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Options for deformable segmental lining systems for tunnelling in squeezing rock

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ABSTRACT

The rock pressure developing when shield tunnelling through squeezing rock may damage the segmental lining. This paper analyses the extent to which the application range of shielded TBMs in squeezing rocks might be widened by using deformable lining systems, while considering the aspects of structural safety, construction management, TBM technologies and construction costs. Deformable lining systems exploit a basic feature of squeezing ground: the rock pressure decreases when deformations are allowed to occur. Two basic options are available: radially deformable linings, where rock deformations occur outside the lining extrados; and tangentially deformable linings which can accommodate a reduction in their circumference. Comparative analyses of radially or tangentially deformable linings and conventional, practically rigid segmental linings show that deformable lining systems offer advantages only for deep tunnels crossing rocks of relatively fair quality. In such cases, rock pressure can be decreased significantly by allowing deformations to occur, so that a deformable lining (particularly, a tangentially deformable one) offers a more effective use of the available bored profile than a thicker stiff lining of the same concrete quality.

1. Introduction

One major hazard of shield tunnelling in squeezing rock is the overstressing of the segmental lining (Ramoni and Anagnostou, 2010a). Basically, there are two main support principles for squeezing rock: the resistance principle and the yielding principle (Kovári, 1998). Stiff lining systems can be classified as tunnel supports which follow the resistance principle. Their effectiveness and limitations specifically for shield tunnelling through squeezing ground was investigated in the companion paper by Mezger et al. (2017). According to the yielding principle, the rock pressure and thus the thickness of the lining can be reduced by allowing deformations to occur. (In reality, a situation always arises somewhere between these two extreme cases. For the sake of simplicity, however, we speak here of the resistance principle for practically rigid concrete linings and of the yielding principle when using systems incorporating deformable components.)

Two basic options are available for yielding supports (Cantieni and Anagnostou, 2009): radially deformable supports, which allow rock deformations to occur outside the lining extrados (Fig. 1a; see also John Mowlem and Company Limited, 1979), and tangentially deformable linings, which can accommodate a reduction in their circumference (Fig. 1b). Combinations thereof are also possible at least in principle (Fig. 2a).

Radially deformable segmental linings can be implemented by annulus grouting with a compressible backfill or by using pre-fabricated composite segments made of concrete with a deformable layer at their extrados. Another solution proposed in the past is the so-called “convergence-compatible” segmental lining (“CO-CO”), which incorporates ribs on its extrados providing support to the rock, so that the rock can deform in the spaces between the ribs (Vigl, 2003). This system presents the disadvantage of potentially high concentrated loads on the segments (Schneider and Spiegl, 2010). In this regard, composite segments made of concrete (without ribs) and a compressible outer layer (Fig. 2b) are more favourable. They can be applied in combination with a compressible annulus grout such as “Compex” (Schneider et al., 2005), “DeCo-Grout” (Billig et al., 2007a) or with a backfill made of compressible clay pebbles instead of pea gravel (Semeraro et al., 2014). No example of these systems has yet been implemented in practice: Compressive mortars were applied only once, in a tunnel through non-squeezing rocks excavated by a slurry shield (Jenbach Tunnel, Austria; Gamper et al., 2009). Compressible clay pebbles were planned (but not applied) as backfill in the squeezing section of the Fréjus tunnel (Semeraro et al., 2014).

Tangentially deformable supports incorporate special compressible elements made of concrete, steel or plastic (Fig. 3). They have been applied frequently in conventionally driven tunnels (Table 1) and occasionally in tunnelling with gripper TBMs, and they could also be implemented in shield tunnelling by arranging compressible elements in the longitudinal joints of the segments.

As that no yielding system has yet been implemented in squeezing rock in combination with a shielded TBM, this paper evaluates the feasibility of deformable segmental lining systems while taking into

