The effect of a frictional interface in a preliminary yielding support for a deep tunnel

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Abstract: The increasing demand for fast interconnections in modern society leads to the construction of tunnels, bringing with it the necessity to overcome difficult conditions. When deep tunnels are excavated in poor ground, squeezing conditions occur and the design must follow the *yielding principle.* To this aim, special elasto-plastic elements embedded in the temporary support can be employed. The presence of the elasto-plastic elements radically modifies the interaction mechanisms making necessary the use of numerical analyses. Therefore, in this paper a numerical model of a vertical section of a circular tunnel with deformable preliminary lining are developed to study the soil-lining interaction. Through a parametric analysis, special attention is paid to the role of the interface mechanical behaviour between the structure and the ground by varying the interface's friction angle.

Keywords: Tunnelling; Yielding principle; Soil-lining interaction; interface shear strength; Squeezing conditions; Numerical modelling.

1 Introduction

Nowadays our society needs more and more fast link between big cities. For this aim tunnelling became more challenging with the crossing of deeper rock mass with difficult conditions. Not only for environmental reasons, but also for limiting corners and high slopes that reduce the efficiency of the track. In Italy the three main tunnels under construction (Brenner Base Tunnel, Turin Lyon and Terzo Valico del Giovi) are long more than 150km and cost more than 15bn€.

When deep tunnels cross poor grounds the so-called *squeezing conditions* happens, this leads to huge risks for the construction project, high times, and elevated costs (Hoek, 2001). Typically, these conditions are related to rock masses that show a marked rheological behaviour. Furthermore, in conventional tunnelling, extremely high convergence and overload of the preliminary lining can be experienced. The best way to challenge these difficulties is to design the preliminary support following the *yielding principle* (Kovári, 1998). In opposition to the *resistance principle*, where the support consists of a rigid element with a bearing capacity able to resist the rock load limiting the convergence; in the *yielding principle* the support has to be able to deform (Figure 1).

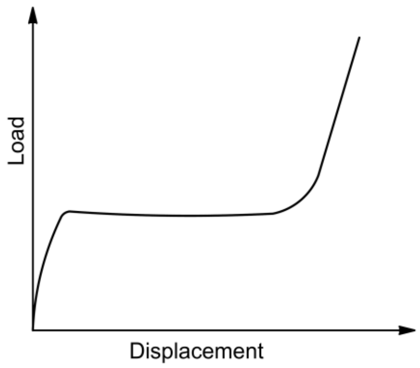

Figure 1. Load displacement curve of a yielding support

Therefore, allowing the ground deformations by so doing, reducing the stress field in the lining structure.

Such yielding support is obtained by inserting in the classic concept, usually made of steel ribs and a concrete shell, deformable elements. These have the purpose of permitting the convergence to develop when reaching the designed load level. The deformation can be mainly in the radial or in the circumferential direction (Cantieni & Anagnostou, 2009). The former consists in the construction of a compressible layer between the inner rigid support and the excavation boundary. Whereas in the latter the support deforms with the ground, then the tunnel circumference shrinks. This is possible through the relative displacements of different parts of the support itself (sliding, or TH, steel ribs) or the yielding of specific elasto-plastic elements (EPE, some examples are the LSC or the hiDCon) (Figure 2). In this case the support axial load is respectively controlled by the frictional shear stress of the sliding elements and the yielding strength of the EPE. The insertion of punctual deformable elements is the solution most utilised nowadays; hence, this paper is going to focus on the regarding technology.

Figure 2. Two examples of elasto-plastic elements: hiDCon (left) and LSC (right)

There is limited literature on the design of yielding support in deep tunneling under squeezing conditions. Radončić et al. (2009) and Moritz (2011) assessed the Convergence Confinement Method (CCM) to yielding lining in order to estimate convergence values. Similarly, Wu et al. (2022) conducted a comprehensive study on concrete EPE, introducing a new characteristic curve for deformable supports. On the other hand, Yang et al. (2022) investigated concrete damage and proposed a numerical model to simulate the yielding support with EPE embedded in the concrete. Nevertheless, the study of the soil-lining interaction (SLI) in the presence of a yielding support has not been widely studied, leaving a notable gap between yielding and rigid support research. Specifically, there is a lack of study on the interface's role between soil and lining, a key-element of the interaction mechanism, and therefore of the whole tunnel behavior. Differently for a stiff support concept, many authors have introduced closed-form solutions and numerical approaches for the study of the interface's influence (Penzien & Wu, 1998; Song et al., 2018). These are well-kwon for the simplifications undertaken by analyzing two extreme cases: full-slip conditions, i.e., no tangential shear force at the interface, and infinite bond strength at the soil-structure interface; both representing an idealization of the real contact between soil and tunnel support.

