VOUSSOIRS SOUMIS À CONDITIONS DE ROCHES POUSSANTES

SEGMENTAL LININGS UNDER SQUEEZING PRESSURE

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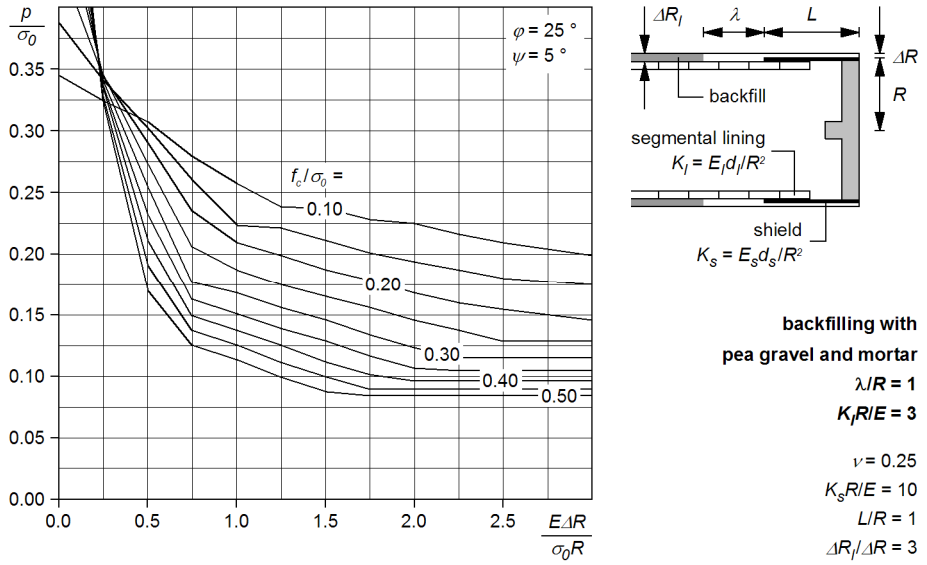
The overstressing of a segmental lining is a major potential hazard in TBM tunnelling through squeezing ground. The paper starts with a review of the segmental lining concepts applied or proposed for shielded TBM tunnelling in squeezing ground. Later, the focus is shifted to the practically rigid segmental linings which are the standard solution for shielded TBM tunnelling, paying attention to the different options for backfilling (i.e., backfilling by pea gravel at a certain distance behind the shield or annulus grouting via the shield tail) and the factors influencing the loading of the lining. The numerical simulation of the effects of backfilling is a demanding problem, because the thickness of the backfilling is not known a priori but depends on the intensity of the squeezing, i.e., on the deformations of the bored profile between the tunnel face and the location of the backfill installation. For this purpose, advanced numerical models are required which, as a rule, are not available to the project engineer. On account of this, the final section of the paper introduces practical decision-making aids for the quick assessment of the loading of a segmental lining. The aids have been worked out by means of a comprehensive parametric study covering the relevant range of ground parameters and initial stresses, as well as different characteristics of the TBM, the segmental lining and the backfilling (type and location).



Nomogram for the determination of the segmental lining load *p*

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1. INTRODUCTION

The Lötschberg Base Tunnel and the Gotthard Base Tunnel in Switzerland [1], the Brenner Base Tunnel between Austria and Italy [2] and the Lyon – Turin Tunnel between France and Italy [3] are all examples of long, deep tunnels excavated for the further development of infrastructure for the transportation of people and goods.

For such long, deep tunnels in particular, the uncertainties of geological exploration may be large. Due to this, and also due to alignment constraints, it is not always possible to avoid with a sufficient degree of certainty situations where the tunnel passes through difficult geological zones. The related risks may put into question both the economical viability and the technical feasibility of applying a tunnel boring machine (TBM), the purpose of which, as a rule, is to reduce construction time and costs.

For a TBM, so-called "squeezing ground" represents a particularly challenging operational environment. In fact, due to the geometrical constraints of the equipment, even relatively small convergences of 10–20 cm (which can be accommodated without any particular problems in conventional tunnelling) may slow down or even obstruct TBM operation. The main problems can be summarized as follows: sticking of the cutter head together with jamming of the shield in the machine area as well as jamming of the back-up trailers, inadmissible deformations of the bored profile or overstressing of the tunnel support. A comprehensive collection of case histories involving TBM problems in squeezing ground can be viewed at [4].

In the recent years, the topic of "TBM tunnelling in squeezing ground" has been the subject of extensive research work at the ETH Zurich [5–8]. The authors reviewed the available countermeasures, commented on possible technological improvements, analyzed the interaction between the shield, ground and tunnel support quantitatively and provided design charts concerning the thrust force needed in order to avoid shield jamming. Furthermore, a recent paper [9] provided design charts for a first assessment of the loading of a segmental lining in squeezing ground, taking account of the effect of the type and location of backfilling.