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Nomenclature

C	type of concrete (defined by its uniaxial compressive strength σ_d)
c_{ij}	cost per linear metre of tunnel for lining solution i in geotechnical situation j
c_0	reference cost per linear metre (tunnel without squeezing)
$\bar{c}_{ij}$	cost per linear metre of tunnel for lining solution i in geotechnical situation j normalised by the reference cost c_0
$\overline{C}_i$	normalised average tunnel cost per linear metre for solution i
d	thickness of the lining
d_s	thickness of the shield
E	Young's modulus of the rock
E_c	Young's modulus of the lining
E_s	Young's modulus of the shield
f_c	uniaxial compressive strength of the rock
F_f	thrust force required to overcome the friction between the shield and the rock
H	depth of cover
h	slot size of the yielding element in the circumferential direction
K_I	(initial) stiffness of the lining before the deformation phase
K_{III}	stiffness of the lining after the deformation phase
K_s	stiffness of the shield
L	length of the shield
$p(y)$	rock pressure in the position y
p_∞	final rock pressure on the lining far behind the shield
p_n	unit price for position n (according to Table 6)
p_y	yield pressure of the lining
Q_{ijn}	quantity per linear metre for lining solution i in geotechnical situation j for position n
R	boring radius
R_{def}	deformed internal radius of the tangentially deformable system
R_{int}	internal radius of the lining system
R_{undef}	undeformed internal radius of the tangentially deformable system
s	thickness of the compressive annulus grouting
SF	safety factor (defined as the resistance divided by the pressure acting on the lining)
$u(y)$	radial displacement of the ground (at the tunnel boundary) in the position y
u_y	maximum radial displacement of the lining in the deformation phase (*i.e.* yield deformation)
u_a	radial displacement of the ground at the tunnel boundary (unsupported opening)
y	axial co-ordinate (distance behind the tunnel face)
α	factor considering site installations, unforeseen costs and TBM acquisition
Δh	slot size reduction
ΔR	radial overcut (difference between boring radius and shield extrados radius)
ΔR_l	annular gap (difference between boring radius and lining extrados radius)
Δu	convergence of bored profile
γ	unit weight of the rock
μ	shield skin friction coefficient
ν	Poisson's ratio of the rock
σ_d	uniaxial compressive strength of the concrete
φ	angle of internal friction of the rock
ψ	dilatancy angle of the rock
χ_j	percentage of tunnel length with geotechnical situation j

account the aspects of structural safety, construction management, TBM technologies and construction costs. The paper starts with a qualitative discussion of conceivable systems from the viewpoints of deformation capacity, installation procedure, serviceability, etc. (Table 2). Subsequently the structural interaction between rock and deformable lining systems is investigated and design aids are presented that allow a quick estimation to be made of the lining loading for a wide range of geotechnical conditions. Finally, the last two sections of the paper compare deformable with stiff linings and investigate the geological conditions for which the use of deformable lining systems is structurally adequate (Section 4) and economical (Section 5).

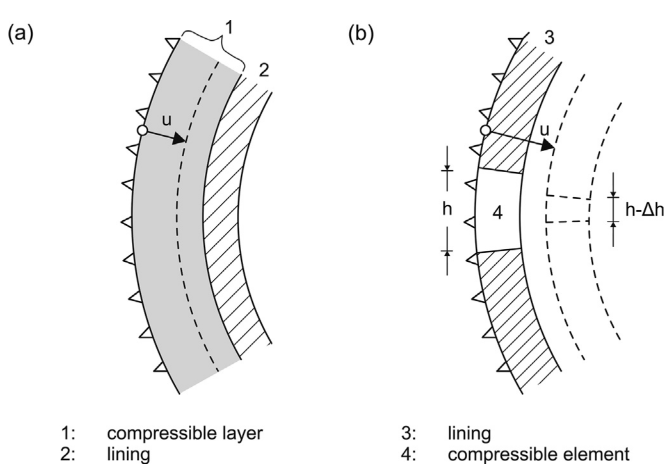

Fig. 1. (a) Radially deformable, (b), tangentially yielding supports (after Cantieni and Anagnostou, 2009).

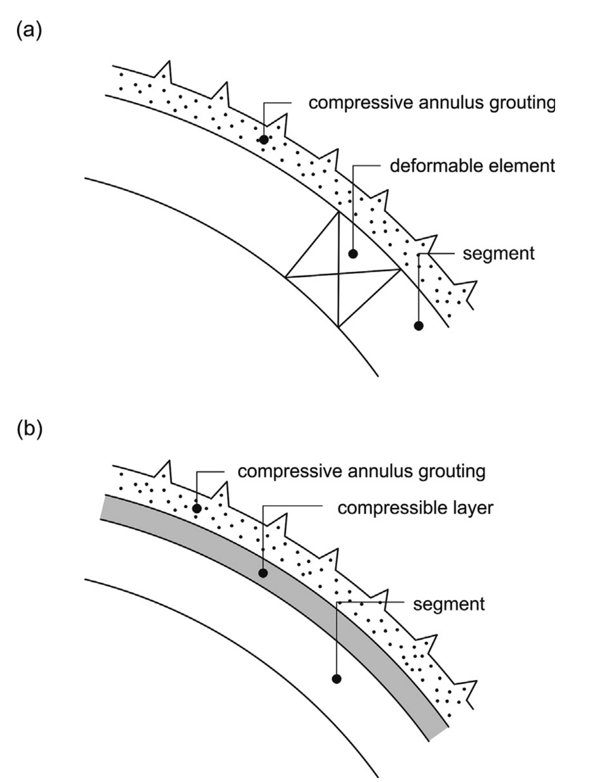

Fig. 2. Tangentially deformable segmental ring, (a), with yielding elements in the longitudinal joints or, (b), radially deformable composite segments, both in combination with a compressible annulus grout.