The effect of an anisotropic in-situ stress on the bending moment in a yielding lining

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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 yielding elements embedded in the preliminary support can be employed. The presence of the yielding elements radically modifies the ground-lining interaction mechanisms making necessary the use of numerical analyses. Particularly relevant is the case of the anisotropic geostatic in-situ stress. The paper reports and discusses some results obtained by 2D numerical ground-lining interaction analyses of yielding preliminary support with initial non-isotropic stress field. Results of classic rigid support and isotropic in-situ stress are also reported and compared. Specific attention will be given to the effect that the stress anisotropy has on the lining bending moment.

1 INTRODUCTION

When dealing with deep tunnels in poor ground the so-called squeezing conditions happen. This leads to huge risks for the construction project, higher construction times and costs (Hoek 2001). Furthermore, in conventional tunnelling, extremely high convergences and an overload of rigid preliminary support 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 circumferential local deformations into the preliminary lining (Wu et al. 2021, Moritz 2011). TH steel ribs, hiDCon, LSC, hiDSte and Wabe are the most commonly yielding elements (*YE*) used in conventional tunnelling.

There is limited literature on numerical modelling for the design of yielding linings (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 the tunnels' behaviour with this kind of supports. Furthermore, there is a lack of study on the effect of geostatic anisotropic in-situ 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 first driven by the basic concepts of *YE* embedment in the steel ribs (Batocchioni et al. 2023). Whereas this paper aims at understanding the mechanical behaviour of a preliminary support following the yielding principle under an anisotropic in-situ 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. Furthermore, the specific effect on the lining's bending moment will be addressed in this work.

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

2 NUMERICAL MODEL

A 2D numerical analysis, modelling a cross section of a circular tunnel (5 m radius) supported by a deformable preliminary support, has been developed with the aim of studying the peculiarity of the *GLI* under an anisotropic stress field. The methodology is in line with Batocchioni et al. (2023), but considering an anisotropic in-situ stress and a deeper focus on the relationship between the lining 's bending moment (*M*), convergence (u, modulus of the lining's displacement vector) and the *YE*'s closure (ε). The variables have been analyzed as the relaxation factor increases (λ) and along a quarter of the tunnel's lining (θ). The necessity of studying the interaction mechanisms along the relaxation process comes from the need to highlight the various phases of differential *YE's* closure (i.e., the *YE* do not reach the complete closure/deformation at the same time). Indeed, under an anisotropy in-situ stress the lining experiences asymmetric deformation.

The analyses were developed through the FDM code FLAC2D (Itasca, 2011). The model reproduces only one quarter of the tunnel thanks to the symmetries (Fig. 1). The mesh is composed of 4876 elements. The boundary constraints are the ones depicted in Figure 1. Several analyses were carried out: lining with (yielding) and without (rigid) *YE* and under isotropic ($k_0 = 1$) and anisotropic ($k_0 < 1$) in-situ stress (keeping the averaged stress constant).

