Some concepts for segmental linings in squeezing rock

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We analyze the application limits of stiff and deformable segmental lining systems for TBM tunneling in squeezing rock, looking at structural behavior and construction management aspects, as well as TBM and concrete technologies. We also present practical design aids that enable different lining systems to be compared quickly so that appropriate systems can be chosen for given geotechnical situations. Comparative investigations show that deformable lining systems are preferable for very deep tunnels crossing rocks of relatively fair quality, as rock pressure can be decreased significantly in such cases by allowing small deformations to occur.

Introduction

So-called "squeezing rock" (cf., e.g., Kovári 1998, Barla 2002) creates particularly difficult geological conditions in which, without suitable countermeasures, large deformations of the opening occur. When tunneling with a shielded TBM, the squeezing rock can make the cutter head stick or cause shield jamming, inadmissible convergences or damage to the tunnel support (Ramoni and Anagnostou 2010a, 2011a). If squeezing rock is encountered at frequent intervals or over long tunnel sections, the economic or technical feasibility of a TBM drive becomes questionable. If possible, problematic sections are avoided (or at least kept short) from the planning stage by choosing a suitable alignment. Another possibility is to treat critical stretches beforehand or to excavate them by conventional tunneling (Ramoni and Anagnostou 2010b). In order to avoid such time-consuming and costly measures, efforts can be made to enhance the operational possibilities of the TBM, so that a TBM drive can be used in what are technically unfavorable zones from a constructional point of view. Among the important issues that have to be considered are those of the structural safety and the suitability of the segmental lining.

This paper presents the results of a research project on segmental linings in squeezing rock (Mezger et al. 2014), which has been financially supported by the Swiss Commission for Technology and Innovation (CTI). The aim of the project was to find out how the application limits of segmental linings can be extended. To this end, we analyzed different lining systems considering the aspects of statics, construction management, TBM and concrete technologies.

Basically, there are two main principles of lining systems in 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, according to which a practically rigid lining is used, which must be strong enough to resist the rock pressure developing when rock deformations are prevented. In 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.

Stiff lining systems

The installation of a stiff segmental lining immediately behind the shield helps to avoid shield jamming, because it favors a longitudinal arching action in the rock around the shield, thus reducing the load on the shield (Ramoni and Anagnostou 2011b). This presupposes, however, that the shield is short, that the segments are completely backfilled immediately behind the shield and that the lining can resist the rock loads, which are higher in the cases of a shorter shield and an early backfilling.

The bearing capacity of the segmental lining can be increased (i) by increasing its thickness, (ii) by using higher-strength building materials or (iii) by installing an additional inner ring made of prefabricated segments or concrete cast in-situ (double-shell lining). Basically four potential systems are available (Fig. 1):

- *Thick single-shell segmental lining made of normal-strength concrete (Fig. 1a).* The thicker segments can be applied either locally in the critical squeezing sections or over the entire length of the tunnel. To maintain the minimum clearance profile, the boring diameter is anyway chosen for maximum segment thickness. Thicker segments are heavier and more difficult to manufacture, transport and handle during erection. In tunneling, thicknesses of up to 0.7 m have been realized to date. Segment thicknesses up to approximately 1.0 to 1.2 m are feasible (Burger 2012).
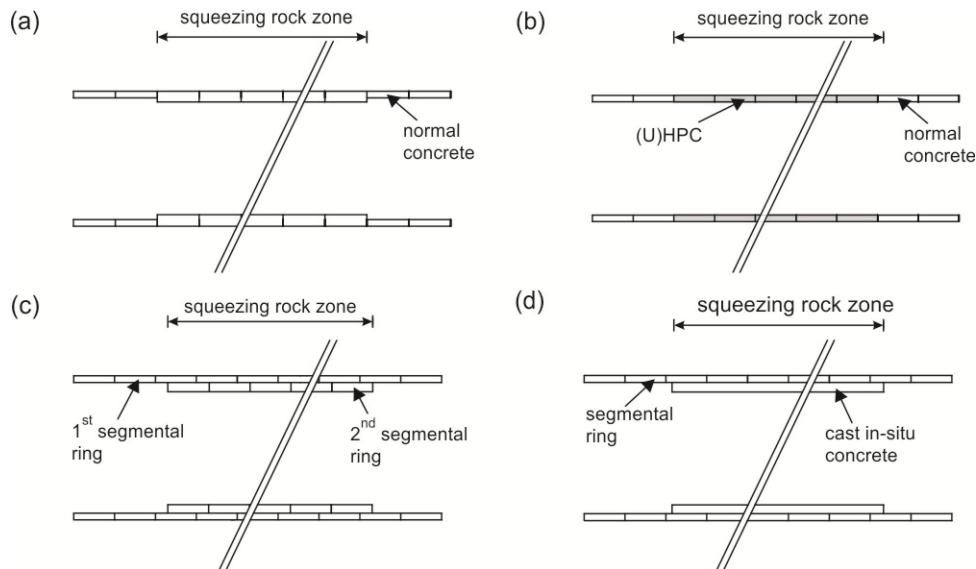

Figure 1. (a) Single-shell lining made of locally thicker normal-strength concrete segments; (b) single-shell segmental lining of uniform thickness, locally made from high performance or ultra-high performance concrete (U)HPC; (c) double-shell lining with segmental rings; (d) double-shell lining with segments and cast in-situ concrete.

