Soil-structure interaction of preliminary deformable lining for conventional tunnel in squeezing conditions using HiDSte elements

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ABSTRACT: The construction of deep tunnels is continuously increasing due to both economic and environmental reasons. High cover and poor geotechnical ground make the construction of tunnels difficult (squeezing conditions). Due to the high loads transmitted by the ground, the preliminary lining can be rarely designed following the so-called resistance principle. The state of the art suggests approaching the lining design by allowing the development of the necessary convergences to adequately reduce the rock load (yielding principle). In this paper, a new steel element (HiDSte), yet to be employed in real tunnel works, is described. The behaviour of the lining made of steel ribs along the HiDSte is illustrated through 2D numerical analyses. The numerical results allowed the evaluation of the peculiar way soil and lining interact and, more in general, the ability of the yielding lining to reduce the in-situ stress level undergone by the lining.

Keywords: Conventional tunnelling, squeezing conditions, yielding principle, preliminary lining with elastoplastic elements, soil-structure interaction.

1 INTRODUCTION

When deep tunnels cross poor ground, squeezing conditions occur; thus leading to huge risks, longer times, and higher costs (Hoek 2011). Regarding traditional tunnelling, there may happen extreme convergences and the excess of the preliminary lining bearing capacity. To prevent these, is essential to understand the soil-structure interaction (SSI) in squeezing conditions and develop technology able to reduce the risks. In extreme conditions the state of the art shows that generally it is not possible to design a tunnel with the "resistance principle", but it is necessary to adopt a preliminary lining able to deform without losing the bearing capacity, following the "yielding principle" (Kovári 1998). A new elasto-plastic element (EPE), known as "HiDSte" (High Deformable Steel Element) has been patented by SolExperts and created by Prof. Kovari with the goal of realizing a yielding element for the steel ribs. The HiDSte can be a valid alternative to the sliding joints in the TH steel ribs. Indeed, it is more suitable for a perfect plastic behaviour, that are more regular and with a clear and reproducible yielding threshold. These elements have never been employed before in a real tunnel.

In scientific literature, there are only a few works treating the design of preliminary deformable linings in deep tunnels under squeezing conditions. Radončić et al. (2009) and Moritz (2011)

compare the different behaviours of the main yielding elements with the aim of studying the expected convergence related to the distance to the face. In particular, they extend the CCM for the design of yielding linings. Wu et al. (2022), similarly to Radončić and Moritz, did a detailed study about the shotcrete with yielding elements embedded, proposing a new form of the equation for the Support Reaction Curve of that kind of linings. Furthermore, Yang et al. (2022) extensively studied the behavior of shotcrete damage and proposed a numerical model to simulate the yielding linings based on the double-node beam element between two interfaces.

Ultimately, in literature, there are not investigations focused on studying how the SSI develops in a preliminary yielding lining. The introduction of the EPE leads to strong deformation stressed to limited zones of the support, i.e. where yielding elements are found. The aim of this paper, and more in general of a new DISG Sapienza research group, is to bridge this gap. From a methodology point of view, the study is based on numerical analyses. The adopted strategy develops 2D numerical analyses in simplified conditions, regarding geometries, constitutive models, and the initial stress state; by explicitly modelling the elasto-plastic elements and intensively studying the role of the interface shear strength adopted to connect the lining to the ground.

Announcing the findings of this work, we can affirm that the presence of the EPE completely modifies the classical SSI mechanisms. For that reason, in the design of such lining typology, a strong numerical study of the interaction is essential to accurately evaluate the stresses acting on structural elements.