The present paper is based upon this research work and focuses on the hazard scenario of overstressed linings in squeezing ground. The paper starts with a critical overview of the pros and cons of the main segmental lining concepts applied with, or proposed for use with, shielded TBMs (Section 2) and continues with a discussion of the effect of the type, location and thickness of the backfilling on the interaction between a squeezing ground and a practically rigid segmental lining (Section 3). The backfilling of a segmental lining is usually carried out with pea gravel in the upper part and with mortar in the bottom third of the cross-section at a given distance behind the shield (Figure 1a). Alternatively, but rather rarely in rock tunnelling, grouting occurs immediately behind the shield via the shield tail (Figure 1b). Taking due account of the backfilling features is indispensable to a realistic estimation of the loading of a segmental lining. Section 3 limits itself to a general illustration of the most important influencing factors. A more detailed discussion of the influencing factors and their interactions, including quantitative considerations, can be found at [9]. Finally, Section 4 provides an outline of design aids and illustrates the ways in which they can be used to allow an easy and rapid preliminary assessment to be made of the lining loading.

2. SEGMENTAL LINING CONCEPTS

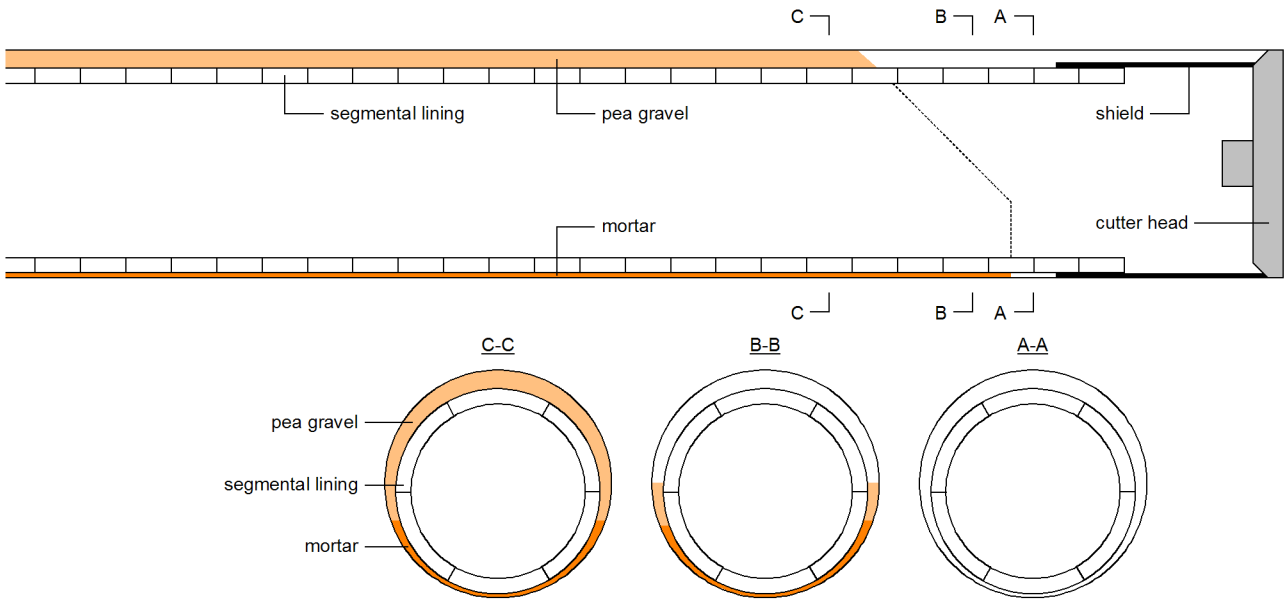
The tunnel support in squeezing ground can be designed either as practically rigid or as deformable (the "resistance principle" or the "yielding principle", respectively [10]). In the first case, the tunnel support has to be strong enough to bear the ground pressure developing through the prevention of ground deformations. In the second case, the ground pressure is reduced by accepting a certain amount of ground deformations.

Practically rigid segmental linings are the standard support applied with shielded TBMs. Due to their high stiffness and strength, they follow the "resistance principle". One main advantage of segmental linings is their prefabrication, as this allows high uniaxial compressive strengths to be achieved in the concrete (up to 50 MPa or even more) with sufficient levels of reliability, thus providing the ability to cope with high ground pressures.

