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The effect of the anisotropic state of stress on the normal force in a deep tunnel preliminary deformable lining

L'effet de l'état anisotrope de la contrainte sur la force normale dans un revêtement déformable préliminaire de tunnel profond

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ABSTRACT: When deep tunnels are excavated in poor ground, squeezing conditions occur and the design of supports must follow the yielding principle. To this aim, special elasto-plastic elements embedded in the temporary support can be employed. The presence of the elastic-plastic elements radically modifies the ground-lining interaction mechanisms making necessary the use of numerical analyses. Particularly relevant is the case of anisotropic geostatic state of stress. The paper reports and discusses, some results from 2D numerical ground-lining interaction of deformable temporary support with initial non-isotropic stress field. Results of the classic rigid support are also reported and compared.

RÉSUMÉ: Lorsque des tunnels profonds sont creusés dans un sol de mauvaise qualité, des conditions d'écrasement se produisent et la conception des supports doit suivre le principe de flexion. À cette fin, des éléments élasto-plastiques spéciaux incorporés dans le support temporaire peuvent être utilisés. La présence d'éléments élasto-plastiques modifie radicalement les mécanismes d'interaction entre le sol et le revêtement, ce qui rend nécessaire l'utilisation d'analyses numériques. Le cas d'un état de contrainte géostatique anisotrope est particulièrement pertinent. L'article rapporte et discute certains résultats de l'interaction numérique 2D entre le sol et le revêtement d'un support temporaire déformable avec un champ de contraintes initial non isotrope. Les résultats du support rigide classique sont également rapportés et comparés.

Keywords: Tunnelling; Yielding principle; Soil-lining interaction; Squeezing conditions; anisotropic state of stress.

1 INTRODUCTION

When deep tunnels cross poor grounds the so-called squeezing conditions happens. This leads to huge risks for the construction project, higher construction times and costs. Furthermore, in conventional tunnelling, extremely high convergences and overload of rigid preliminary lining can be expected. The best way to face these difficulties is to design the preliminary support following the so-called yielding principle (Kovári, 1998): the support must be highly deformable, allowing the ground deformations and, by so doing, reducing the stress acting on the lining. There are various technological solutions to introduce local deformations into the preliminary lining (Wu et al., 2021; Moritz, 2011). This paper is focused on circumferential elastic-plastic elements (EPE). TH steel ribs, hiDCon, LSC, hiDSte and Wabe are the most commonly used ones in conventional tunnelling.

There is limited literature on numerical modelling for the design of yielding supports in deep tunnelling under squeezing conditions (Yang et al., 2022; Barla et al., 2011; Tian et al., 2018; Radončić, 2011). Indeed, the ground-lining interaction (GLI) with a yielding lining has not been widely studied leaving a notable gap on the comprehension of tunnels' behaviour with this kind of supports. Furthermore, there is a lack of study on the effect of geostatic anisotropic state of stress, which is usually faced in squeezing conditions, on the interaction mechanism.

The aim of our work is to fill this existing gap. Our research was firstly driven by the embedment of high deformable elements in the steel ribs (Batocchioni et al., 2023). Whereas this paper aims at understanding the mechanical behaviour of a temporary lining following the yielding principle, under an anisotropic state of stress. Considering that in deep tunnelling the horizontal and the vertical stress can be quite far from equal for the combined effect of gravity and tectonic.

The methodology is developed by following a numerical approach. In order to highlight how the anisotropy of initial geostatic stress field affects the GLI, the results obtained for both rigid and yielding lining, starting from isotropic and then anisotropic geostatic conditions, are presented and discussed.

2 NUMERICAL MODEL

2D numerical analyses, modelling a cross section of a circular tunnel supported by temporary lining, have been developed with the aim of studying the peculiarity of GLI under an anisotropic stress field. The methodology is in line with the one used by Batocchioni et al. (2023), but with a focus on the relationship between lining‘s normal force, *N*, and the EPE‘s closure as relaxation increases. Indeed, study the effects on *N* give a first clear picture on the GLI mechanism. The analyses were developed through the FDM code FLAC2D (Itasca, 2011). The model reproduces only one quarter of the tunnel thanks to the symmetries (Figure 1). The mesh is composed of 4876 elements. The boundary constraints are the ones depicted in the Figure 1. Several analyses were carried out: the lining with (yielding) and without (rigid) the EPE, with an isotropic ($k_0 = 1.0$) and anisotropic ($k_0 = 0.5$) state of stress while keeping the average in-situ stress constant. For symmetry reasons, by neglecting the gravity and studying $k_0 = 0.5$ condition is equivalent to study also $k_0 = 2$ condition.