- *High performance (HPC) or ultra-high performance concrete (UHPC) segmental lining (Fig. 1b).* The higher-strength segments are applied in the critical tunnel sections. In contrast to the previous solution, the thickness of the lining can be kept constant over the entire TBM drive; the squeezing rock zones are thus not decisive in terms of the boring diameter. Additionally, the use of (U)HPC results in a considerably higher load-bearing capacity in the joints (Leucker et al. 2009). The main problems of (U)HPC are its higher brittleness and, due to its higher density, lower fire-resistance. These problems can be overcome by adding steel- or PP-fibers to the concrete or by using fire-resistant plasters.

- *Double-shell lining consisting of two segmental rings (Fig. 1c, Ramoni and Anagnostou 2010a).* The two rings can be installed by the following procedure (Burger 2012): The outer ring is constructed as usual. The position of the keystone is thereby variable. The inner ring can be constructed with the keystone at the bottom, like a non-waterproof segmental lining consisting (as is usual in Switzerland) of five segments and a keystone, which can be installed without the need for hydraulic jacks (Maidl et al. 2011). The segments can be installed using a double erector (Burger 2012). As the second segmental ring is placed directly on the first ring, the requirements are high with respect to manufacturing and erection precision of the segments. Such a lining system requires a non-standard TBM, which must be planned and designed in close cooperation with the machine manufacturer.

- *Double-shell lining with inner ring of cast in-situ concrete* (Fig. 1d). From the point of view of structural behavior, the difference between this lining system and the double segmental lining is that it develops its full bearing capacity later, due to the later installation of the inner lining and the setting-time of the cast-in-situ concrete. A further difference is that the inner lining must be made of normal-strength concrete, as (U)HPC cannot be cast in-situ; factory production would be necessary to achieve the high strengths. In order to achieve a high support pressure early on, the inner lining should be installed as soon as possible behind the shield, which is difficult; it can be constructed only in the back-up area, and no closer than the space used for temporary segment storage. Such a system presupposes, therefore, that the rock pressure develops so slowly over time that it reaches its final value in the back-up area far behind the TBM. Predictions about the time-development of rock pressure are, nevertheless, unreliable in most cases. To avoid standstills in squeezing rock, the TBM drive and the construction of the inner ring have to be

decoupled by providing a sufficient length of back-up area. This lining system is very challenging with regard to logistics (the formwork always interferes with the logistic path of the segments, so that crossing material flows arise) and requires a lot of manual work.

For the first three lining systems it is also possible to install an inner ring of in-situ concrete for reasons of serviceability as well. The inner shell is installed far behind the shield (or even after the completion of the TBM drive) over the whole tunnel length. This solution is familiar and does not present any logistical problems.

Yielding lining systems

Yielding segmental linings allow rock deformations to occur in a controlled way. This results in a lower load on the lining, but is rather unfavorable with respect to the rock pressure acting upon the shield (reduced longitudinal arching action). The thrust force required to overcome the skin friction and keep the machine advancing is therefore higher than in the case of a stiff lining. At the same time, the resistance of a yielding lining to the axial force is probably lower. The problem of shield jamming is therefore more critical (Ramoni and Anagnostou 2010a).

There are two basic types of yielding lining systems: radially deformable and tangentially deformable systems.

The radially deformable systems consist of rigid segmental rings in combination either with a compressible mortar in the annular gap, or with a compressible layer that is fixed at the extrados of the segments during pre-fabrication. A compressible annular grout should be injected directly behind the shield, ideally continuously during the advance, through openings in the shield tail, so that a certain level of rock support exists right from the start. Two compressible mortars were developed for grouting the annular gap: the "Compex" and the "DeCo-Grout" (Schneider et al. 2005, Billig et al. 2007).

Hitherto, tangentially deformable systems with special compressible elements (made of concrete, steel or plastic profiles) have been used mainly in conventional tunneling or in tunneling with gripper TBMs (Cantieni and Anagnostou 2009, Ramoni and Anagnostou 2010a). In shielded tunneling, compressible elements can be arranged in the longitudinal joints of the segments. The common elements are hiDCon (Kovári 2005), Lining Stress Controller (LSC, Schubert 1996), Wabe (Podjadtke and Weidig 2010) and Meypo (Brunar and Powondra 1985). No such yielding system has yet been implemented in squeezing rock in combination with a shielded TBM.