2   METHODOLOGY

In the presence of elasto-plastic elements (EPE), used to improve the lining ability to convergence, a variety of 2D numerical analyses were carried out, in order to explore the particular interaction mechanism between the ground and the lining. In all these analyses, the interaction was studied with the stress-relaxation method (ref), assuming a relaxation factor (λ) of 70% (a typical value of λ in squeezing conditions, when the lining is installed just behind the excavation front) at the installation of the lining. The peculiarity of the interaction whit EPE embedded into the lining, were highlighted by comparison through analyses. These were carried out assuming that the lining is constituted by one circular homogeneous HEB 240 steel rib per meter. For sake of simplicity, it is supposed that shotcrete has the single purpose of transferring the load from the soil to the steel ribs; thus, in the simulations carried out in this study, the presence of concrete is neglected and the preliminary lining, made just of steel ribs, interacts directly with the ground. Other three numerical analyses were carried out with a lining obtained by introducing into the HEB 240, eight HiDSte (arranged every 45°, special elastoplastic elements, see Figure 1), and assuming three different sets of strength parameters for the interface, employed to connect the lining to the ground. As expected, in fact, the shear strength between lining and ground plays a decisive role.
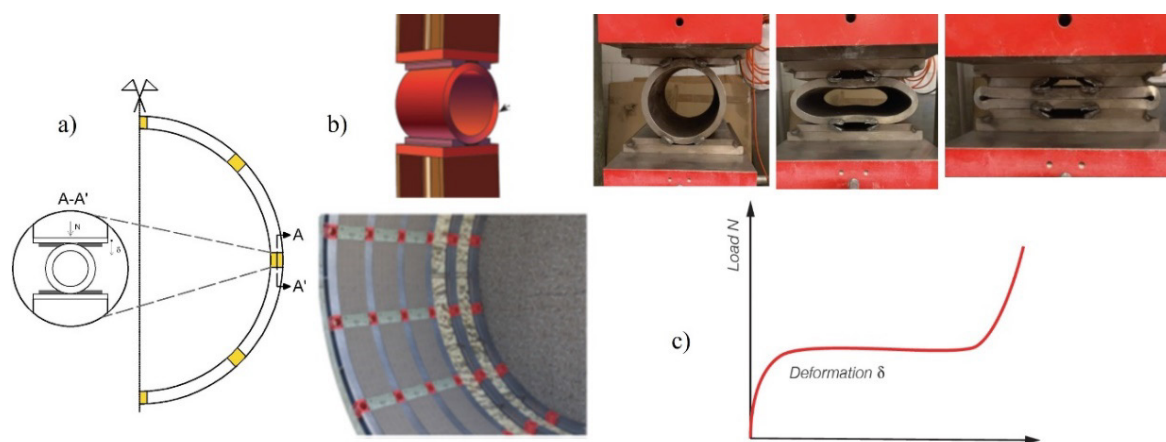

Figure 1. a) HEB 240 arranged with 8 HiDSte, b) Elasto-plastic element (HiDSte) and arrangement, c) mechanical behaviour.

The HiDSte is a simple steel circular sectioned pipe, with a length that cannot be bigger than the high of the steel beam, while the external diameter, when completely closed, cannot exceed the width of the steel beam (see Figure 2). When stressed by a normal load, the pipe gets squashed and shows a mechanical behaviour characterized by a first elastic part, a consecutive long section comparable to perfectly plastic conditions, and an ending where the resistance quickly grows again (see Figure 1c). The ending trend coincides with the closure of the pipe. Hence, the yielding lining goes back to a rigid behaviour as if the EPE are not present, and with a rock load that is indeed lower. By changing the external diameter and the quality of the steel, is possible to modify the yielding stress, Ny, and the maximum displacement that the EPE can experience.

More in detail, the 2D numerical analyses were carried out employing the Finite Difference code FLAC. The model represents half of the tunnel, assuming the vertical axis as the axis of symmetry. The mesh is made of 3600 elements and kinematic constraints are imposed at the boundary, avoiding normal displacements (see Figure 2). The initial stress state is assumed isotropic. The rock mass behaviour is simulated as isotropic elastic-perfectly plastic medium, with the physical and mechanical parameters summarized in Table 1. Considering the tunnel dept and the poor resistance parameters of the ground, the resultant severity of the state of stress is very high as occurs in squeezing conditions. The conventional lining is modelled with continuous elastic perfectly plastic beam elements, while the deformable support is modelled by a sequence of continuous beams with the geometrical and mechanical properties of the HEB240 profile, and beams of 15 cm simulating the properties of the HiDSte (see Table 1). The selected yielding load for the HiDSte was 50% of the HEB240 one, the maximum selected displacement was 15 cm. In order to simulate the behaviour of the HiDSte, assimilable as a hinge, an extremely small yielding bending moment was assigned to the beam (1 kN*m). Both rigid continuous and deformable support were installed at 70% of the stress-relaxation level. After the closure of the pipes is reached, the limit value of 15 cm, a specific set up routine automatically (while stepping) modifies the mechanical behaviour of the beam, simulating the EPE that becomes infinitely elastic and stiff. The lining interacts with the ground through an interface characterized by high compression strength and finite shear strength (Table 1).