Therefore, the aim of this work is to extend the lining knowledge and concept to the *yielding principle*, thus seeking to fill the existent gap. Our work (Batocchioni et al., 2023 a, b) was driven by the embedment of high deformable steel elements (hiDSte) in the steel ribs, which work along deformable concrete elements in the shotcrete (such as the hiDCon) as a coupled system, as shown in Figure 3a. Thus, the investigation focuses on embedding 8 EPE in the steel ribs (Figure 3b), studying the SLI using firstly analytical methods and secondly, numerical ones.

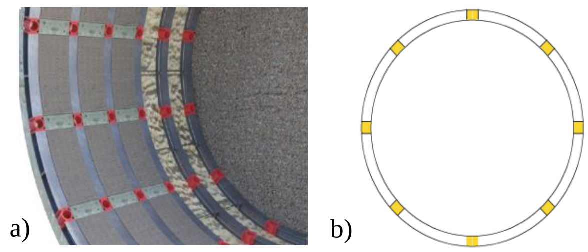

Figure 3. a) hiDSte and hiDCon as a coupled system, and b) vertical cross-section of tunnel lining with 8 EPE embedded in the steel ribs

Indeed, it is believed that the numerical approach is crucial for yielding support design due to the simplifications that limit the analytical approach. With this vision and aiming for a deeper understanding, this paper focuses on the influence of the interface between soil and structure. Motivated by the radical change in both the cinematic and stress field distribution on the interaction mechanisms. This change is due to the introduction of the EPE in the temporary lining, which leads to strong and punctual deformation near the elements. The methodology is developed following the numerical approach, carrying out a parametric analysis regarding the friction angle of the soil-lining contact. The importance of carrying out parametric analyses with numerical computations has been widely proven by many authors (Kovári et al., 1976). The numerical model is based on a vertical section of a circular conventional tunnel, where simplified hypotheses are taken into consideration regarding the geometry, the constitutive model, and the initial stress field. The primary objective of this research is to study how by varying the shear strength of the interface, the SLI modifies.

2 Methodology

In this paper 2D numerical analyses that model a temporary support following the *yielding principle*, have been developed with the aim of studying the peculiar SLI and more in particular, the interface's influence on it. The methodology is in line with the one used at Batocchioni et al. (2023 a,b), but with a deeper focus on the shear strength of the interface using the N-M interaction diagram representation. The analysis has been developed through the FDM code FLAC2D (Itasca, 2011). The model represents one quarter of the tunnel thanks to the symmetry planes (Figure 4). The mesh is composed of 4876 elements.