The main criterion for the choice of a yielding lining system is its deformability in relation to that of the rock. Radially deformable systems with compressible annulus grouts can accommodate relatively small rock deformations, particularly if squeezing develops rapidly and the rock comes into contact with the shield. In this case, only the space between the extrados of the segmental ring and the extrados of the shield can be grouted. As the thickness of the shield tail seals cannot be increased arbitrarily, the space available for the annulus grout is limited. The potentially small thickness of the compressible annulus limits the effectiveness of this solution. A radially deformable system could accommodate a larger rock deformation only by fixing a compressible layer at the extrados of the segments already during pre-fabrication.

Tangentially deformable linings allow for larger deformations to occur. However, for serviceability reasons (e.g. waterproofing), the installation of an additional inner lining may be necessary in this case.

The yield pressure (i.e. the rock pressure under which the lining starts to deform plastically under a constant load) and the initial stiffness of the lining are also important factors in the selection of a yielding system. The smaller the initial stiffness is, the later the rock pressure will reach the yield pressure. Low yield pressures and small initial stiffnesses are unfavorable with respect to shield loading (there is less pronounced longitudinal arching action in the rock around the shield) and may result in loosening of the rock. Most importantly, the lower the yield pressure of the lining, the higher will be the final rock pressure in most cases (Cantieni and Anagnostou 2009). Therefore, a high yield pressure should be the aim.

In conclusion, even if the choice of a suitable yielding system is a complex issue, it is possible to formulate some general guidelines. Segmental linings incorporating hiDcon elements or radially deformable lining systems with a compressible layer fixed at the extrados of the segments are promising because they fulfill the requirement for sufficient deformability at high yielding pressure.

Considerations about the type of lining

In order to show some basic aspects of the behavior and effectiveness of the abovementioned lining concepts, we compare a stiff segmental lining (resistance principle) with a deformable lining (yielding principle) for two different rock qualities (defined in terms of Young's modulus E and uniaxial compressive strength f_c, see Fig. 3) and two different depths of cover (i.e. for four different geotechnical conditions in total).

The stiff lining is taken 50 cm thick. Considering a useable radius of R_{int} = 4.35 m (which is typical for single-lane traffic tunnels) and an annular gap equal to 15 cm, the boring radius R comes to 5.0 m and the radial lining stiffness K_l (=$E_l d/R^2$, Ramoni et al. 2011a) to 800 MPa/m.

The structural behavior of a yielding lining is governed by its characteristic line, i.e. by the relationship between its loading p and its radial displacement u (Fig. 2d). The two main parameters are: yield pressure p_y and yield deformation u_y (i.e. the radial displacement reaches the deformation capacity of the lining). A general procedure for determining the characteristic line can be found in Ramoni and Anagnostou (2011b). We consider a tangentially deformable system with an initial stiffness of K_I = 400 MPa/m (which is typical for a segmental lining incorporating hiDCon elements in the longitudinal joints), a yield deformation of 20 cm and a yield pressure of 1 MPa. Table 1 summarizes the machine data and the properties of the lining systems for the computations.
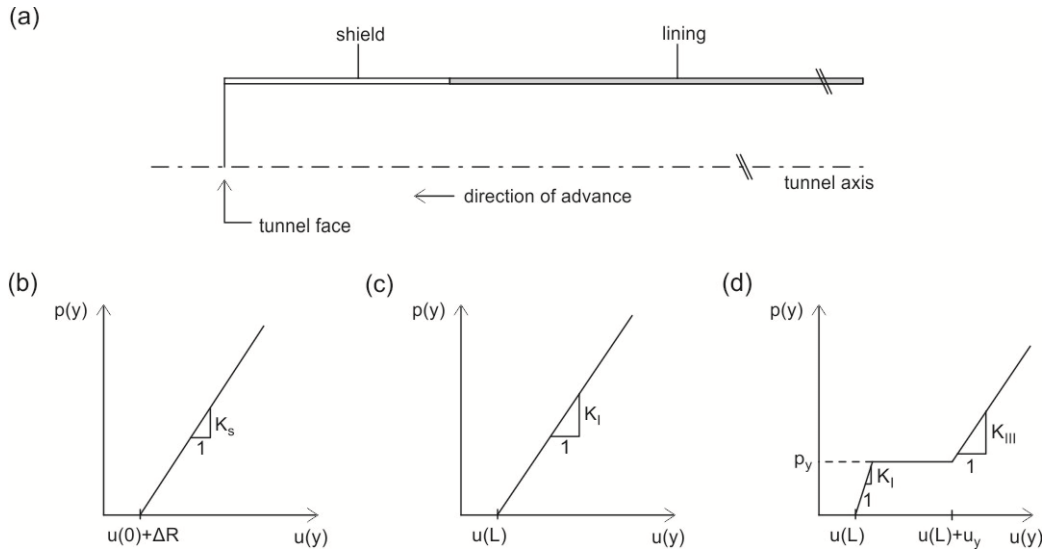

