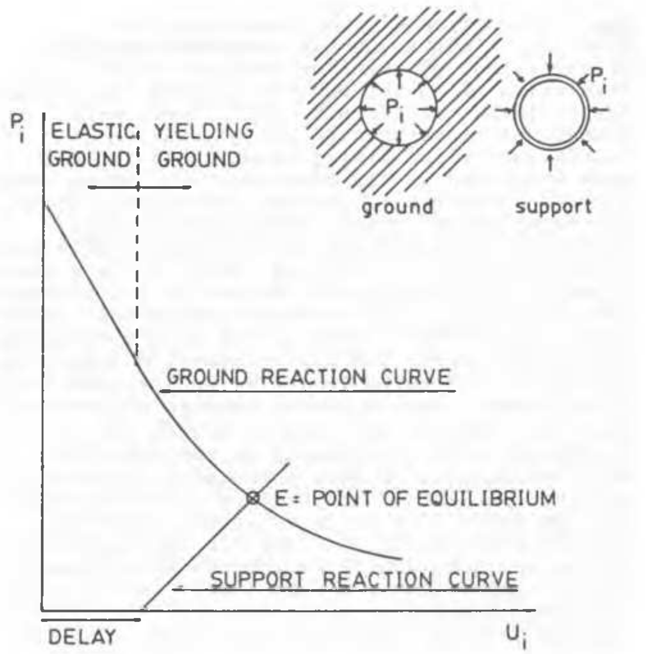

Fig.1 Concept of Soil Structure Interaction by the Convergence-Confinement Method.

The number of published solutions for SRC is also large. SRC's are determined, on the basis of the theory of elasticity, from the lining stiffness, load capacity and the displacement that occurs before the lining activation, as indicated in Figure 1. The support stiffness is defined as the uniform all around pressure required to cause unit diametral strain on the lining. Support stiffnesses and support bearing capacity for different liners have been presented by Lombardi (1973) and Hoek and Brown (1981).

The idealization of the ground-support interaction by the two reaction curves, obtained from closed form solutions, is only valid for the two-dimensional cylindrical model in which, irrespective of the lining and ground mechanical properties, the soil and support follow the same radial mode of deformation. This is a major limitation of the method as far as shallow tunnels are concerned, since the proximity of a free surface above the tunnel, a non-hydrostatic stress field ($K_o \neq 1$) and the effects of gravity around the tunnel cannot be included in the analysis.

A review of other available lining design methods, presented by Branco (1981), indicated that there is no simple design method for shallow tunnels.

In the following sections the applicability of the C.-C. method is investigated with special regard to the influence of a free surface above the tunnel.

C.-C. METHOD OF LINING DESIGN OF SHALLOW TUNNELS IN STIFF SOILS

The construction of two tunnels in the city of Edmonton, Alberta, Canada, enabled the analysis of the effect of the free surface on the prediction of tunnel behaviour using the C.-C. method to be carried out. The tunnels were extensively instrumented for ground displacements and lining loads. Both tunnels were excavated in the Edmonton till, using very similar construction methods. The first tunnel, the experimental tunnel (EXP tunnel), was comprehensively studied by El-Nahhas (1980) and Eisenstein et al. (1980 and 1981). It is a small diameter tunnel (D=2.56m) driven by a full face TBM at a depth of 27 metres to the tunnel centre line. The primary lining of one of the sections of the EXP tunnel comprises segmented steel ribs (WF100x19) 1.5 metre centre to centre, and 5 x 20 cm timber lagging placed between the webs of the ribs. The rib and lagging system was assembled within the shield of the TBM. The drilling machine is then advanced by jacking against the ribs of the temporary lining. When the TBM advanced sufficiently that the rib emerged from the shield, the rib was expanded by hydraulic jacks and 10 cm spacers were placed in the two upper joints of the steel rib. The next rib-lagging assembly was placed in the shield and the drilling operation continued.