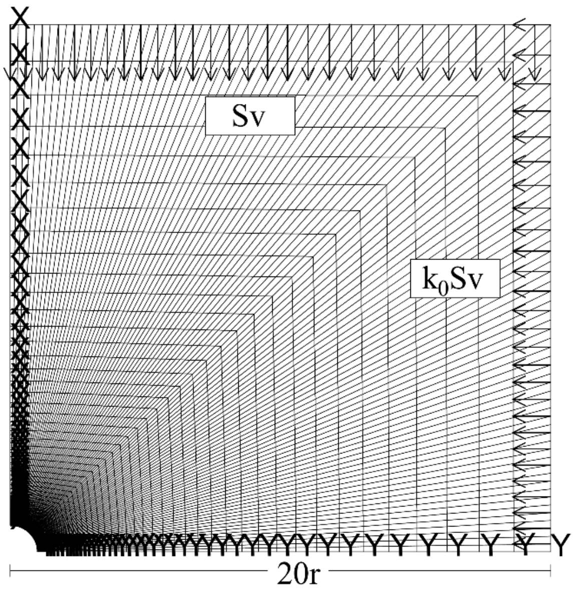


Figure 1. Numerical grid on FLAC 2D.

The mechanical behaviour of the ground has been modelled as isotropic elastic perfectly plastic with the parameters reported in Table 1. The severity of the conditions are quite high, in fact, the ratio between the uniaxial compressive strength and the mean in-situ stress is extremely low (≈ 0.06). Thus, leading to squeezing conditions (Ramoni and Anagnostou, 2010).

The excavation phase has been simulated with the well-known relaxation method, assuming the lining installation corresponds to a relaxation factor of 70%. The preliminary support has been modelled with one HEB240 steel rib per meter. For sake of simplicity, the presence of the shotcrete was neglected. The lining has been modelled with elastic perfectly plastic beam (yielding normal force of 2915 kN). Also the EPE has been simulated with the same beam elements, but with lower values of Young‘s modulus and yielding normal force. The EPE has been modeled as a generic yielding element, but akin to the hiDSte (the best solution to embed in the steel rib). Therefore the Young‘s modulus magnitude is the one obtained by compression in experimental analyses, whereas the yielding normal force has been set as half of the steel rib one. In the analyses, the EPE behave as a hinge, assuming a null value of the plastic moment of the beam. This is a reasonable simplification, because the capacity of withstanding bending moments of the EPE is quite small respect to the one of the steel rib. To simulate the controlled deformation of this kind of lining, a special FISH routine was written in FLAC. Thus making the EPE extremely rigid when they reach the 97% of its maximum deformation.

The lining is connected to the ground through an interface characterized by infinite compressive strength (elastic behaviour) and shear elastic-plastic behaviour with frictional Mohr-Coulomb criterion.

The accuracy of the numerical results is guaranteed by the high density and dimensions of the mesh (20 times the tunnel radius) and by the stringent convergence criterion set in the code (*sratio* equal to 10^{-5}). As well as by verifying the achievement of stationary conditions with the progress of calculation steps of the most relevant variables of the interaction problem.

Table 1. Parameters used in the numerical analyses.

