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Geotechnical Model for Pipe Roof Supports in Tunneling

G.M. Volkmann
ALWAG Tunnelausbau GesmbH, Austria

W. Schubert
Graz University of Technology, Institute for Rock Mechanics and Tunneling, Austria

ABSTRACT: Pipe Roof Support systems are increasingly being used in weak ground tunneling although the design is often only based on experience. The results of an intensive measurement campaign, including settlement measurements ahead of the face, were used to determine a geotechnical model for this pre-support system. The measured ground-support interaction was reproduced utilizing three-dimensional numerical calculations with FLAC-3D. This study confirmed the model created by the in situ data and clarified the influence of the design parameters on both the supporting effect and the ability to control displacements. This enables a more informed decision in the design stage on whether a Pipe Roof System or more cost- and time-consuming support systems must be used to guarantee the project requirements during construction.

1 INTRODUCTION

The increasing population in metropolitan areas requires a concomitant upgrade of the infrastructure. The majority of the infrastructure is located subterranean, especially in congested urban areas. Due to the pre-existing structures on the surface, the construction of new projects is subjected to specific restrictions such as subsidence and/or noise limitations during construction. In urban areas, the ground generally consists of sedimentary soil and/or highly weathered rock mass. Both types of ground can be associated with major displacements during tunneling. In these cases, the project limitations control the entire design process, as compliance with the design requirements may require time and cost intensive additional support systems including ground freezing, jet grouted columns or pipe jacking.

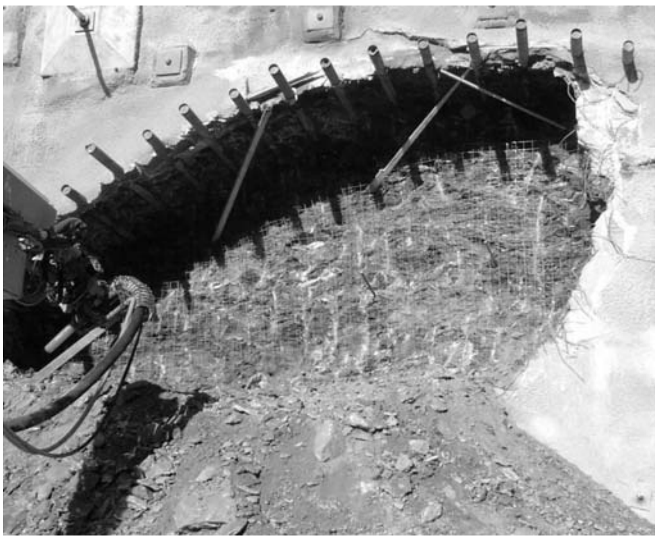

Figure 1. West portal of the Birgl tunnel (AUSTRIA) supported by a pipe roof

An alternative support system is the "Pipe Roof Umbrella" System, which is also referred to in literature as "Steel Pipe Umbrella" (Oreste & Peila 1998), "Umbrella Arch Method" (Kim et al. 1996), "Pipe Fore-Pole Umbrella" (Hoek, 2003), "Long-Span Steel Pipe Fore-Piling" (Miura, 2003) or "Steel Pipe Canopy" (Gibbs et al. 2002). Compared to this system the previously mentioned pre-support systems are stiffer but pipe roof systems are less time and cost intensive. These facts have led to an increase in the use of the pipe roof method without an accompanying increase in the knowledge about the ground support interaction associated with this system.

In order to obtain a better understanding of this support system in situ measurements, using inclinometer chains installed parallel to the pipe roof support, were performed. The measurements of the inclinometer chain were linked to the geodetical displacement measurements taken inside the tunnel and on the surface. These measurements display the longitudinal distribution as well as the magnitudes of settlements in the crown level of the tunnel (Volkmann et al. 2003). The outcome was a geotechnical model for pipe roof systems.

Additional laboratory investigations on the ground and the pipes were performed in order to obtain their strength- and stiffness parameters. Both the geotechnical model and the parameters, describing the behavior of the applied materials, were used for the numerical investigations.

2 TYPES AND DEFINITIONS

The pipe umbrella system is one among the group of pre-support systems. The terminology for pre-support systems is not clearly defined and in order to avoid confusion with other systems a brief description is given below.