The second tunnel, the LRT-South Extension tunnel (LRT-SE tunnel), was extensively analysed by Eisenstein and Branco (1985, a and b), and Branco (1981). It is a large diameter tunnel (D=6.1 m) driven again by a shielded TBM, with the tunnel centre line at a depth of 11.8 m. The primary lining of the LRT-SE tunnel is composed of segmented steel ribs, W6x25, 1.22 m centre to centre and 10 x 15 cm timber lagging between webs of successive ribs. Its installation is similar to the one used in the EXP tunnel. Table I summarizes the lining and ground parameters, related to the two tunnels, used throughout the calculations of this paper. Both tunnels were excavated under an approximately hydrostatic stress field ($K_o \cong 1.0$). The difference in the depth ratio (depth of the centre of the tunnel to the tunnel diameter) of the LRT-SE tunnel and the EXP tunnel is the most important difference between the two tunnels. Otherwise the tunnels are quite comparable particularly in terms of host ground and lining method. The EXP tunnel has a depth ratio of 10.56, and will be regarded as a deep tunnel, while the LRT-SE tunnel has a depth ratio of 1.9 and will be considered as a shallow tunnel. The assumption of whether the tunnels are deep or shallow was based on the expected development of tangential stresses in the ground, at the tunnel wall, as proposed by Mindlin (1940).

Excluding three-dimensional and gravity effects inherent to any tunnel construction, the EXP tunnel fulfills all the boundary conditions associated with the C.-C. method. On the other hand, for the LRT-SE tunnel, in addition to three-dimensional and gravity effects, the proximity of the free surface violates the imposed boundary conditions. This indicates that the C.-C. method should better predict the behaviour of the ground-support interaction for the EXP tunnel than for the LRT-SE tunnel.

TABLE I

Lining and Ground Parameters for the LRT-SE and EXP Tunnels

			EXP TUNNEL (AFTER EL-NAHHAS, 1980)	LRT-SE TUNNEL (AFTER BRANCO, 1981)
GROUND PARAMETERS		YOUNG'S MODULUS (MPa)	75	150
		POISSON'S RATIO	0.4	0.4
		COEFFICIENT OF DILATANCY	1	1
		FRICTION ANGLE (DEGREES) (EFFECTIVE)	30	40
		COHESION (MPa) (EFFECTIVE)	0	0
	SOIL DISPLACEMENTS TOWARDS THE TUNNEL (mm) (AT THE SPRINGLINE)	BEFORE FACE	4	0
		BEFORE EXPANSION	19	2.5
		AFTER EXPANSION	2.5	0.5
LINING PARAMETERS		YOUNG'S MODULUS (MPa)	207000	207000
		POISSON'S RATIO	0.25	0.25
		MOMENT OF INERTIA (m^4)	4.76×10^{-6}	22.2×10^{-6}
		CROSS-SECTION AREA (m^2)	24.7×10^{-4}	47.3×10^{-4}
		RIB SPACING (m)	1.5	1.2
		DIAMETER (m)	2.56	6.1
		FINAL RADIAL LOAD AT THE SPRINGLINE (Pi/Po)	0.02 TO 0.12	0.18 TO 0.24

Figures 2 and 3 present the ground reaction curves for the EXP tunnel and for the LRT-SE tunnel respectively. These curves were derived according to the formulation presented by Kaiser (1980) for a circular opening, excavated in a material that is assumed to be linearly elastic, brittle-perfectly plastic, with yield surfaces described by the Coulomb failure criterion.

Three different points of equilium for the ground-support interface are shown in Figures 2 and 3 for both tunnels. They are Ea, Eb, Ec.

Point Ea

Ea is the point of equilibrium defined by the intersection of the theoretical ground reaction and the support reaction curves. The plot of the SRC's shown in Figures 2 and 3 requires a knowledge of the compressive stiffness of the support and of the ground displacement close to the ground-support interface, that takes place before the lining expansion. In this paper the latter is obtained by the sum of two ground displacements:

(a) ground displacements that take place ahead of the face of the tunnel: assumed to be 1/3 of the elastic wall displacement of the unlined tunnel (Ranken and Ghaboussi, 1975).

(b) ground displacements that take place along the length of the TBM shield: assumed to be one half of the difference between the excavated diameter and the diameter of the expanded primary lining.

Branco (1981) presented a detailed estimation of the displacements for both the tunnels.

Point Eb

Eb is another point of equilibrium defined by the intersection of the ground reaction and the support reaction curves. The difference between Ea and Eb is in the ground displacement that is allowed to take place before the lining is expanded. In order to find Ea the ground displacement that takes place before the lining expansion was estimated without taking into account any information derived from the tunnel instrumentation. On the other hand, the plot of the SRC that defines the point of equilibrium Eb, is based on the *measured* ground displacements that takes place before the lining expansion. These displacements, obtained from field instrumentation, were presented by Branco (1981) and summarized in Table I.