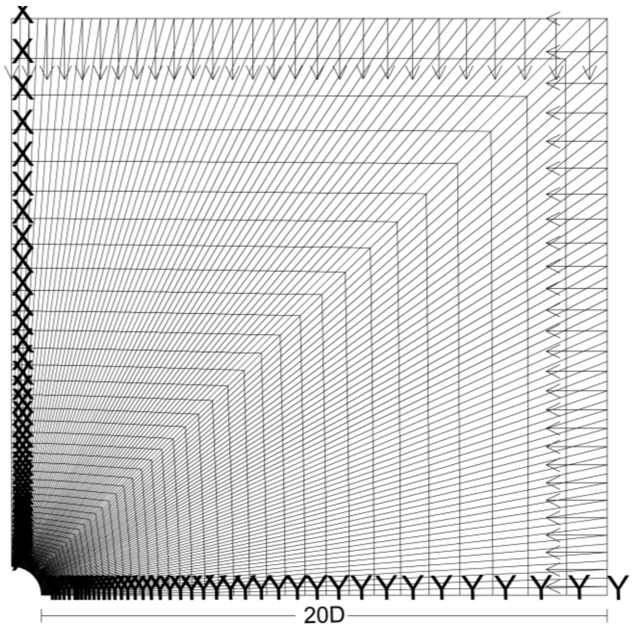

Figure 4. Numerical grid

At the boundary, tensional constraints have been applied. Whereas cinematic constraints, preventing normal displacements, have been applied on the two internal boundaries with the direction radial at the tunnel. The initial stress field is isotropic. The ground has been modelled with parameters typical of a rock mass, with an elastic perfectly plastic behaviour, assumed to be isotropic (Table 1). Considering the depth of the tunnel and the poor ground, the ratio between the uniaxial compressive strength (f_c) and the initial stress field (p_o) has been chosen to be extremely low (≈ 0.06) (Anagnostou & Kovári, 1993; Ramoni & Anagnostou, 2010).

Table 1. Parameters used in the analyses.

	Rock mass	Steel ribs	EPE	Interface
Young's modulus, E(MPa)	1000	210000	177	
Area, A (m^2)		106	106	
moment of inertia, I (cm^4)		11.26	11.26	
Yielding stress, S_y (MPa)		275	138	
Plastic moment, M_y (MPa*m)		-	0	
Angle of friction, φ (°)	30			0 to 45
Cohesion, c (kPa)	100			0
Dilatancy, ψ (°)	0			
Tunnel radius, r (m)	5			
Initial stress field, p_0 (kPa)	6000			
Coefficient of earth pressure at rest, K_0 (-)	1			

Thus, leading to squeezing conditions. Despite that the numerical analyses do not consider the time effect connected to the rheological behaviour. This is a consequence of the following assumption: the time scale related to the creep phenomenon is much bigger than the excavation one. By so doing, the excavation phase and the creep phase can be modelled separately. The focus on this paper is only on the first, considering that the aim is to understand the SLI mechanism. Furthermore, the creep effect can be considered by simply reducing the rock mass strength parameters that simulates long-term conditions (Lombardi, 1975).

The excavation phase has been simulated with the well-known relaxation method, assuming an installation corresponding to a relaxation factor of 70%. The preliminary support has been modelled with one HEB240 steel rib per meter. For the sake of simplicity, with a conservative hypothesis, the concrete has been neglected. Therefore, assuming it has the sole function of transferring the load from the ground to the steel ribs, the lasts become the only load-bearing elements. The lining has been modelled with beam elastic perfectly plastic elements, with values of the Young's modulus (*E*) and the compressive yielding stress (*Sy*) higher in the steel ribs and lower in the EPE. Furthermore, in order to make the yielding elements behave as a hinge, their plastic moment has been assumed to be null. That is a reasonable simplification, for the EPE's negligible capacity of withstanding bending moments in front of the steel ribs' one. The other geometric parameters, the area (*A*) and the moment of inertia (*I*), do not defer between the steel ribs and the EPE. This last simplification can be considered reasonable too, bearing in mind that: (1) the effect of the beam elements' axial stiffness (*EA*) is negligible if compared to the deformations that occur in the yielding state and (2) the EPE's bending stiffness (*EI*) is negligible, due to their null plastic moment. The lining interaction with the soil is considered through an interface characterized by infinite compressive strength (elastic behaviour) and shear elastic-plastic behaviour with frictional Mohr-Coulomb shear strength. A parametric analysis was conducted by varying the values of the interface's frictional angle. In order to evaluate the Ultimate Limit State (ULS) mobilization of temporary support, the results are reported on N-M diagram together with ULS domain.

The accuracy of the numerical results has been guaranteed by the relatively high density and dimensions of the mesh and by the high convergence criterion set in FLAC (*sratio*). Particularly, the mesh is 20 times the tunnel radius and the *sratio* is 10^{-5}. Furthermore, the accuracy of the analyses has been controlled verifying the achievement of stationary conditions with the calculation steps of the most important variables of the interaction problem. Furthermore, the accuracy of the numerical model has been verified comparing the value of the axial load in the lining with the one obtained by the analytical methodology based on Convergence-Confinement Method (CCM).