The accuracy of the numerical results is guaranteed as a consequence of relatively high mesh density and small unbalanced force (stress ratio is set to 10^{-5}). The accuracy was also verified by distinguishing the stabilization control variables, linked to the different calculus steps. Finally, at least for the "no-lining" excavation conditions, the accuracy of the numerical solutions was verified by the coincidence between the numerical and the analytical Ground Reaction Curve. This fact guarantees also that the mesh dimension is enough to avoid boundary effects in the proximity of the tunnel.

Table 1. Parameters used in the analyses.

|	Rock mass	Steel ribs	HiDSte elements	Interface I, II, III
Young Modulus, E (MPa)	1000	210000	177	
Poisson's Ratio, υ (-)	0.3			
Beam element area, a (m^2)		106	106	
Moment of Inertia, I (cm^4)		11.26	11.26	
Yielding Stress, $S_{y,comp}$ (MPa)		275	138	
Plastic moment, M_y (kNm)		∞	0	
Angle of Friction, φ (°)	30			0, 20, 30
Cohesion, c (kPa)	100			0, 0, 60
Dilatancy, ψ (°)	0			
Tunnel's radius, r (m)	5			
Far-field stress, S (kPa)	6750			
Coefficient of earth pressure at rest, K_0 (-)	1			
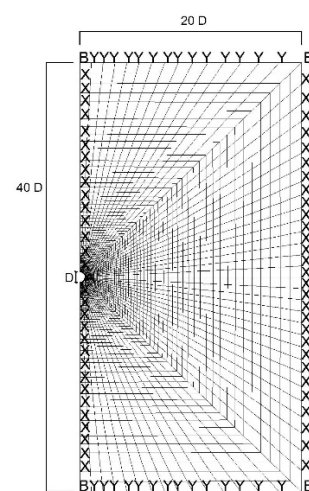
Figure 2. Numerical grid.

3   RESULTS

Figure 3 (left) shows the Ground Reaction Curve (GRC) and the Support Reaction Curve (SRC) of both rigid (continuous line) and yielding (dashed line) linings. The latter was obtained with EPE. The rigid lining reached equilibrium, after yielding for axial compression, for more or less10 cm of convergence after the installation. While the yielding lining, thanks to the HiDSte, reached the equilibrium after a convergence that is higher (about 20 cm), with the steel ribs that remained in elastic condition, not being damaged. Therefore, this simplified interaction model highlights that the stress level in the HEB240, thanks to the EPE, remains much below the yielding threshold of the section bar. The Convergence – Confinement Method (CCM) here used, can be considered as a simple pre-design tool to define the characteristic and the number of the EPE. Nevertheless, as it will be seen later, the main aspects of the SSI change after the insertion of the EPE elements, and this leads to bending moments and shear force that the CCM cannot consider.
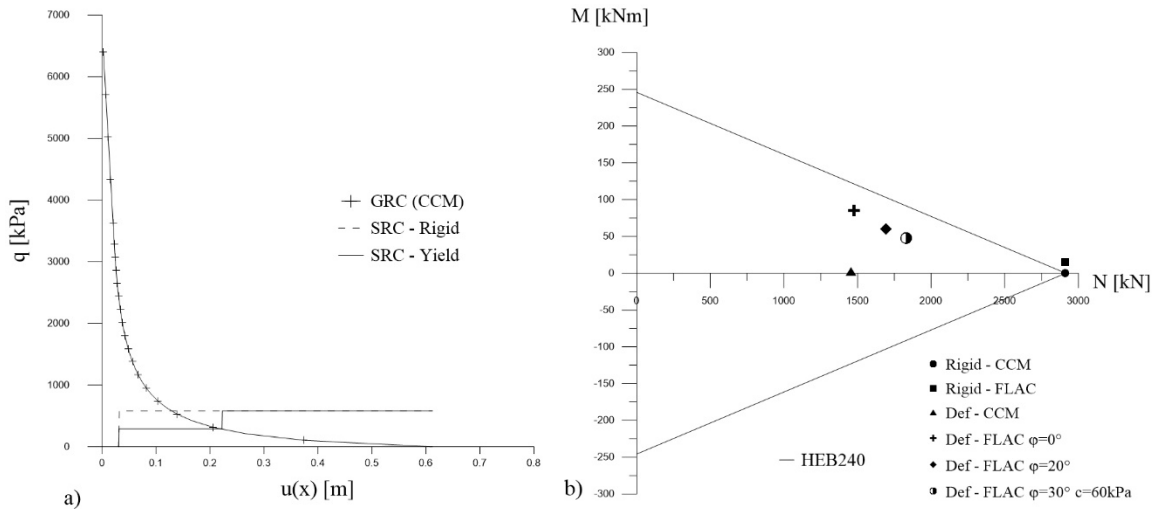

Figure 3. a) Convergence-Confinement Method for rigid lining and yielding lining, b) NM capacity domain with the results of the different analyses: maximum axial force and bending moment.