Figure 2. (a) Problem layout and boundary conditions at the tunnel wall for the simulation, (b), of the shield, (c), of a stiff lining and, (d), of a yielding lining (u(0) and u(L) denote the radial displacement of the rock at the face and at the shield tail, respectively, while y denotes the distance behind the tunnel face).

Table 1. Machine data and properties of the lining.

	Stiff lining system	Yielding lining system
Boring radius R	5 m	5 m
Length of shield L	10 m	10 m
Radial overcut ΔR	5 cm	5 cm
Thickness of shield d_s	7.5 cm	7.5 cm
Young's modulus of the shield E_s	210 GPa	210 GPa
Lining thickness d	50 cm	50 cm
Stiffness K_I (Figs. 2b and 2c)	800 MPa/m	400 MPa/m
Stiffness K_{III} (Fig. 2c)	-	800 MPa/m
Yield pressure p_y (Fig. 2c)	-	1 MPa
Yield deformation u_y (Fig. 2c)	-	20 cm

The interaction between the advancing shield, the ground and the lining can be simulated with an axially symmetric elasto-plastic model (Fig. 2a). The shield and the lining are taken into account by introducing appropriate boundary conditions: After the closure of the overcut ΔR a rock pressure develops on the shield, which is taken as linearly elastic (stiffness K_s, Fig. 2b); the stiff lining, too, is taken as linearly elastic with a constant stiffness K_l (Fig. 2c), which presupposes that the annular gap is grouted directly behind the shield; the yielding lining is accounted for by imposing a mixed boundary condition according to its characteristic line (Fig. 2d), which also presupposes that the annular gap is grouted directly behind the shield. Further modeling details can be found in Ramoni and Anagnostou (2010b, 2011b).

The numerical calculations, which in the present case were carried out by the finite element program HYDMEC of the ETH Zurich using the so-called "steady state method" (Anagnostou 2007), provide the final rock pressure p_∞ acting upon the lining far behind the TBM, as well as the rock pressure distribution along the shield. The latter is important for estimating the thrust force F_f that is required to overcome the shield skin friction. If the required thrust force is higher than the installed one, the shield will get stuck. Conditions for which shield jamming may occur do not need to be considered in the evaluation of the lining systems.

The results are presented in the diagrams of Figure 3. The marked points show the final lining pressure p_∞ and the radial displacement of the rock at the tunnel boundary (including its pre-deformation ahead of the face) for each lining system. In order to understand the differences between the four geotechnical conditions better, Figure 3 also shows the characteristic lines of the rock, i.e. the relationships between rock pressure and deformation. (The numerical results are located above the characteristic lines for reasons explained in Cantieni and Anagnostou 2009.)
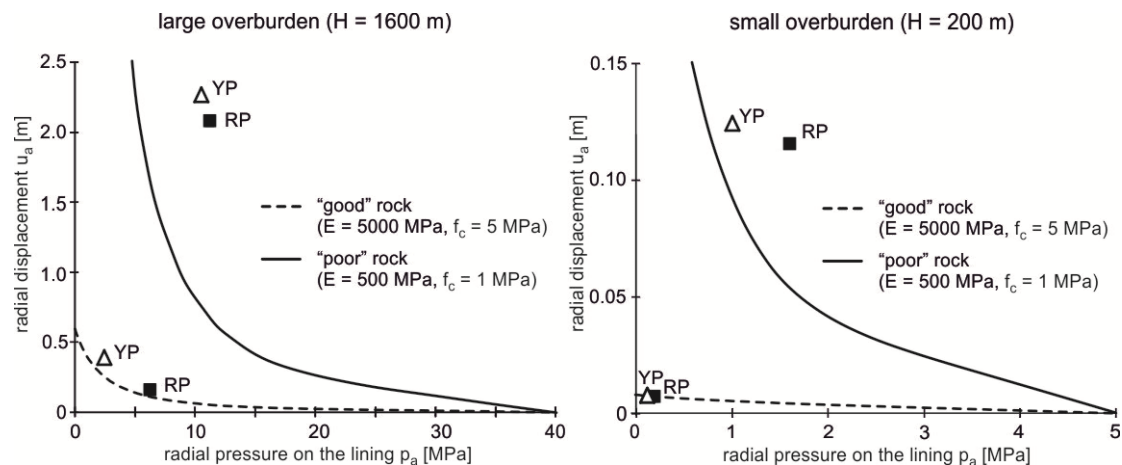

Figure 3. Characteristic lines of the rock and numerical results (marked points) for a large overburden (left hand side) and for a small overburden (right hand side), for two rock qualities, for a stiff (RP) and a deformable lining (YP) (Young's modulus E and uniaxial compressive strength f_c: see labels inside the diagrams; Poisson's ratio $v = 0.25$, friction angle $\varphi = 25°$, dilatancy angle $\psi = 5°$, unit weight $\gamma = 25$ kN/m³).