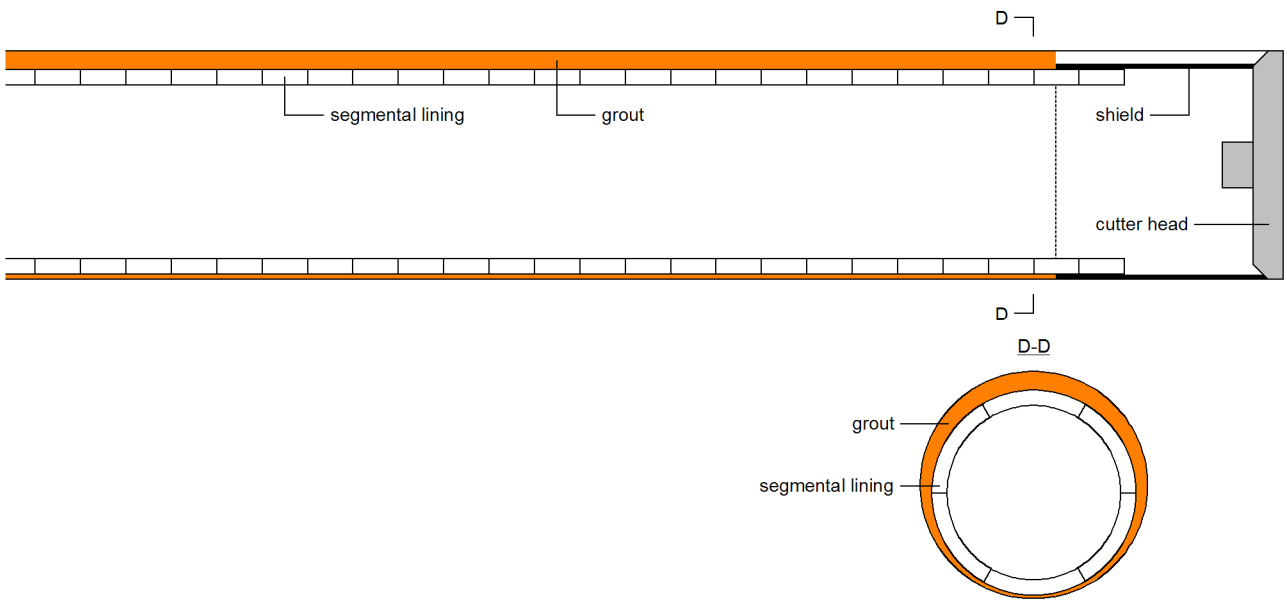
The time required for the installation of the segments is relatively short (compared, for example, with the time required for the application of shotcrete during a gripper TBM drive) and their characteristics do not depend on time (unlike shotcrete, for example, the strength of which increases during hardening). If properly bedded, therefore, a practi-

cally rigid segmental lining is able to offer ground support rapidly.
However, in squeezing ground where very high ground pressures may develop, the applicability limit of practically rigid segmental linings may be exceeded, despite the enormous potential strength of the concrete. In addition, the required thickness of the segments increases with greater loading and this may lead to very thick segments which require a greater boring diameter and are difficult to handle. In order to avoid the disadvantages of the "resistance principle" and to extend the applicability range of segmental linings, much research has been done into the development of deformable segmental lining systems for application with shielded TBMs – e.g., [11–13]. Figure 2 shows the main concepts.

The first concept (Figure 2a) allows convergence by means of a compressible layer arranged between the squeezing ground and the segmental lining. In this case, the ground can converge, while the segmental lining experiences only small deformations. This concept can be implemented with the addition of a compressible layer installed at the extrados of the segments in combination with traditional annular grouting or a compressible grout [11, 12]. Two examples of compressible annulus grouting, which can be compressed up to 50 %, are the so-called "DeCo Grout" [11] and the so called " Compex" [12]. A further "convergence-compatible" segmental lining is the so-called "CO-CO-system" [13]. The segments of this system incorporate supporting ribs at their extrados, which are in contact with the ground. The space between the ribs can be either



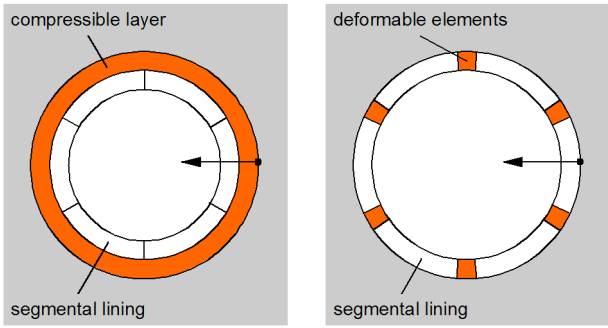
(a)



(b)

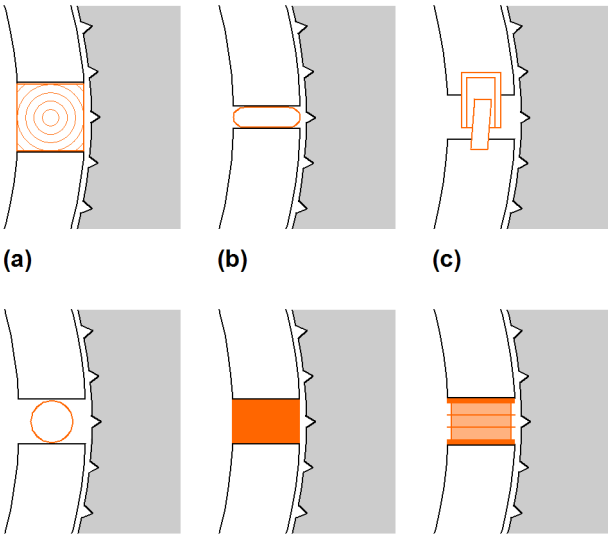
Figure 1. Backfilling of a segmental lining [9]: (a) with pea gravel and mortar; (b) annulus grouting via the shield tail.