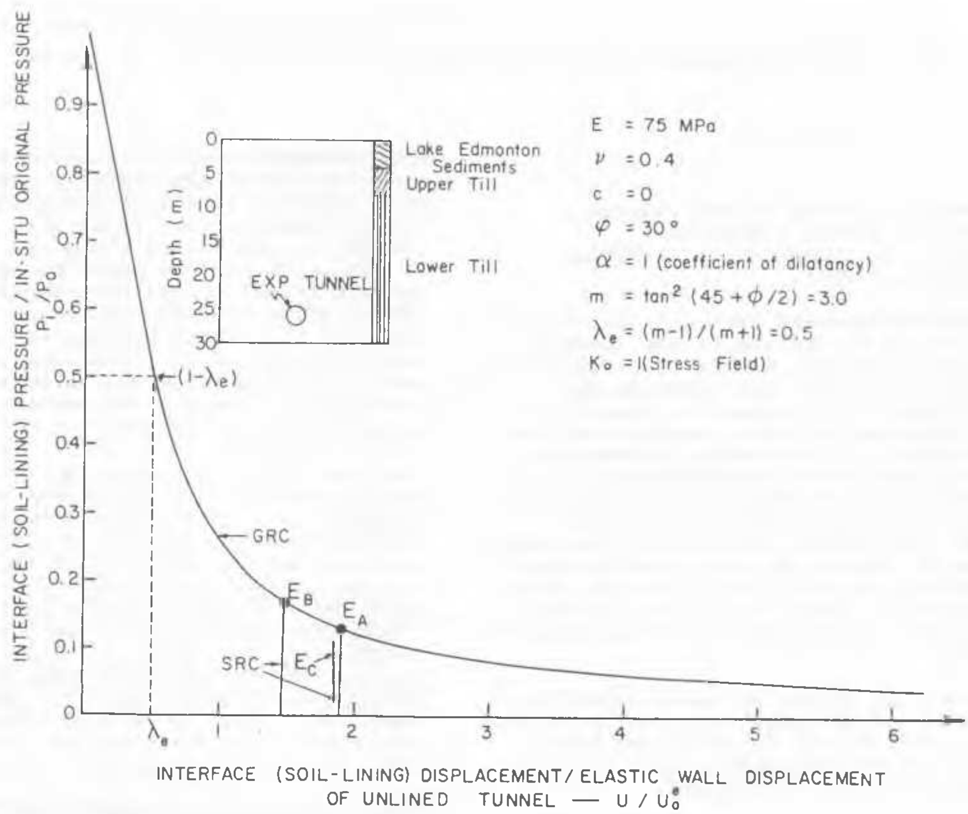

Fig.2 The Confinement-Convergence Method at the Springline of the EXP Tunnel

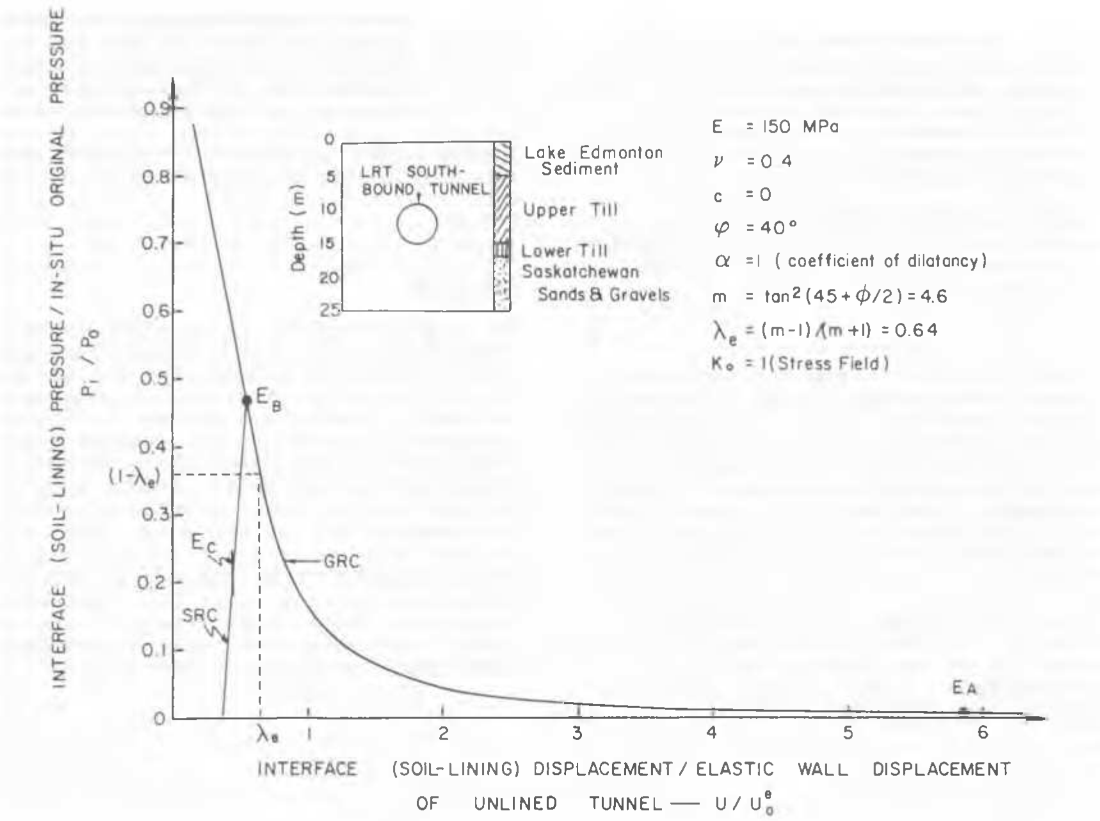

Fig.3 The Confinement-Convergence Method at the Springline of the LRT Tunnel

Point Ec

Ec is the range of points of equilibrium obtained from the lining and ground instrumentation, as presented by El-Nahhas (1980) and Branco (1981).

The loads and displacement ratios defining Ec are related to the springline of the tunnels because at this location, a more complete set of field data was available. Also the gravity effects, not taken into account in the C.-C. method, are minimized at this location and can thus be neglected. It is relevant to mention that for both tunnels the displacements associated with Ec were obtained at a distance of approximately one quarter of the tunnel diameter from the support springline. This means that the true Ec values, at the ground-support should be shifted to the right of the Ec shown in Figures 2 and 3, since, the closer to the tunnel walls, the larger are the radial ground displacements.

The analysis of the points of equilibrium, Ea and Ec, plotted for the ground-support interface of the EXP tunnel on Fig. 2, indicates that thrusts and lining displacements were reasonably well predicted by the C.-C. method.

On the other hand, the comparison between Ea and Ec in Fig. 3, for the LRT-SE tunnel, indicates that the C.-C. method predicts loads and displacements completely different from those measured. After the measured ground displacements that took place ahead of the lining expansion are taken into account and when the SRC is positioned along the horizontal axis of Figure 3, the new point of equilibrium, Eb, is much closer to Ec. This shows that a much better prediction of the lining behaviour is obtained and indicates that the discrepancy between measured (Ec) and expected (Ea) loads and lining displacements is basically due to the inaccurate estimation of ground displacements ahead of the lining activation.