Let us consider first the case of a large overburden (left hand side of Fig. 3). If the quality of the rock is poor, then an extremely high rock pressure ($p_\infty > 10$ MPa) develops far behind the TBM, even when deformations are allowed to occur. Since a lining with such a high bearing capacity cannot be constructed, a TBM drive is not feasible in this case. In the case of better quality rock, the rock pressure developing upon a stiff lining would be prohibitively high. However, allowing a small convergence to occur would result in a significantly lower rock pressure, thus making mechanized tunneling (in combination with a yielding segmental lining) feasible, provided that the lining can sustain the thrust force that is needed to overcome shield skin friction. In the present example (overburden 1600 m) the required thrust force amounts to 352.5 MN, which is technically unfeasible. (Comparative calculations for a depth of cover of 1000 m, all other parameters being the same, showed that the required thrust force for a yielding lining decreases to 98.9 MN, which is manageable, and that the use of a yielding lining leads to a final pressure of 1 MPa, compared to a stiff lining, which has to resist pressures of 3.1 MPa.)

Under a small depth of cover (right hand side of Fig. 3), the rock pressure is manageable with a stiff lining, even if the rock quality is poor. Allowing rock deformations to occur by installing a deformable

lining system would only lead to a small reduction in the rock pressure. This means, in combination with the potential problems of a yielding lining system (movability, serviceability and higher thrust force), that the resistance principle is more appropriate in the case of small depths of cover.

In conclusion, a lining based on the yielding principle seems to be appropriate specifically for tunnels through squeezing rock of relatively high stiffness and strength under a large overburden – always provided that the thrust force that is required to overcome skin friction is not prohibitively high.

Design Diagrams

In order to facilitate the assessment of stiff and yielding lining systems for given geotechnical conditions, we carried out a parametric study considering several depths of cover, rock qualities and lining systems, and worked out design diagrams. The parameter ranges (Table 2) have been chosen so that relevant squeezing occurs. In addition to the lining systems introduced in the previous section, further systems were also analyzed: On the one hand, in order to explore the limits of the resistance principle, a lining thickness d of 160 cm was also analyzed (resulting in a boring radius R of 6.1 m and a radial lining stiffness K_l of 1720 MPa/m). On the other hand, tangentially deformable systems with a yield deformation of 5 or 20 cm and a yield pressure of 0 or 1 MPa were also considered (Table 1).

The design diagrams can also be used for radially yielding linings with a compressible layer that is fixed at the extrados of the segments, since such lining systems can also be modeled by the characteristic line of Figure 2c. This is not the case for radially deformable lining systems with a compressible annulus grout, because the actual thickness and thus also the stiffness of the backfilling depend also on the rock deformation, thus necessitating an iterative computational procedure (Ramoni et al. 2011a).

Table 2. Rock parameters and depths of cover.

Young's modulus E	500 f_c, 700 f_c or 1000 f_c
Poisson's ratio v	0.25
U.C.S. f_c	1, 3 or 5 MPa
Friction angle φ	25°
Dilatancy angle ψ	5°
Unit weight γ	25 kN/m^3
Depth of cover H	200, 500 or 800 m

Figure 4 shows the required thrust force F_f as well as the final pressure p_∞ acting upon the lining far behind the TBM for different depths of cover and rock qualities. The upper four diagrams apply to linings based on the resistance principle, the lower four diagrams are for deformable linings.

As mentioned above, the results concerning the required thrust force are necessary for evaluating the risk of shield jamming. Investigating the structural performance of the lining makes sense only for geological conditions under which the required thrust force is not prohibitively high. Conditions under which shield jamming may occur (even after taking all possible measures such as short shield, adequate overcut, lubrication of the shield, immediate grouting of the annular gap, auxiliary hydraulic jacks) do not need to be considered in the evaluation of the lining systems.