empty or filled with a compressible material, thus allowing the ground to converge.
In the second basic concept (Figure 2b), the segmental lining itself reduces its circumference according to the deformability of special elements arranged in the longitudinal joints. Figure 3 gives an overview of the technical possibilities in this respect. The first material used for making deformable longitudinal joint elements for prefabricated concrete elements was wood [14]. More recently, experiments have been made using neoprene elements and hydraulic devices. The technical literature also includes other types of deformable elements, such as plastic bodies filled with polyurethane or lightweight concrete, steel or plastic tubes, steel grids or highly deformable concrete elements.
Up until today, the only implementation of the "yielding principle" in combination with a shielded TBM and a segmental lining involved the application of "Compex" compressible mortar in a 20 m long test drive within the framework of the Jenbach Tunnel in Austria [15]. The test was successful from the point of view of handling. It should be noted, however, that the test was not carried out in squeezing ground. In this respect, there are some potentially critical aspects that are common to all of the proposed concepts.
First of all, it should be kept in mind, in the case of shielded TBM tunnelling, that the segmental lining applied usually represents not only a temporary support but also a final lining as well. It therefore has to provide stability, the required clearance profile and water tightness over the entire lifetime of the tunnel. A deformable segmental lining, however, adjusts its shape according to ground deformations and is therefore far less suited to fulfilling the requirements mentioned above, particularly in the case of non-uniformly distributed ground deformations or pressures.
The selection of a larger boring diameter – in order to ensure sufficiently large tolerances – may be contemplated as a countermeasure against violation of the required clearance profile. This would be necessary for the entire tunnel (i.e., including stretches where squeezing ground is not expected) and may therefore be uneconomical. In this respect, continuous adjustment of the boring diameter would be a valuable solution. However, the actual overboring technology is not yet reliable enough to be applied systematically during TBM excavation [5] and reliable forecasting of ground deformations is often difficult (an underestimation of the required over-excavation will cause overstressing of the support, which is not acceptable for a final structure).
A further specific disadvantage of the systems comprising deformable longitudinal joints concerns the high cost (in terms of materials and construction time). This is particularly true for single shell tunnel linings that have to be waterproof, as in this case the deformable elements need to perform a sealing function as well.



(a) **(b)**

Figure 2. Concepts of deformable segmental linings [5]: (a) compressible layer between squeezing ground and lining; (b) deformable elements in the longitudinal joints between the segments.



(a) **(b)** **(c)**

(d) **(e)** **(f)**

Figure 3. Prefabricated segmental lining with compressible longitudinal joints [4]: (a) wood [14]; (b) neoprene layers and flatjacks [16]; (c) hydraulic jacks [17]; (d) steel tubes [18]; (e) highly deformable concrete elements [19]; (f) Wabe-elements [20].

Regarding the other type of deformable segmental linings (employing a compressible layer between the lining and the rock), questions arise over the bedding of the segments. In this respect, there are difficulties due to the fact that the backfilling material has to be deformable (in order to allow convergences), but at the same time stiff enough to ensure the proper bedding of the segmental lining, as this is important with respect to the accommodation of jacking forces and ground pressure (particularly in the case of non-uniformly distributed loads).
When comparing the different tunnel support concepts, it is necessary to consider the positive effect of lining stiffness on shield loading and, therefore, on the risk of the shield jamming. This is important taking in account the fact, as is shown from tunnelling experience [4] and numerical investigations [5], that under adverse conditions, squeezing will

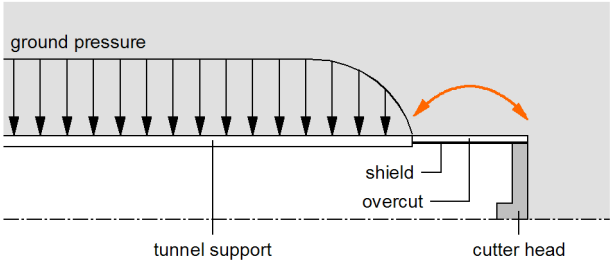


Figure 4. Arch action in the longitudinal direction around the shield in the presence of a rigid lining [5].

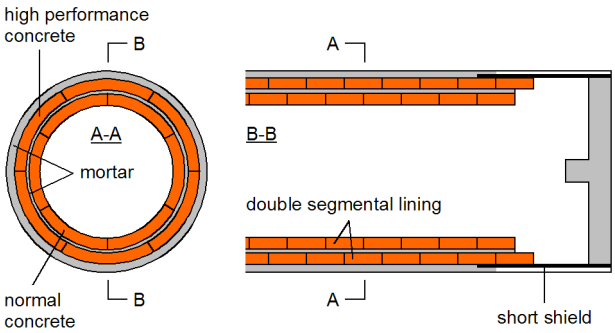
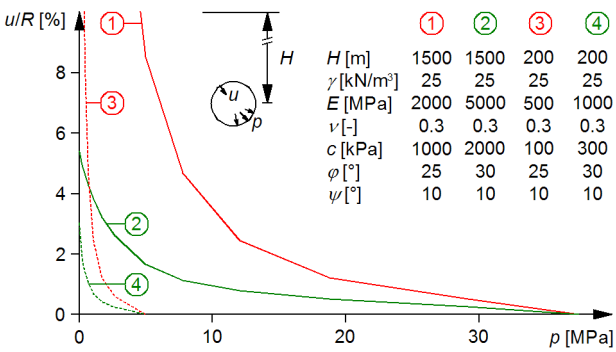