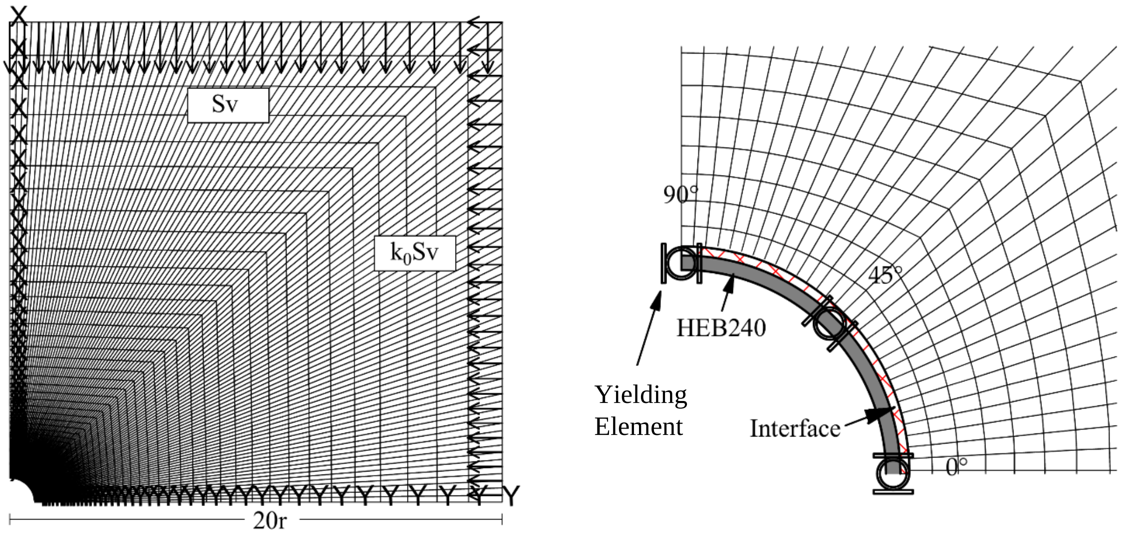

Figure 1. a) Numerical grid on FLAC 2D; b) zoom on the ground-lining interface.

All the parameters of the tunnel scenario have been chosen to be the ones representing a typical deep tunnel in squeezing conditions. More specifically 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 is quite high, as a matter of fact, the ratio between the uniaxial compressive strength and the average in-situ stress is extremely low (0.05). Thus, leading to squeezing conditions (Ramoni and Anagnostou 2010). These extreme conditions are caused by a relatively deep tunnel (overburden of $250m$) through a weak rock mass ($UCS = 350kPa$). In this condition an un-supported tunnel with this radius should experience convergence with an order of magnitude of 1 meter.

The excavation phase has been simulated with the relaxation method, assuming the lining installation at a typical value concerning the conventional tunnelling ($\lambda = 0.7$). The yielding temporary lining has been modelled with one HEB240 steel rib per meter with one *YE* embedded each 45°. For sake of simplicity, the presence of the shotcrete was neglected. Whit this simplification is possible to realize a 2D model with the lining consisting only in the steel ribs. The lining has been modelled as an elastic perfectly plastic beam. Also, the *YE* has been simulated with the same beam elements, but with lower values of the Young's modulus and yielding normal force. The *YE* has been modeled as a generic yielding element, but akin to the hiDSte (the best solution to embed in the steel ribs). Furthermore, 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 *YE* behave as a hinge, then assuming a null value for the beam element's plastic moment. This is a reasonable simplification, considering that the capacity of the *YE* to withstand *M* is quite small with respect to one of the steel ribs. To simulate the controlled deformation of this kind of lining, a special FISH routine was written in FLAC. Thus, making the *YE* extremely rigid when they reach the 97% of their maximum deformation (ε_{max}).

The lining is connected to the ground through an interface characterized by infinite compressive strength (elastic behavior) and shear yielding behavior with frictional Mohr-Coulomb criterion. The accuracy of the numerical results is guaranteed by the high density and dimensions of the mesh 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 of the most relevant variables with the progress of calculation steps.

Table 1. Parameters used in the numerical analyses.

	Ground	Steel Rib	YE	Interface
Friction angle (°)	30			20
Cohesion (kPa)	100			0
Normal and shear bond stiffness (MPa)				4.7e4
Young's modulus (MPa)	1000	21e4	177	
Yielding normal force (kN)		2915	1458	
Yielding moment (kNm)		-	0	
Average in-situ stress (MPa)	6.75			
Coefficient of earth pressure at rest (-)	0.5, 1.0			

3 RESULTS AND DISCUSSION

Figure 2a reports the variation of *u* (convergence, modulus of the lining's displacement vector) along the lining during the relaxation process. Except for the tunnel section where there are the beam elements representing the *YE* ($\theta = 0°, 45°, 90°$), where this representation is not able to consider the change of direction in the displacement vector (leading to the discontinuities in the convergence trend), this plot is a good reference for understanding both the amount of convergence and the steel ribs curvature (*k*). Concerning the magnitude of the convergence, comparing to the isotropic case (dashed line in Fig. 2a), it appears to be higher at the sidewall (where the direction of the radial stress coincides with the minimum initial principal stress, σ_3) and lower at the crown (direction of the radial stress coincident with the maximum initial principal stress, σ_1). Whereas, regarding the *k*, that was small in the isotropic case, it appears to be definitely higher in the upper part of the tunnel. More specifically in the high steel rib beam (45°-90°), as the relaxation and then the loads on the lining increases, the curvature tends progressively tends to increases. On the other hand, in the low steel rib beam (0°-45°), the *k* remains small for all the relaxation and the structural element rigidly moves with a pronounced rotation (the near ground is more loosened)