The thrust forces of Figure 4 were determined by considering both the situation during TBM advance (boring and overcoming sliding friction) and the conditions at TBM restart after a standstill (overcoming static friction; Ramoni and Anagnostou 2010b). Assuming lubrication of the shield extrados, the skin friction coefficient μ was taken equal to 0.10 during ongoing excavation (sliding friction) and to 0.15 for the static friction prevailing during restart (Ramoni and Anagnostou 2011c). The overcut ΔR was taken constant to 5 cm (without additional conicity of the shield).

For stiff lining systems and the usual traffic tunnels diameters, an installed thrust force of the TBM with auxiliary hydraulic jacks of 250 MN is technologically feasible (Ramoni and Anagnostou 2010a). However, it is questionable whether such a high force is also realistic with a yielding segmental lining. In the case of eccentric loading, the movability of the segmental ring (which is due to the compressible elements in the longitudinal joints) and, in the case of compressible annulus grouts, the soft lining embedment, may impose limits on the thrust force which can be applied on the segments.
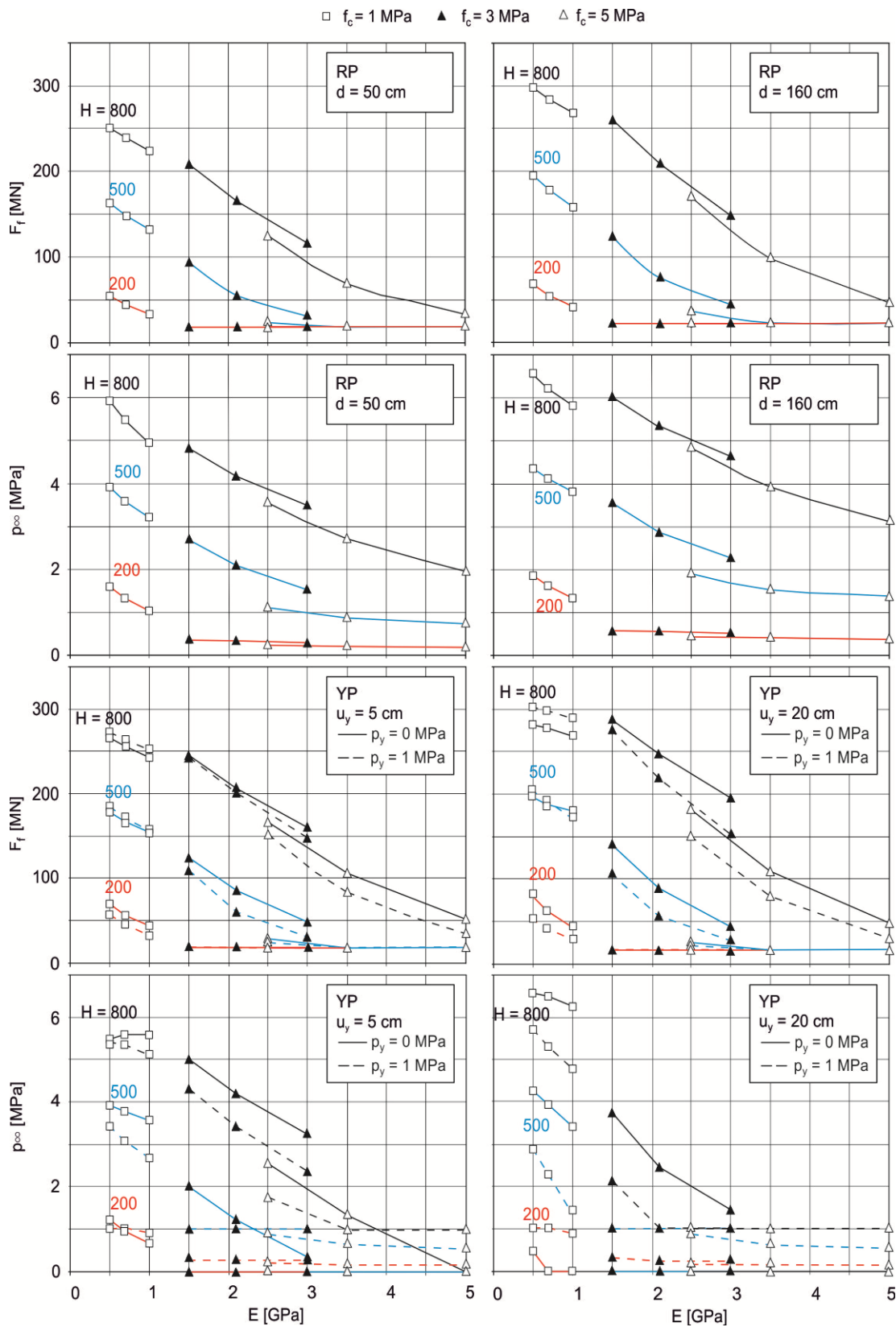
Figure 4. Required thrust force F_f and final lining pressure p_∞ for linings according to resistance principle (RP) and yielding principle (YP); all other parameters according to Tables 1 and 2.