Figure 5. Double segmental lining [5].



ground quality	depth of cover	
	high	low
poor	① (resistance principle ?)	③ resistance principle
fair	② yielding principle or resistance principle	④ resistance principle

Figure 6. Qualitative definition of the applicability range of the "resistance principle" and the "yielding principle" by means of the ground response curve.

probably halt the TBM advance before endangering the structural safety of the segmental lining.

The installation of a stiff lining near to the shield leads to an "unloading" of the shield because of an arching action in the longitudinal direction (Figure 4). Of course, this leads to a higher load developing upon the lining. However, there are various options for improving the bearing capacity of a practically rigid segmental lining and, therefore, for enlarging the applicability range of the "resistance principle". Firstly, one can increase the thickness of the segments. Due to operational aspects such the handling of the segments, the maximum possible thickness is about 70 cm. A second option is to use high performance concrete (HPC), i.e., to increase the compressive strength of the segments to a design value of up to 50–60 MPa.

If a further increase is required in the resistance of the segmental lining, it is possible to design a lining system consisting of two concentric segment rings (Figure 5). This solution allows the thickness and weight of the segments to be kept within a manageable range. The outer ring can be made of HPC. The inner ring, applied (by the same erector) only when required, can be made of HPC or of normal concrete (this would be advantageous with respect to fire resistance). Depending on the water pressures, it might be also possible for the inner ring alone to be waterproof. A solution with a double segmental lining makes sense only in heavily squeezing ground, and should therefore be combined with a minimum possible shield length in order to reduce the surface exposed to ground pressure and to utilize the favourable longitudinal arching sketched out in Figure 4. As far as the boring diameter is concerned, the double segmental lining solution presents the same disadvantage as a deformable lining: a larger boring diameter must be selected for the entire tunnel.

The application of the "yielding principle" seems to be appropriate only in cases where a small convergence leads to a significant reduction of the ground pressure. In such cases, the introduction of a compressible layer between the segments and the ground makes it possible to reduce the lining loading without having to manage high ground deformations (which, as said above, may be problematic for a yielding lining system). As visualized in Figure 6 by means of the ground response curve, such a situation may occur if the depth of cover is high and the ground "quality" is relatively good (case 2 in Figure 6). In such cases, the ground response curve is rather flat (i.e., the ground pressures p are relatively high but the deformations u small). In cases 1, 3 and 4, practically rigid segmental linings seem to be more appropriate. In case 1, the ground deformations which a deformable segmental lining should allow would lead to the problems mentioned above. Of course, in this case, it has to be checked if the segmental lining is able to accommodate the high ground pressure. In cases 3 and 4, where the cover is small and the maximum ground pressure relatively low, there is no reason at all to apply a yielding segmental lining.

In conclusion, the standard solution of a practically rigid segmental lining seems to be more appropriate for most cases of shielded TBM drives crossing squeezing ground. One the one hand, properly bedded precast segments can bear high ground pressures and high thrust forces. On the other hand, it seems contradictory to incorporate expensive, high-quality precast segments (constructed with tolerances of 1–2 mm) into a support system that may experience uncontrollable deformations of several cm. The large flexibility of deformable segmental linings is favourable with respect to their structural safety but (almost by definition)

unfavourable with respect to their serviceability requirements, which are particularly important for permanent structures.

3. TYPE, LOCATION AND THICKNESS OF THE BACKFILLING

3.1 Backfilling with pea gravel and mortar

The effect of backfilling will be discussed under the simplifying assumption of axial symmetry. In reality, the shield slides along the tunnel floor and, therefore, the gap around the shield and the segmental lining is wider above the centre than in the lower portion of the tunnel cross-section (cf. Figure 1). However, the simplifying assumption of axial symmetry can be made without loss of generality in terms of the conclusions.

For a given set of ground characteristics, the loading of the lining will depend on the stiffness of the segmental lining and the backfilling. The stiffnesses of these two support components depend on their geometry (thickness, radius) and material properties.