With the introduction of the EPE, the lining kinematic is completely changed. The continuous support, in fact, due to the interaction with the ground, tends to contract radially (the same for the ground); while, due to the local circumferential contraction of the HiDSte, the metallic profile between two consecutives EPE, tends to move as a rigid body (see Figure 4).
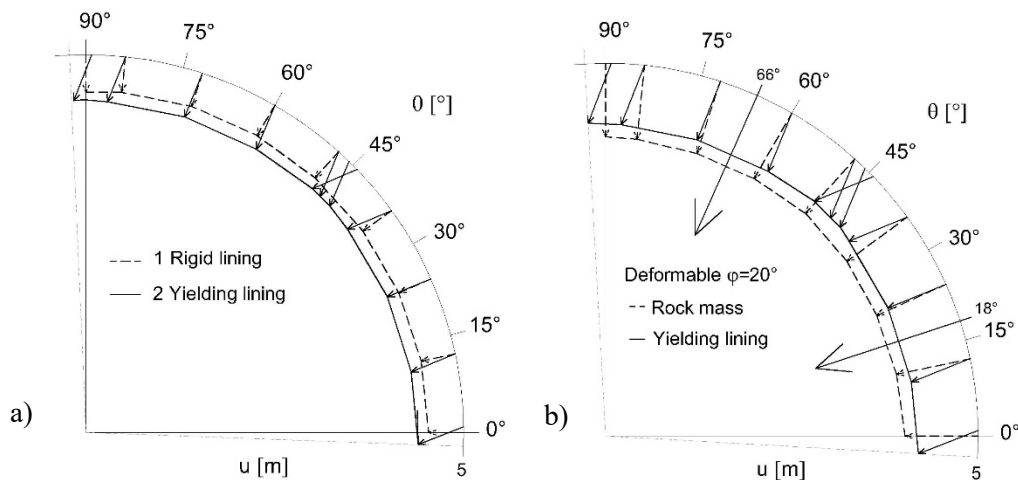

Figure 4. a) Displacement of the rigid lining and of the deformable lining with smooth interface, b) displacement of the rock mass and of the yielding lining in the third analysis with a low frictional interface.

The ground continues to contract radially, therefore a specific SSI occurs with 3 relevant consequences. Firstly the normal interaction stresses, σ_n (rock load), tends to concentrate in correspondence with the extremity of the HEB240 (see Figure 5d), where they are connected with the EPE (a sort of arch effect). Secondly, the introduction of the EPE, regardless the interface shear strength, leads to a strong reduction of the σ_n. More in detail, the rigid lining rock load goes from about 600 kPa to about 300 kPa for the yielding lining. Then if the interface has a notnull shear strength, important shear stresses arise in consequence of the relative displacements between the yielding lining and the ground (see Figure 5e).

As a consequence of this peculiar SSI, the introduction of EPE produces a huge reduction of normal force on the lining, N, and, at the same time, leads to a not negligible bending moment, M, and shear force, T (see Figure 5a, 5b, 5c). It means that, with a smooth interface, the maximum reduction of N is obtained (N=1500 kN instead of about 3000 kN with rigid lining) but, at the same time, relatively high values of M e T arise. It is worthy to note that, as a consequence of the smoothness of the interface, N assumes a constant value along the lining. As the interface shear increases, N is no longer constant, and its maximum value slightly increases. Both M and T decrease appreciably. From a kinematic point of view, as the strength of the interface increases, the contraction of the lining reduces.