In the low steel rib, the *M* assumes very low values (Fig. 2b), whereas in the high steel rib the *M* tends to grow significantly, reaching values much higher than the ones obtained under isotropic in-situ stress (dashed line in Fig. 2b). By focusing on the most significant and critical section, i.e., the higher steel rib's section, the *M* tends to grow until almost the end of the relaxation process. The trend changes as soon as the first hiDSte reaches the ε_{max}. Specifically, the upper tunnel *YE* ($\theta = 45°, 90°$) closes at $\lambda_I = 0.9$ whereas the one at the sidewall, later at $\lambda_{II} = 0.995$. In the upper part tunnel, until λ_I the *M* continues to grow reaching the maximum value (around 200 kNm) and then decreases a little. The final value (around 160 kNm) is still high and similar to the one obtained by modelling the lining without embedding any *YE* (brown line in Fig. 2b).

Even under an isotropic in-situ stress, as a sort of arch effect, the concentration of normal stress at the interface between the ground and the lining in correspondence of the *YE,* that represents a weak point, leads to the formation of not negligible *M* in the steel ribs (Tian et al 2016, 2018, Batocchioni et al. 2023). With a $k_0 < 1$ the higher loads coming from the ground at the crown and, on the other hand, the lower loads coming at the sidewall, lead the *M* to be further and decidedly higher in the first case and lower in the second.

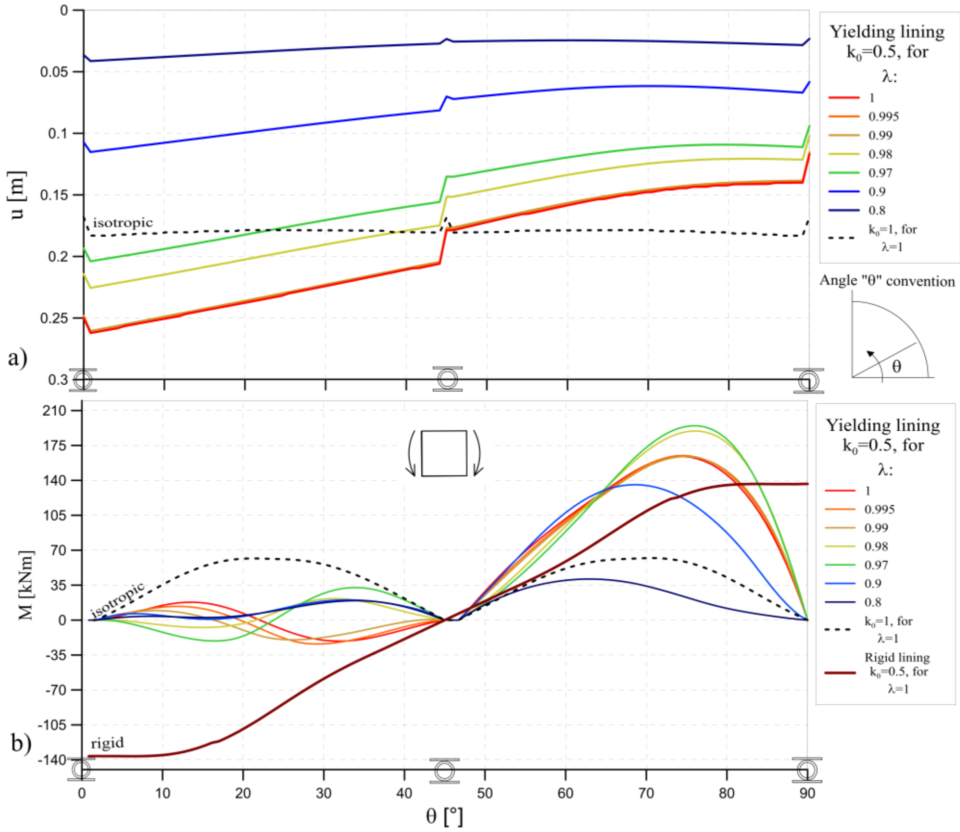

Figure 2. a) u and b) M along the lining as the relaxation proceed.