3 Results

The inserting of the EPE in the preliminary support of a deep tunnel in *squeezing conditions* reduces the loads acting on the structural elements. Moreover, the design of a preliminary support following the *yielding principle* in extremely severe conditions, may results the only effective solution to manage in-situ stress field that can reach several MPa.

Figure 5 shows the Ground Reaction Curve (GRC) and the Support Reaction Curve (SRC) of both rigid (red line) and yielding (continuous line) linings.

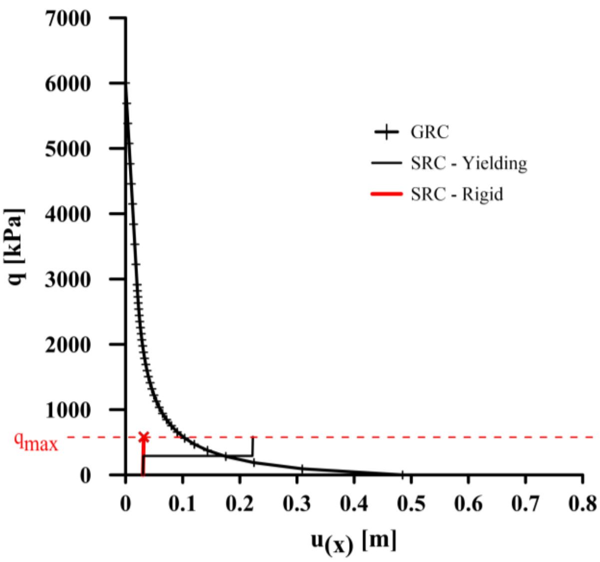

Figure 5. Characteristic curves of a rigid lining (red line) and a yielding lining (black line)

The latter was obtained with 8 EPE inserted in the support. The rigid lining reaches its structural capacity in axial compression when the rock load reaches about 700 kPa and collapses for occurrence of buckling phenomenon. The yielding lining, vice versa, thanks to the EPE, reached the equilibrium after a convergence of about 18 cm, with the steel ribs that remain in elastic conditions. Therefore, this

simplified analytical interaction model highlights that the stress field in the HEB240, thanks to the EPE, remains below its bearing capacity.
The CCM has been also used as a reference for validating the numerical model, both with and without the EPE installed. Figure 6 shows that the values of the lining axial load obtained by the CCM, and the numerical model's ones are coincident. Here both models (rigid and yielding) have a smooth interface considering that the CCM is not able to consider an interface with shear strength. Furthermore, as it will be possible to see more in detail later, this figure clearly shows that the introduction of the EPE, also with a smooth interface, lead to important values of bending moment. One can then assume that the CCM can be considered as a simple pre-design tool to define the characteristics and the number of the EPE. But it is not possible to use it as a complete design instrument.