For stiff lining systems, the upper diagrams of Figure 4 show that the greater the thickness of the segments is, the higher the rock pressure acting on the lining will be. This is because the stiffness of the lining and, for a given overcut, also the boring diameter have a big influence on the rock pressure.

As mentioned before and as can also be seen in the lower diagrams of Figure 4, in the case of deformable linings, a lower yield pressure generally leads to higher final rock pressures p_∞. However, when the yield deformation is not used up, the final pressure corresponds to the chosen yield pressure p_y. Of course, in these cases, an increase in the yield pressure does not lead to a reduction in the final rock pressure. Figure 4 also shows that, in some cases, an increase in the yielding deformation u_y from 5 cm to 20 cm does not lead to a further reduction in the final pressure. For these cases, the deformations developing in the ground are smaller than $u(L)+u_y$ for both cases of u_y (5 and 20 cm) and therefore the final rock pressure corresponds to the yield pressure. As soon as the yield deformation has been used up, the pressure increases significantly (the stiffness of the lining K_{III} is large). Therefore, a small increase in the overburden can lead to a considerably higher final pressure.

In some geological conditions, a reduction in the uniaxial compressive strength (i.e. a poorer quality of the rock, all other parameters remaining the same) leads to a decrease in the end pressure p_∞ and the required thrust force F_f. A discussion of this issue can be found elsewhere (Cantieni and Anagnostou 2011, Ramoni and Anagnostou 2010b).

Lining resistance

The maximum rock pressure p_∞ that can be resisted by a stiff lining can be determined by considering the lining as a thick-walled cylinder under external pressure and by setting the maximum hoop stress equal to the compressive strength of concrete σ_d. Incorporating a safety factor of 4.0 (which accounts in a simplified manner for material imperfections and bending moments) we obtain:

$$ p_\infty = \frac{\left(\dfrac{R_{int}+d}{R_{int}}\right)^2 - 1}{8 \times \left(\dfrac{R_{int}+d}{R_{int}}\right)^2} \cdot \sigma_d \,, \tag{1} $$

where R_{int} and d denote the inner radius and the thickness of the lining, respectively. Figure 5 shows the lining resistance as a function of the thickness d and of the compressive strength of the concrete.
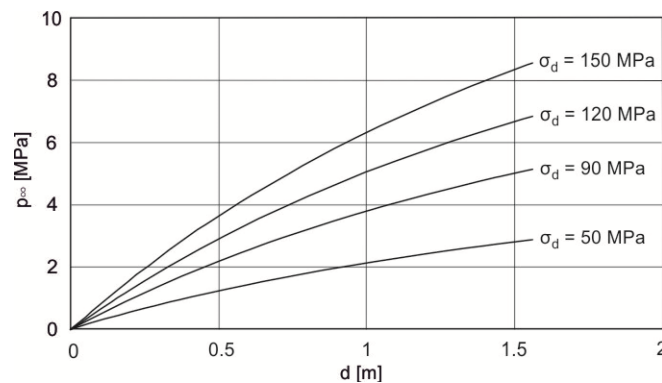

Figure 5. Lining resistance p_∞ as a function of the lining thickness d and compressive strengths σ_d.

Figure 5 can also be used for double-shell lining systems, provided that the two rings exhibit the same strength. If their strengths are different, then Figure 5 will be only approximately correct. Therefore only lining systems with rings of the same strength will be considered here.

Under the simplifying assumption that the stiff lining system is subjected only to normal forces (a safety factor was introduced to account for bending moments), there is no difference between a single and a double shell lining of the same thickness and concrete strength with respect to the ultimate load. In the case of a highly non-uniform rock pressure, a double shell lining would exhibit a lower resistance than a single ring of the same thickness because there is no shear bond between the inner and outer shell and, therefore, the bending resistance is lower.

Eq. (1) can also be used for deformable systems to assess the structural safety of the segmental lining under the load that develops after its deformation capacity has been used up.

Application example

As an example for the usefulness of the diagrams presented (Figs. 4 and 5), let us take the following question: Given the boring diameter, how can the space available for the lining be best used? Is it better to install a thicker lining based on the resistance principle or to install a thinner deformable segmental lining and use the remaining space for accommodating deformations (i.e. the yielding principle)?

For example, an available space of 55 cm can be used either to install a 55 cm thick stiff segmental lining or a tangentially deformable, 50 cm thick lining with compressible joint elements which allow a rock deformation u_y of 5 cm to occur. Table 3 shows the safety factor SF (defined as the ratio of the lining resistance to the actual rock pressure) for different geotechnical conditions (combinations of depths of cover and rock qualities) and for different linings. Brackets are used in order to mark situations in which the required thrust is higher than the installed thrust force. The latter is taken equal to 250 MN in the case of stiff lining, and to 150 MN in the case of deformable linings. Situations with a safety factor less than 1 or with an insufficient installed thrust force are marked in grey.