	Ground	**Steel Ribs**	**EPE**	**Interface**
Friction angle (°)	30			20
Cohesion (kPa)	100			0
Normal and shear bond stiffness (MPa)				47e3
Average in-situ stress (MPa)	6.75			
Coefficient of earth pressure at rest, (-)	0.5, 1.0			
Young’s Modulus (MPa)	1000	21e4	177	
Yielding Normal force (kN)		2915	1458	
Yielding Moment (kNm)		-	0	

3 RESULTS AND DISCUSSION

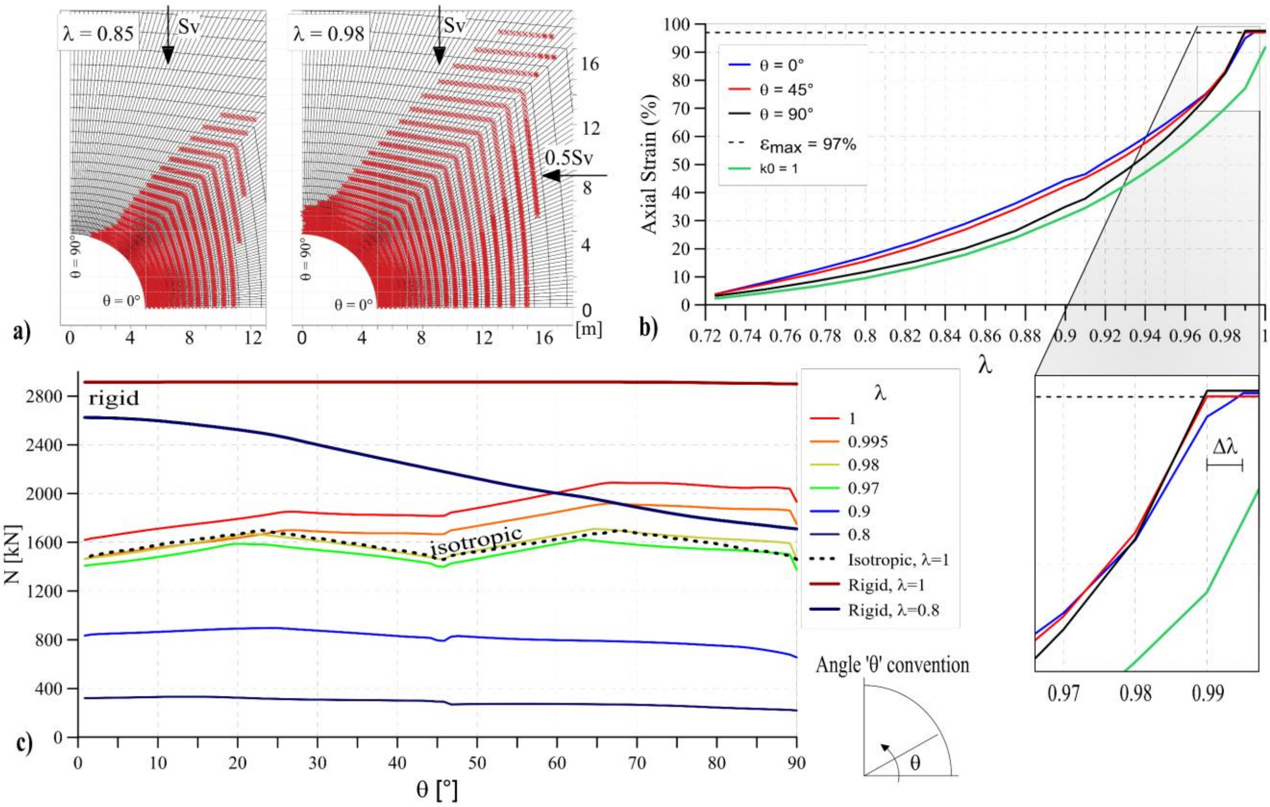
The Figure 2c reports the variation of *N* along the lining. As the relaxation increases, the *N* tends to incrase; the initial trend, higher at the sidewall, is a direct consequence of $k_0 < 1$ (arch effect). With further relaxation, the EPE start to close with progressively higher gradient (Figure 2b). As expected, initially the EPE at the sidewall ($\theta = 0° \ and \ 45°$) closes more than the rest. Thus, tending to mitigate the strong N difference along the rigid lining (see Figure 2c dark-blue lines, rigid vs yielding at $\lambda = 0.8$). Continuing the relaxation, the closure gradient of the crown EPE ($\theta = 90°$) grows and at $\lambda = 0.98$ all the 3 EPE are close at the same level (around 80%). Whatching the N along the lining (Figure 2c, light green line), from this relaxation on until the first EPE reach the adimissible deformation, the trend is substantially the same with the istropic one (Figure 2c, black dotted line). This continue to emphasise the good benefit of the yielding lining on anisitropic mitigation. Indeed in these conditions, appear evident the effect of the EPE imposing the passage of the N-curve at their yielding value (1458 kN) and by so doing impeding the N value to rise more.