Estimating the stiffness of the backfilling layer is problematic because its actual thickness d_b depends also on the deformations of the ground, i.e., on the radial displacement of the bored profile u_b occurring behind the tunnel face up to the point at which the backfilling is completed (Figure 7a):

$$d_b = \Delta R_l - u_b \ , \tag{1}$$

where ΔR_l is the planned size of the radial gap of the segmental lining and

$$0 \le u_b \le \Delta R_l \ . \tag{2}$$

ΔR_l is equal to the difference between the boring radius R and the radius of the segmental lining extrados $R_{l,o}$ (cf. Figure 7a) and represents an upper limit for the radial displacement of the bored profile u_b. Equation 1 disregards the (very small) deformations of the segmental lining. The greater the deformations of the ground, the lesser will be the thickness of the backfilling layer and, consequently, the higher will be its stiffness [9]. Two borderline cases can be distinguished. If the ground does not deform (i.e., u_b = 0, Figure 7b), the backfilling will be as thick as the planned size ΔR_l of the radial gap between segments and ground. On the other hand, if the ground closes the radial gap before backfilling occurs (i.e., $u_b = \Delta R_l$, Figure 7c), the thickness of the annular gap becomes equal to zero and backfilling is no longer possible.

The radial gap size of the segmental lining ΔR_l is geometrically coupled with the radial gap size of the shield ΔR (which is the difference between boring radius R and radius of the shield extrados $R_{s,o}$ (cf. Figure 7a). An increase in the radial gap ΔR leads automatically to an increase in the radial gap ΔR_l:

$$\Delta R_l = \Delta R + d_s + t_s \ , \tag{3}$$

where d_s is the thickness of the shield and t_s the difference between the radius of the shield intrados $R_{s,i}$ and the radius of the segmental lining

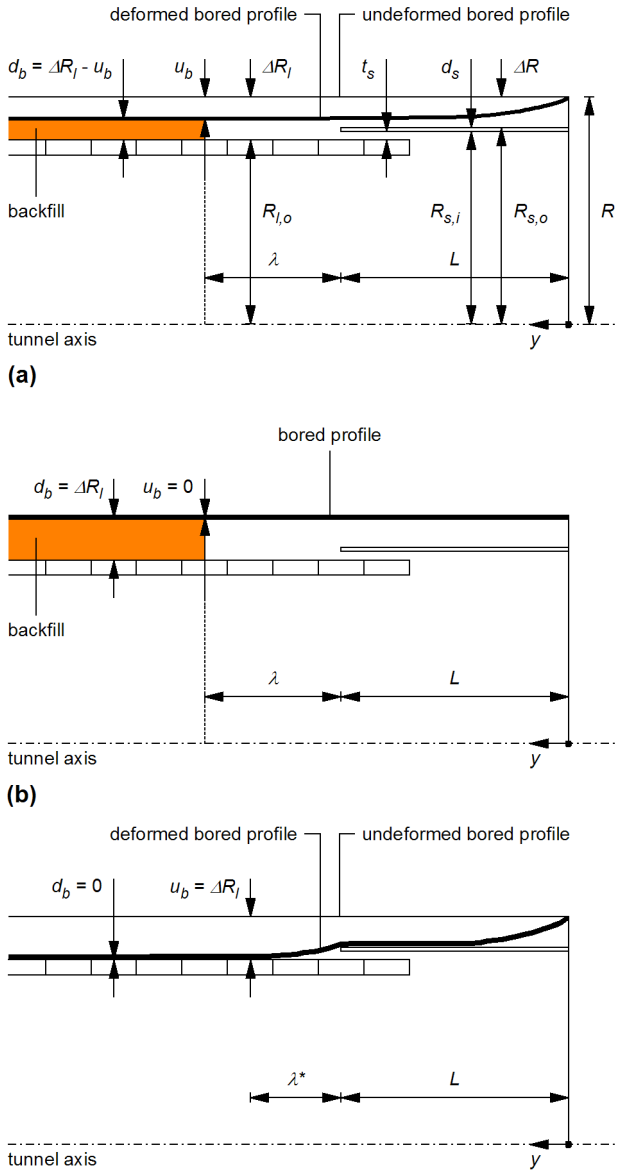


Figure 7. Thickness of the backfilling d_b when applying pea gravel and mortar [9]: (a) general case; (b) borderline case of practically zero ground deformations between the face and the location of the backfilling; (c) rapidly converging ground closing the gap around the lining before the execution of backfilling.

extrados $R_{s,o}$ (cf. Figure 7a). With respect to the radial gap ΔR, it has also to be mentioned that if the shield has a "conical" shape the radial gap size will increase with increasing distance from the tunnel face, i.e., $\Delta R = \Delta R(y)$.

The radial displacement of the bored profile u_b not only affects the thickness of the backfilling d_b but also has a direct effect on the ground pressure, as it is a part of the "pre-deformation" that the ground experiences before the segmental lining becomes loaded. For given ground characteristics, the radial displacement u_b depends on the advance rate and on two geometric factors: the shield length L and the distance behind the shield λ (cf. Figure 7a), where backfilling should occur.

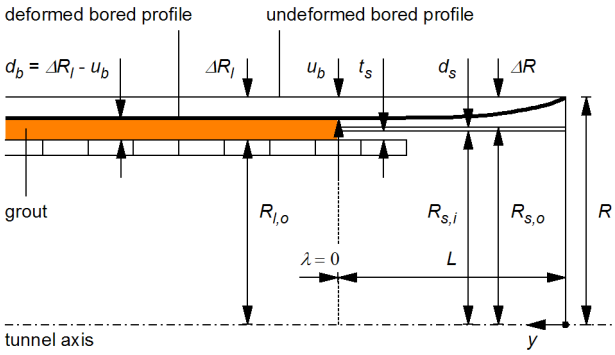


Figure 8. Thickness of the backfilling d_b in the case of grouting via the shield tail [9].