The inaccurate assessment of ground displacements that take place before the lining expansion is mainly attributed to the non-axisymmetric mode of deformation around shallow tunnels, even in the case where the initial stress field ratio (K_o) is approximately equal to 1. This conclusion is confirmed by the field measurements that indicated uniform lining convergence with respect to the tunnel centre line and by the improved prediction of the tunnel behaviour by the C.-C. method. This improvement results from the taking into account the ground displacements that occurred before the lining was installed.

The loads and displacements associated with Ec in Fig. 3 would be closer those associated with Eb, if the ground displacements were measured closer to the tunnel support.

CONCLUSION

The study presented herein indicates that for the two tunnels constructed in stiff clay in Edmonton, the prediction of tunnel behaviour based on the C.-C. method yielded good results for the deep tunnel but not for the shallow one.

The discrepancy between predicted and measured displacements is attributed to the fact that the mode of deformation and development of plasticity in the soil surrounding the shallow tunnel was not axisymmetric, as assumed by the C.-C. method. The departure from the uniform radial (axisymmetric) mode of behaviour with the LRT-SE tunnel was due to the proximity of the ground surface. It was shown that most of the non-axisymmetric deformation took place before the lining activation. This suggests that, for the development of a design method for shallow tunnels, special attention should be paid to the ground behaviour before the lining activation. As has been shown, for this type of host material, after the lining is erected, generally simple uniform radial displacements are expected to take place.

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