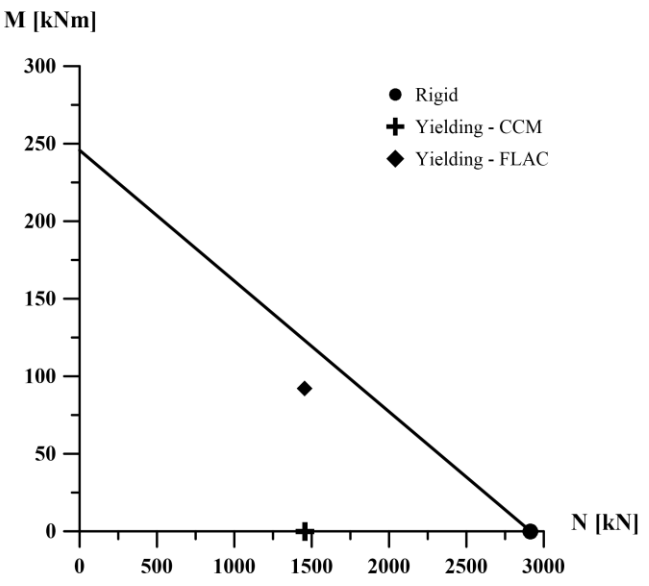

Figure 6. N-M interaction diagram for smooth soil-lining contact

From a kinematic point of view, the rigid lining tends to contract homothetically, congruent with the surrounding ground (Figure 7, red arrows). On the other hand, consequently to the local deformation of the EPE, the steel rib between two EPE tends to move as a rigid body in a radial direction (watching from the midpoint of the beam, Figure 7, black arrows). However, the soil tends to have a homothetical contraction, thus leading to a peculiar SLI with 2 main consequences. By comparing in Figure 8 only the rigid lining (continuous lines) and the yielding lining with smooth interface (lines with symbols) it can be said: 1) with the yielding support the normal stress at the interface (σ_n) tends to concentrate near the extremities of the rigid part of the lining, as a sort of arch effect; 2) the normal stress transmitted by the ground to the lining is decisively lower than the rigid case. Considering instead also the effect of the interface shear strength (dashed lines) 2 further considerations can be done: 3) the relative displacements between soil and lining lead to important shear stress (τ) at the interface and 4) the normal load tends to grow again in the midpoint of the beam where the relative displacements soil-lining is zero for symmetry.

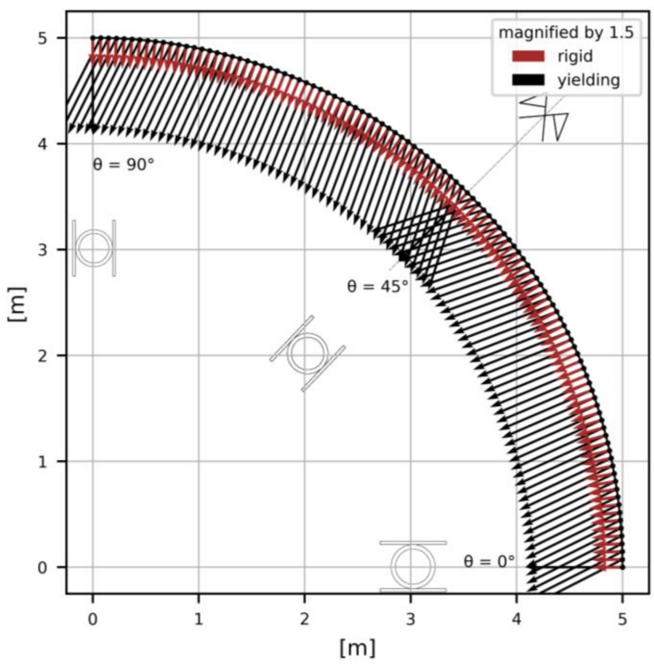

Figure 7. Kinematic interaction mechanism of rigid (red) and yielding (black) lining

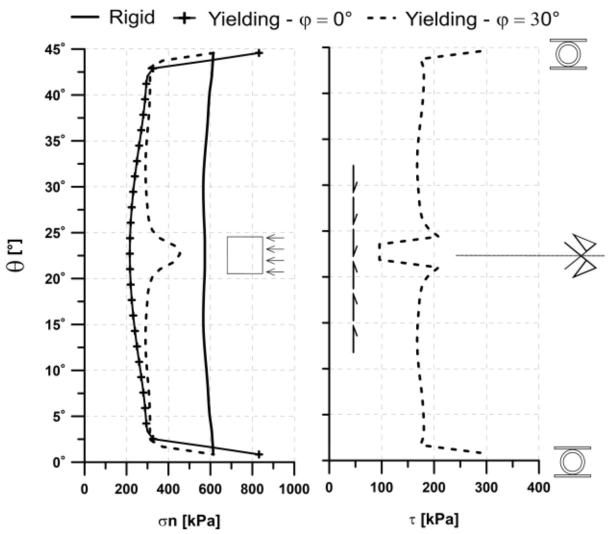

Figure 8. Interface variables: normal (σn) and shear (τ) stresses

As a consequence of the contact stress distribution, the axial load notably decreases and, in the meantime, great shear load and bending moment values arise (Figure 9). More in detail, if comparing the behaviour of a rigid lining with a yielding lining with smooth interface, in the latter: 5) the axial load (N) is limited by the yielding stress of the EPE and 6) bending moment (M) develops for the normal stress peaks. While, if considering again the effect of the shear strength interface: 7) the axial load tends to increase in the midpoint of the beam for the shear stress that arises at the interface, whereas 8) the normal stress concentration at the beam midpoint has a beneficial effect mitigating the bending moment values.

