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Evaluation of higher capacity segmental lining systems when tunnelling in squeezing rock

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ABSTRACT

Overstressing of the segmental lining is a potential hazard of shielded tunnelling in squeezing rock. Due to their stiffness, segmental linings allow only very limited convergences to occur, which results in higher rock pressures than light or deformable rock supports. This paper investigates the extent to which the application range of shielded TBMs could be broadened in squeezing conditions by using linings of higher bearing capacity. Besides the obvious option of increasing segment thickness, an investigation is made into the technical and economic feasibility of double shell solutions as well as that of high performance or ultra-high performance concretes from the standpoints of structural engineering, TBM technology, process engineering, material technology and construction cost. Additionally, design aids are presented that allow a quick evaluation of the application limits of the various lining options to be made for a given geotechnical situation.

1. Introduction

Overstressing of the segmental lining is the main hazard of TBM tunnelling in squeezing rock (Ramoni and Anagnostou, 2010a). Due to their stiffness, segmental linings allow only very limited convergence, thus resulting in higher rock pressures than light or deformable rock supports. Ramoni et al. (2011) investigated the rock pressure developing upon segmental linings taking account of the backfilling materials and procedures, and presented design nomograms for the lining loading. Under certain geotechnical conditions, the rock pressure exceeds the resistance of the usual segmental linings, thus necessitating higher capacity linings in order to extend the operational possibilities for TBMs in squeezing rock.

The first and easiest solution is to increase the thickness of the segments. Usually, lining segments with a thickness of 20–50 cm are used, but thicknesses of up to 70 cm have been implemented in the past (*e.g.*, Sparvo Highway Project, 4th tube of the Elb Tunnel, Orlovski Tunnel). However, should it be necessary to further increase lining resistance (beyond the limits of manageable thicknesses and weights), either segmental linings made of high or ultra-high performance concretes (abbreviated to HPC and UHPC, respectively), or lining systems consisting of two segmental rings can be used (Ramoni and Anagnostou, 2010a).

The present paper starts with an overview of these basic options for increasing the bearing capacity of segmental linings (Section 2), and continues with a discussion of the different solutions from the perspectives of TBM technology, the construction process and materials technology (Sections 3–6). The range of rock pressures that can be sustained by these lining systems is then estimated (Section 7) and design aids are presented that allow a quick estimate of the actual lining loading to be made for a wide range of geotechnical conditions (Section 8). Finally, Section 9 compares the costs of the different systems under specific geological situations and using the structural design aids in Sections 7 and 8.

2. Lining systems

The bearing capacity of a segmental lining can be increased, (i), by increasing its thickness, (ii), by using higher-strength concrete or, (iii), by installing an additional inner ring made either of prefabricated segments or of cast in-situ concrete (double-shell lining). Basically, four systems are possible (Fig. 1): a single shell segmental lining made of normal-strength concrete (Fig. 1a); a single shell segmental lining made of HPC or UHPC (Fig. 1b); a double shell lining consisting of two segmental rings (Fig. 1c); and a double shell lining with an inner ring of cast in-situ, normal-strength concrete (Fig. 1d). For the first three lining systems, it is also possible to install an inner ring made by cast in-situ concrete for reasons of serviceability as well. In this case, the serviceability requirements