The shield length L is a matter of TBM design, while the length λ depends on the type of the backfilling material and on operational decisions taken on the construction site. The greater the distance from the tunnel face $L + \lambda$ (cf. Figure 7a), the larger will be the radial displacement of the bored profile u_b and therefore the lesser will be the thickness of the backfilling d_b. In the extreme case of Figure 7c, where the convergence u_b uses up the available space ΔR_l at a certain distance $\lambda^* \leq \lambda$ behind the shield, backfilling is no longer possible. It should be noted that a delayed backfilling might also be problematic with respect to the thrust force that the segmental lining can accommodate. In fact, as already stated in Section 2, an improper bedding of the segmental lining reduces its bearing capacity in case of eccentric loading and this may limit the effectively available thrust force and slow down the TBM advance.
A faster TBM advance results, as a rule, in smaller ground deformations in the machine area [8]. However, in adverse ground conditions it is generally more difficult to maintain a fast TBM advance. For example, a high ground pressure may lead to an overstressing of the segmental lining, thus necessitating repair work that may cause standstills and, consequently, reduce the advance rate. Furthermore, if the segmental lining near the TBM is subjected to a loading close to its bearing capacity, it may be impossible to utilise the full installed thrust force of the TBM, if required, and the TBM may become jammed.

3.2 Backfilling with grouting via the shield tail

Immediate backfilling with grouting via the shield tail is rather rare in rock tunnelling. Basically, the same factors apply as in Section 3.1, the main difference being the parameter λ, which becomes equal to zero (Figure 8). Consequently, the thickness of the backfilling d_b is governed by the radial displacement u_b of the bored profile at the shield tail and this displacement is limited by the overcut ΔR. In contrast to the case of "backfilling with pea gravel and mortar", where rapidly converging ground may make annulus backfilling impossible, the thickness of the backfilling layer is at least equal here to the radius difference between the lining extrados and the shield extrados:

$$d_b = \Delta R_l - u_b \geq d_s + t_s \ , \tag{4}$$

where

$$0 \leq u_b \leq \Delta R \tag{5}$$

and, as before, the deformations of the segmental lining and the shield are disregarded.
Another difference to the case of backfilling with pea gravel and mortar concerns longitudinal arching between segmental lining and ground ahead the tunnel face (cf. Figure 4). This effect is more pronounced here, as the segmental lining begins to support the ground at a shorter distance behind the tunnel face. This is particularly true if a rapidly hardening mortar is used, because the backfilling and the segmental lining then constitute a stiff system right from the start.

4. DECISION AIDS

According to Section 3, a realistic computation of the ground pressure acting upon a segmental lining requires an advanced computational model which takes due account of the actual thickness of the backfilling. This is a demanding problem, because the thickness of the backfilling is not known a priori but depends on the intensity of squeezing, i.e., on the deformations of the bored profile between the tunnel face and the location of the backfill installation. As shown in [9], the non-linearity of the problem can be handled efficiently by applying an iterative procedure specifically developed for the problem under investigation.
The efficiency of the computational model has been exploited in [9] by carrying out a comprehensive parametric study into the ground pressure acting upon a segmental lining. The results of the computations are presented in the form of dimensionless design charts. These nomograms cover the relevant range of ground parameters and initial stress, as well as different characteristics of the TBM, the segmental lining and the backfilling (type and location) and allow a quick preliminary assessment to be made of the loading of a segmental lining. They represent, together with the nomograms presented in [6] for the fast estimation of the thrust force required, a set of decision aids worked out at the ETH Zurich for the planning of TBM drives in squeezing ground [4].
In general, the radial loading developing upon a segmental lining depends on the material constants of the ground (E, ν, f_c, φ and ψ), on the initial stress (σ_0), on the characteristics of the TBM (boring radius R, radial gap size ΔR, shield length L and stiffness K_s) and on the characteristics of the backfilled segmental lining (stiffness K_l, radial gap size ΔR_l and location of backfilling λ). Due to the high number of parameters affecting the ground pressure p, a trade-off was necessary between the completeness of the parametric study and the cost of computation and data processing. A discussion

of the underlying assumptions, as well as a detailed description of the computational model and procedure, can be found in [9].

Figure 9 shows, by way of example, one of a total of 45 dimensionless nomograms. This nomogram apply to a segmental lining that is completely backfilled with pea gravel and mortar at a distance of half a boring diameter behind the shield. Each nomogram applies to a different pair of values (λ/R, K_lR/E) – describing the location where the backfilling occurs and the stiffness of the segmental lining, respectively – and to different values of the angle of internal friction φ and of the dilatancy angle ψ. The curves of each nomograms show the normalized ground pressure p/σ_0 as a function of the dimensionless parameter $(E/\sigma_0)(\Delta R/R)$ and of the normalized uniaxial compressive strength f_c/σ_0. Other parameters (ν, K_sR/E, L/R and $\Delta R_l/\Delta R$) have been kept constant, either because their influence on the normalized ground pressure p/σ_0 can be disregarded or because a conservative assumption has been made.