Finally, Figure 3 (right) reports the N-M capacity domain of HEB240 profile together with the numerical results. It clearly shows that, differently from the rigid lining, the introduction of EPE makes the lining able to sustain safely the resultant load in terms of a combination of N and M. Moreover, the effects of increasing interface strength are beneficial for the load state of the lining, because the state of stress tends to move slightly away from the limits of the capacity domain.
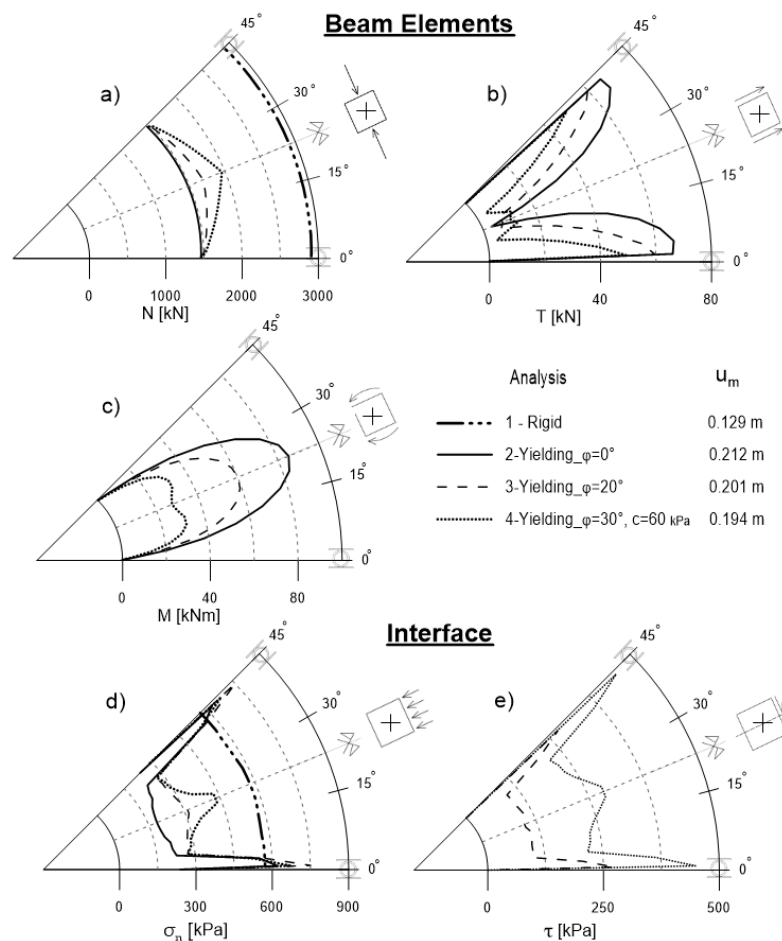

Figure 5. Polar representations of: axial force (a), shear force (b), bending moment (c) acting on the lining; the normal stress (d) and the shear stress (e) acting on the lining by the rock mass.

4 CONCLUSIONS REMARKS

When conventional tunnelling in squeezing conditions, due to high loads transmitted by the ground, the state of the art suggests approaching the design of preliminary lining allowing the development of the convergences necessary to adequately reduce the loads acting on the support. For reaching that, different technologies can be employed. One of these is the use of special yielding element called HiDSte with limited deformation and final closure, able to break the continuity of the ribs.

In order to explore the interaction mechanism between the ground and the lining, when yielding elements are embedded in the temporary lining, in this study different 2D numerical analyses were carried out. Three different situations were studied considering the shear strength of the interfaces connecting the lining to the ground. The main results of this study, came out by discussing the numerical results obtained and by comparing them with the behaviour of classical continuous lining, are summarized in the following:

- The insertion of elasto-plastic elements leads to an increase of the convergences and an important reduction of the rock load.
- The kinematic change completely: the closing of the elasto-plastic elements leads to circumferential deformation, which makes the steel beam move rigidly toward the inside of the tunnel with movements that are no longer only radial.
- As a consequence to the specific kinematic, a different soil-structure interaction develops, with the formation of normal circumferential stresses concentration in correspondence to the ending parts of the beam (near the yielding elements) that can assume particularly high values (peaks). Moreover, if the interface has a shear strength, there are also shear stresses at the interface with similar trend to the normal stress.
- Consequently, there is a strong decrease of the axial force on the lining at the cost of not negligible bending moments and shear force.
- However, the in-situ stress level turned out to be considerably reduced, and it is as lower as higher the interface shear strength is.
- In the design of this kind of lining, the soil-structure interaction must be studied with numerical analyses in order to accurately calculate the load acting on the support for the correct asses the structural capacity.
- However, the Convergence-Confinement Method resulted to be extremely useful for the preliminary evaluation of the deformable elements number and their geometrical and mechanical characteristics.

The results provided the first novel insights into the soil-structure interaction mechanism of deformable linings in simplified conditions. Further developments are necessary to explore more real conditions regarding constitutive laws, supports geometry, role of shot-concrete, strength of the interfaces, and non-isotropic lithostatic state of stress.

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