Whereas between the two EPE (in the rigid lining segment) the N rises because of the interface's shear strength, reaching the maximum value in the middle of the rigid segments (Radončić et al., 2009; Tian et al., 2018; Batocchioni et al., 2023).

The scenario changes when at $\lambda = 0.99$, the EPE in the crown is the first to reach the admissible deformation and finally at $\lambda = 0.995$ (Figure 2c, orange line) all the EPE are fully closed. In spite of such a small relaxation ($\Delta\lambda = 0.005$, Figure 2b), the effect on the N-curve is decisively clear: the interaction changes and inside all the lining with the close EPE (upper part of the tunnel) the N can rise. This difference of N (around 300kN) will remain constant until the end of relaxation considering that now on the lining behave as completely rigid (Figure 2c, red line). Therefore the final arrangement of the N is characterized by higher values at the crown. Unlike what was expected.

The explanation of these behaviours likely is in the different stress paths that experience the ground near the tunnel. Especially, looking at Figure 3, the first ground's element to reach the yielding (the only one before $\lambda = 0.7$, i.e. the installation of the lining) is the one at the sidewall; where the stress path induced by tynnelling tends to increase the mobilization of shear strength. The last to yield is the element in the crown (almost at the end of relaxation), where the deviatoric stress tends initially to reduce and after becoming isotropic, it tends to incrase, with an inversion of the principal stress direction. Thus, the plastic zone starts at the sidewall and then it extends to the upper part of the tunnel (Figure 2a).

In conclusion the effectiveness of the yielding lining can be highlighted by comparing the two dark-blue lines (Figure 2c, both thick and thin ones) representing the N on yielding and rigid lining



(respectevely with and without the EPE) for the same level of relaxation ($\lambda = 0.8$). The N acting on the rigid lining are markedly higher than yielding one. Although less effectively than under isotropic stress field, the deformable lining is able to mitigate the effect of the anisotropic geostatic state of stress: the variation of N along the support is less pronunced respect to the rigid lining and the magnitude are rather lower.

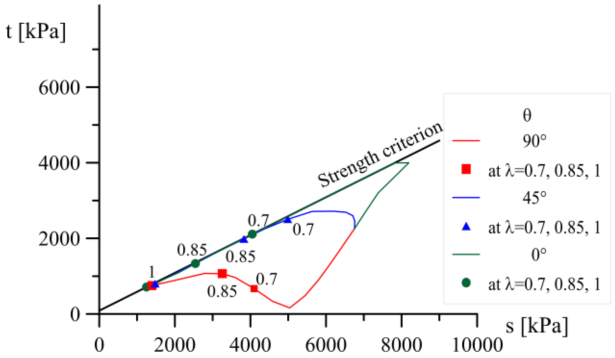


Figure 3. Stress path of different ground zone near the tunnel: green (θ=0°, sidewall), blue (θ=45°), red (θ=90°, crown) and black (strength criterion).

4 CONCLUSIONS

In the design of deep tunnel's preliminary lining squeezing conditions can be faced. In this case, a yielding lining must be conveniently employed. Moreover, due to the combined effect of gravity and tectonic, the initial stress state can be very far from isotropic.

In this paper, 2D numerical analyses have been developed with the aim of studying the interaction between temporary lining equipped with elasto-plastic elements and ground under geostatic anisotropic state of stress.

The main outcomes are the following:

- the study of the ground's plastic zones development is essential to understand the complex ground-lining interaction;
- if none of the elasto-plastic elements reach the admissible deformation, the yielding lining is able to minimize the effect of the anisotropic state of stress on the normal forces;
- if one or more elasto-plastic elements reach the admissible deformation, the most critic section turn out to be the one towards the maximum principal stress direction, differently from what happens with a rigid lining.

Regarding further development, in order to achieve a more complete picture of the ground-lining interaction of a yielding support under anisotropic state of stress, it will be necessary to consider the distribution and evolution of shear and bending moment, expected to be relevant.

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