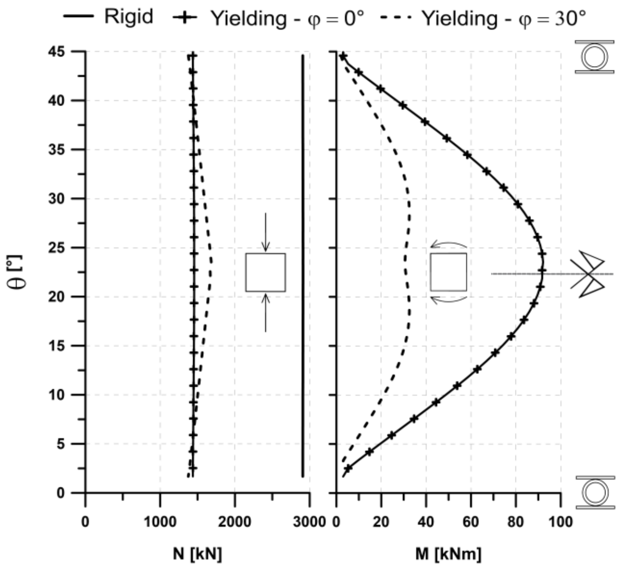

Figure 9. Structural variables: axial load (N), and bending moment (M)

In line with the previous assumptions, i.e. with the rising value of the interface's friction angle, the maximum axial load increases and the maximum bending moment decreases, the authors find very interesting and useful to represent this trend on the N-M interaction diagram (Figure 10).

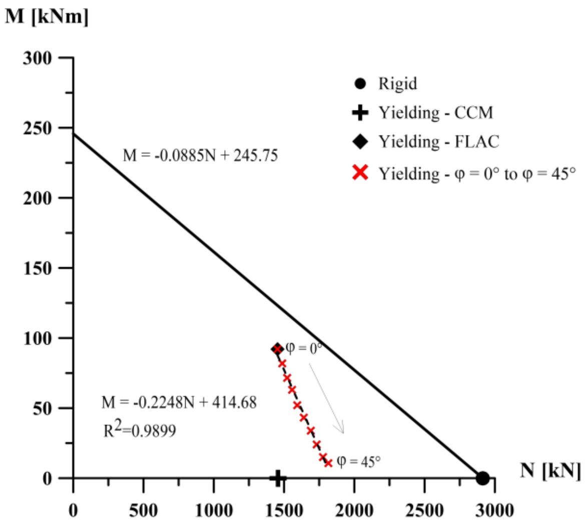

Figure 10. N-M interaction diagram with increasing interface's friction angle (φ from 0° to 45°)

This graph clearly shows that the results fit in a linear relationship with a higher gradient than the one of the HEB240 N-M interaction domain. This means that as the friction angle of the contact between soil and lining increases, the severity of load acting on the support tends to reduce (structural beneficial effect). Furthermore, the parametric analysis shows that with the increment of the interface's friction angle, the EPE's axial closure reduces.
In short, the friction of the contact between soil and lining can be seen as a dissipative device that helps the soil-lining system to support high load.

4 Conclusions

In the design of preliminary support, followed by the *yielding principle* in *squeezing conditions,* for the extreme rock loads, can be necessary the application of elasto-plastic elements embedded in the lining. These allow the development of the required convergence for sufficiently reducing the load acting on the lining.
In this paper specific 2D parametric numerical analyses have been developed with the aim of studying the soil-lining interaction mechanisms. Particular attention was given to the effects of the interface between soil and lining. The main outcomes can be summarised as follows:

- the insertion of the elasto-plastic elements in the rigid lining leads to an increase of the convergence with an important decrease of the axial load and the emergence of not negligible bending moment;
- the ability of the interface to develop a frictional strength has a beneficial effect on the behaviour of the support system;
- in the design of a yielding lining is of utmost importance the development of numerical analyses, whereas analytical simplified models, such as the Convergence-Confinement Method, should be used as a preliminary tool for preliminary design.

The results obtained by this work provide some relevant insight on the soil-lining interaction of the preliminary support following the *yielding principle*. These are useful to highlight the peculiar aspects of the interaction mechanism both from a kinematic and a static point of view and correctly develops the project.

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