It should be mentioned that the nomograms of [9] were developed for single shielded TBMs but can also be applied to double shielded TBMs provided that the radial gap size of the rear shield is taken into account in the computations (instead of the radial gap size of the single shield ΔR).

The usefulness of the nomograms will be demonstrated by means of an application example concerning the hypothetical case of a tunnel with an overburden of H = 400 m crossing weak ground (E = 1000 MPa, f_c = 4 MPa, φ = 25 °, γ = 25 kN/m^3). The boring diameter is equal to 10 m (R = 5 m) and the shield 10 m long. The segmental lining has a thickness of d_l = 45 cm (E_l = 30 GPa, $f_{c,l}$ = 30 MPa) and has a radial gap size of ΔR_l = 15 cm. Backfilling is planned 5 m behind the shield (λ = 5 m).

The first step is to choose the nomograms to be used. For the example under consideration, λ/R = 1 and K_lR/E = 2.7 ≈ 3 ($K_l = E_ld_l/R^2$ = 480 MPa/m). Considering that φ = 25 °, in this example the nomogram of Figure 9 can be applied (otherwise, the use of another nomogram or a linear interpolation between different nomograms would be necessary). A further step is the calculation of the dimensionless parameter $E\Delta R/\sigma_0R$. In this example, $E\Delta R/\sigma_0R$ = 1 ($\Delta R = \Delta R_l/3$ = 5 cm, $\sigma_0 = H\gamma$ = 10 MPa). The appropriate curve has to be selected according to the actual value of the normalized uniaxial compressive strength. In this example, f_c/σ_0 = 0.2. As can be seen from Figure 9, for these parameters, the normalized ground pressure p/σ_0 amounts to 0.21 and, therefore, the loading p of the segmental lining is equal to 2.1 MPa. Assuming that the bearing capacity p_{max} of the segmental lining is equal to $f_{c,l}\, d_l\, /R$ (i.e., 2.7 MPa), the safety factor p_{max}/p is equal to 1.3.

Other calculations can be carried out very quickly in the same way, thus allowing, for example, a fast sensitivity analysis to be made, in order to identify the critical geotechnical conditions with respect to a given set of design criteria and problem parameters, as the intensity of squeezing may vary significantly along a tunnel alignment.

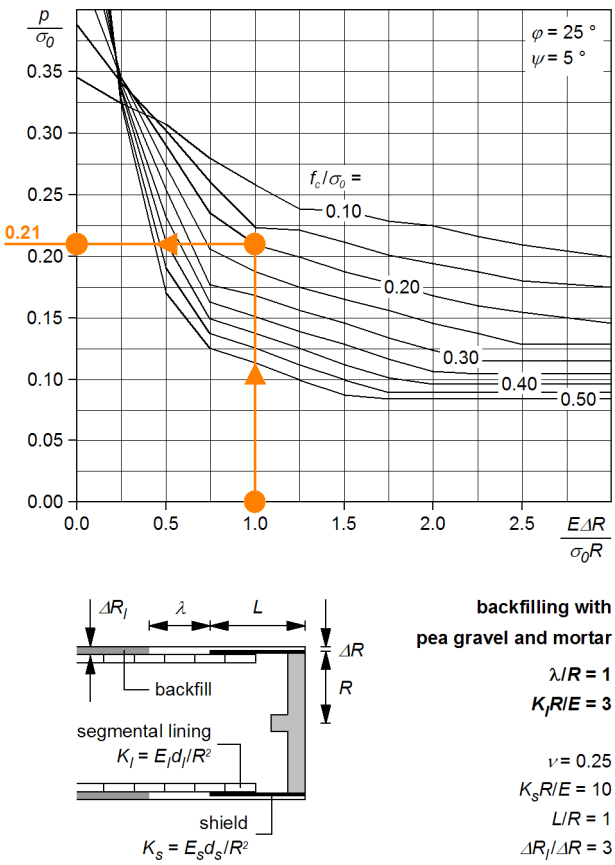


Figure 9. Nomogram for the determination of the segmental lining load p [9].

5. CONCLUSIONS

For reasons explained in Section 2, standard, practically rigid segmental linings seem to be more appropriate at least for moderate depths of cover, while deformable lining systems may be advantageous in deep tunnels crossing fair quality rock.

For the application of practically rigid segmental linings, a reliable estimation of the ground pressure to be accommodated is very important, in order to avoid overstressing. This requires advanced computational models which have been specifically developed for this purpose and which take due account of the backfilling features (type, location and thickness). The problem is very demanding because the thickness of the backfilling is not known a priori, as it depends on the ground deformations.

Therefore, the design charts provided in [9] and briefly illustrated in Section 4 represent a valuable contribution to decision-making in the planning phase, as they allow quick and easy preliminary estimates to be made of the segmental lining loading.

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