The explanation of these behaviours should be searched in the different stress paths that experience the ground near the tunnel. Looking at Figure 3a, the first ground's element to reach the yielding (the only one before λ=0.7, i.e., the installation of the lining) is the one at the sidewall; where the stress path induced by tunnelling 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 increase, 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 only in the last part of the relaxation process (Fig. 3b). Furthermore, leaving the upper part of the tunnel lining with a higher level of confinement and then being more stressed without the possibility to rotate (i.e., higher *k* and *M*). Differently from what happens to the lower part of the tunnel (the rigid steel rib beam at the sidewall).

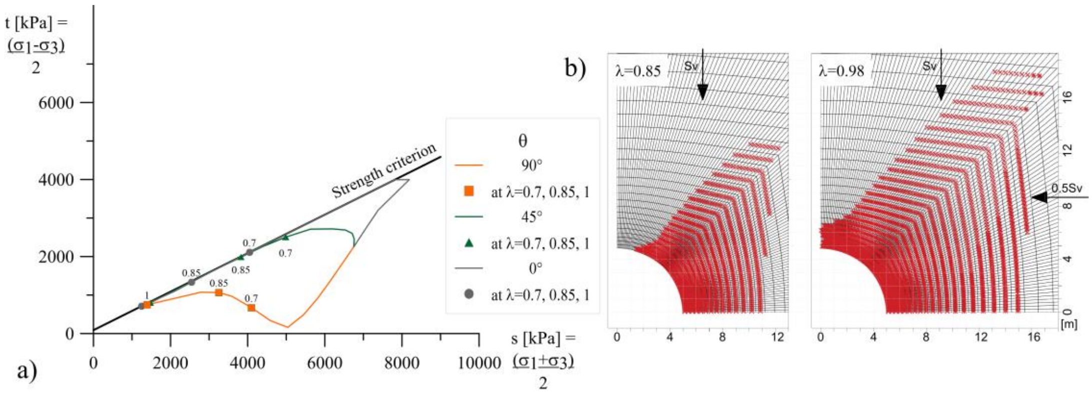

Figure 3. a) Stress path of different ground zone near the tunnel: grey (θ=0°, sidewall), green (θ=45°), orange (θ=90°, crown) and black (strength criterion); b) plastic zones around the tunnel with 2 different levels of relaxation.

4 CONSLUSIONS

When deep tunnels face poor ground quality squeezing conditions can occur. In that case, the most efficient solution is to design the lining following the yielding principle. Moreover, due to the combined effect of gravity and tectonic, the initial in-situ stress can be very far from isotropic. This paper has been studied, through numerical analyses, a specific case study: a deep circular tunnel in isotropic and anisotropic geostatic conditions, supported by both temporary rigid and yielding lining installed at 70% of the relaxation level. The results obtained showed that, in the case of huge anisotropy, the yielding elements embedded in the lining are able to reduce the axial load (Batocchioni et al. 2024), but the same is not true for the bending moment. Consequently, in the preliminary support design following the yielding principle under anisotropic in-situ stress, particular attentions should be paid to the structural capacity of the ribs regarding the bending moments. However, the buckling of the steel ribs due to exceeding the yielding axial load is decisively more dangerous that a formation of a plastic hinge due to exceeding the plastic bending moment. Therefore, it is possible to assume that the yielding principle is a good solution to design preliminary lining in squeezing conditions thanks to its ability to keep under control the axial load.

In order to understand the basic interaction mechanisms between a lining following the yielding principle and the surrounding ground under an anisotropic in-situ stress, is sufficient to realize a simple 2D model with a lining consisting only in the steel ribs. Then neglecting the effect of the shotcrete. Further developments should go in the direction of a real 3D model, with the possibility to model explicitly the conventional lining with the succession of steel ribs and shotcrete. This will unlock the possibility to consider the different interaction of each component of the lining. Essential to have a deeper understanding of the interaction mechanisms.

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