Let us first consider the case of a small overburden. In this case, if the quality of the rock is relatively good (see results, e.g., for $H = 200$ m, $E = 5$ GPa and $f_c = 5$ MPa), all the linings reach high safety factors and thus also a thinner stiff lining could be chosen (a yielding lining is unnecessary). However, if the rock quality is poor, the structural safety can only be achieved by installing a stiff lining of C90 or a yielding lining; both systems having advantages and disadvantages.

In the case of a great depth of cover, neither a stiff lining, nor a yielding lining would suffice for structural safety if the quality of the rock is poor (see results for, e.g., $H = 800$ m, $E = 0.5$ GPa and $f_c = 1$ MPa). If the rock quality is good, however, the yielding lining as well as the stiff lining of C90 would meet the safety requirements to an acceptable level (see results, e.g., for $H = 800$ m, $E = 5$ GPa and $f_c = 5$ MPa). An even higher overburden (e.g. $H = 1000$ m) would lead to higher load pressures on the stiff lining (of HPC) and thus to a safety factor smaller than 1, whereas a yielding lining allowing a deformation of 5 cm would still fulfill the safety requirements.

Table 3. Safety factor SF for an available space of 55 cm (YP: 50 cm thick lining yielding by 5 cm under a yield pressure of 1 MPa; RP: 55 cm thick lining).

H [m]		200			500			800		
E [GPa]		5	2.1	0.5	5	2.1	0.5	5	2.1	0.5
f_c [MPa]		5	3	1	5	3	1	5	3	1
YP	C50	9.9	4.8	1.2	2.3	1.2	(0.4)	1.2	(0.4)	(0.2)
RP	C50	7.2	3.9	0.8	1.8	0.6	0.3	0.7	0.3	(0.2)
	C90	11.1	6.7	1.5	3	1.1	0.6	1.2	0.6	(0.4)

Table 4. Safety factor SF for an available space of 70 cm (YP: 50 cm thick lining, yielding by 20 cm under a yield pressure of 1 MPa; RP: 70 cm thick lining).

H [m]		200			500			800		
E [GPa]		5	2.1	0.5	5	2.1	0.5	5	2.1	0.5
f_c [MPa]		5	3	1	5	3	1	5	3	1
YP	C50	9.9	4.8	1.2	2.3	1.2	(0.4)	1.2	(1.2)	(0.2)
RP	C50	7.4	4.3	1	1.9	0.7	0.4	0.8	0.4	(0.3)
	C90	11.4	7	1.7	3	1.2	0.7	1.2	0.6	(0.5)

Let us consider next, an available space for the lining of 70 cm (Table 4), which can be used either to install a stiff segmental lining consisting of 70 cm thick segments of different concrete strengths, or a tangentially deformable lining consisting of 50 cm thick segments (of C50) and allowing a rock deformation u_y of 20 cm. It is evident that an increase in the thickness of the stiff lining from 55 to 70 cm (of the same concrete-strength) is generally of little benefit, as it results in a higher lining stiffness and thus also a higher rock pressure. It helps only if the structural safety is just below the acceptable level, especially in the case of a small depth of cover and poor quality rock (e.g.

$H = 200$ m, $E = 0.5$ GPa and $f_c = 1$ MPa). For these specific rock conditions, a 70 cm thick stiff lining consisting of normal-strength concrete would also fulfill the safety requirements. This solution based on the resistance principle (in particular with C50) seems to be more appropriate in this case, as is already known. A further increase of the yield deformation of 20 cm (compared to 5 cm) has no advantages in the rock conditions under consideration, since the required thrust force increases and therefore shield jamming occurs (e.g. $H = 800$ m, $E = 2.1$ GPa and $f_c = 3$ MPa).

Closing remarks

The procedure developed for the choice and design of the lining system offers a valuable tool for engineering practice. It provides an estimation of the required thrust force and the rock pressure acting on the lining for shielded TBM tunneling in squeezing rock and therefore an assessment of the applicability of lining systems for given geological conditions. The conclusions of the comparative investigations (resistance principle vs. yielding principle) can be summarized as follows: Yielding linings are adequate for tunnels through slightly-moderately squeezing rock under a great overburden, where the loading of a stiff lining would be very high, while a small deformation suffices to reduce the pressure. An increase in the structural safety of a single shell lining cannot be achieved only by increasing the segment thickness, because a thicker lining is also stiffer, thus resulting in a higher load.

Acknowledgements

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