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Nomenclature

b_1	outer radius of the inner ring
b_2	outer radius of the outer ring
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 ground type 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 ground type 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_1	thickness of the inner ring
d_2	thickness of the outer ring
d_s	thickness of the shield
E	Young's modulus of the rock
E_1	Young's modulus of the inner ring
E_2	Young's modulus of the outer ring
E_c	Young's modulus of the lining
E_s	Young's modulus of the shield
$f_{1,2,3}$	coefficients
f_c	uniaxial compressive strength of the rock
F_f	thrust force required to overcome the shield skin friction
H	depth of cover
K_l	stiffness of the lining
K_s	stiffness of the shield
L	length of the shield
n	position for the cost analysis
$p(y)$	rock pressure in the position y
p_n	unit price of position n
p_∞	final rock pressure developing far behind the shield
$p_{\infty 1}$	pressure at which the inner ring fails
$p_{\infty 2}$	pressure at which the outer ring fails
Q_{ijn}	quantity per linear metre for lining solution i in ground type j for position n
r	radial co-ordinate
R	boring radius
R_1	axis radius of inner ring
R_2	axis radius of outer ring
R_{int}	internal radius of the lining system
u	radial displacement
y	axial co-ordinate (distance behind the tunnel face)
α	factor considering site installations, unforeseen costs and TBM acquisition
ΔR	radial overcut (difference between boring radius and radius of the shield extrados)
ΔR_l	annular gap (difference between boring radius and radius of the lining extrados)
γ	unit weight of the rock
μ	shield skin friction coefficient
ν	Poisson's ratio of the rock
ν_c	Poisson's ratio of the concrete
ν_1	Poisson's ratio of the inner ring
ν_2	Poisson's ratio of the outer ring
σ_d	uniaxial compressive strength of the concrete
σ_{d1}	uniaxial compressive strength of the inner ring
σ_{d2}	uniaxial compressive strength of the outer ring
σ_{t1}	tangential stress in the inner ring
σ_{t2}	tangential stress in the outer ring
σ_k	contact pressure of the two shells
φ	angle of internal friction of the rock
ψ	dilatancy angle of the rock
χ_j	percentage of tunnel length with ground type j

for the segmental lining (cracking limits, fire safety, waterproofing) are less stringent.

The above-mentioned lining systems are discussed in the following Sections 3–6; Table 1 provides a comparative overview. The fundamental issues concerning TBM technology and the construction process of the different lining systems were clarified with a machine manufacturer (Burger, 2012). Generally, novel lining systems are inherently characterised by higher technological risks. This is due, on the one hand, to the high requirements placed on the shielded TBM and, on the other hand, to the complexity of the logistics and of the installation and manufacturing procedure.

3. Single shell segmental lining made of normal-strength concrete

Thicker segments can be applied either over the entire length of the tunnel or only in certain critical squeezing rock zones. To maintain the minimum clearance profile, the boring diameter is anyway chosen for the maximum segment thickness. A solution with segmental lining of variable thickness is envisaged, *e.g.*, for the Bossler Tunnel, where thicker segments shall be installed over a 1.7 km long section (about 20% of the total length; Edelhoff et al., 2015).

Thicker segments are heavier and more difficult to manufacture, transport and handle during erection. Specifically, the manufacturing tolerances are more difficult to achieve for thick segments. In addition, transport (rather than the machine handling, *i.e.* erection) limits the weight and thus the dimensions of the segments. Considering a weight limit of 20–22 t, segment thicknesses of up to 1.0–1.2 m are feasible.

If the segments are too heavy, the vacuum system of the erector can no longer be used and the segments have to be gripped and installed mechanically by the erector. In this case, the segments are subject to concentrated loads, which have to be considered in their design.

If the thicker segments are installed only in the critical squeezing zones (Fig. 1a), the lining has a variable thickness, while the boring diameter is of course constant. Consequently, the following points have to be considered in the planning stage:

- As soon as the thicker segments have to be installed in a potentially critical squeezing zone, the suction plates and gripping systems have to be exchanged. This requires one to three weeks and has to take place during a planned standstill, in good time before advancing into the squeezing zone. Reliable advance ground probing is essential in this respect. If additional suction plates and gripping systems are installed on the TBM (*e.g.*, a double erector), no standstill is required. This, however, might necessitate a longer shield, which is unfavourable under squeezing conditions (higher risk of shield jamming).
- The machine should advance with the same arrangement of hydraulic jacks over the entire length of the tunnel (*i.e.* also in the squeezing zones). This can be achieved by using the same geometrical subdivision for the segments. In the tunnel sections with thicker segments, however, the hydraulic jacks are arranged eccentrically on the segmental lining. This is not a problem for the machine. As usual, the segmental lining has to be designed so that it has the capacity to bear the thrust force safely. Due to the eccentric arrangement of the hydraulic jacks,