The aforementioned terms are simply descriptions of the system itself. Steel pipes, and sometimes fiberglass pipes, are installed from the actual tunnel face to the front (fore-poling system) arranged like an umbrella or a canopy around the area to be excavated (Figure 1).

The diameter of the steel pipes is usually between 60 mm and 200 mm with a wall thickness of 4 mm to 8 mm. The length of one umbrella is generally 12 m or 15 m. The excavated length underneath (length of a pipe roof field) ranges from 6 m to 12 m. When the end of a pipe roof field is reached, there is still a part of the pipe remaining in the ground ahead of the face. This length is called the "overlapping length" of the pipe roof system.

3 SYSTEM BEHAVIOR

The observation and the interpretation of movements caused by tunneling is one of the principles when using the New Austrian Tunneling Method (NATM) (Rabcewicz 1944, Rabcewicz 1975). The observations and their interpretation are used to control the ground support interaction. Specific evaluation techniques allow changes in the ground conditions in front of the face to be predicted (Steindorfer & Schubert 1997). The support system is continuously adapted to the actual ground conditions encountered during tunneling, leading to an economical construction progress. This is possible as the measurements represent the ground-support interaction and not the ground or the support reaction separately. The observed interaction is commonly referred to as System Behavior (Goricki 2003, ÖGG 2001).

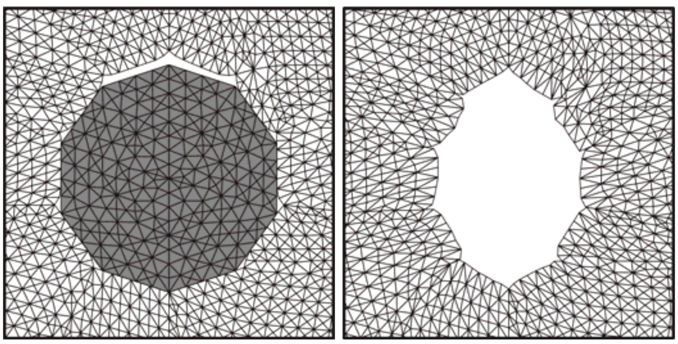

Figure 2. Result of a numerical study in UDEC on the deformation characteristic of the cased drilling system (left) and the pre-drilling system (right) (Volkmann & Schubert 2006)

The main problem with developing the geotechnical model for pre-support systems is that the geodetical survey only measures the system behavior in the already supported section of a tunnel, while the pre-support systems primarily influences the system behavior ahead of the supported tunnel. The observation of the system behavior, influenced by a pipe roof system, was enabled by performing measurements with horizontal inclinometer chains, installed in the tunnel crown.

4 MEASURED BEHAVIOR

4.1 *Installation*

Conventional drill jumbos or special machines can be used to install the pipes. From the geotechnical point of view, there are two different methods for the installation: the pre-drilling system and the cased-drilling system. The significant difference is, when using the cased-drilling system the pipe follows directly behind the drilling bit providing immediate support for the installation hole. When using a pre-drilling system, the hole for the installation is drilled first and in a 2nd step the pipe is installed in the unsupported hole. In weak ground a pre-drilling system has a higher risk for settlements than a cased-drilling system (Figure 2) (Volkmann 2004).

In weaker ground the stress transfer related to the drilling of the installation holes may cause the closure of the annular gap between the ground and the pipes before the excavation under the pipe roof starts. However this closure does not result in any significant pre-stressing and hence the internal forces of the pipes are still practically zero. The initial loadings are not influenced by the method used to remove drill cuttings; water or air. However, one must considered that the use of water, when flushed through the annular gap and not within the pipe, may result in a decrease in the engineering performance of the ground. Additionally, the installed fan of pipes operates as a drainage system until the pipes are grouted (Sellner 2005).

4.2 *The first meters*

The space that is needed for the installation of the next pipe roof fan requires a constant widening of the profile during the excavation of a pipe roof field. The new installation generates a ring of shotcrete at the end, respectively the beginning of every pipe roof field. During the excavation of the first 1 to 3 rounds after the installation, the inclinometer measurements displayed smaller settlement magnitudes. This observation is explained by the stiff shotcrete arch that creates a foundation for the longitudinal arching effect during stress transfer processes.

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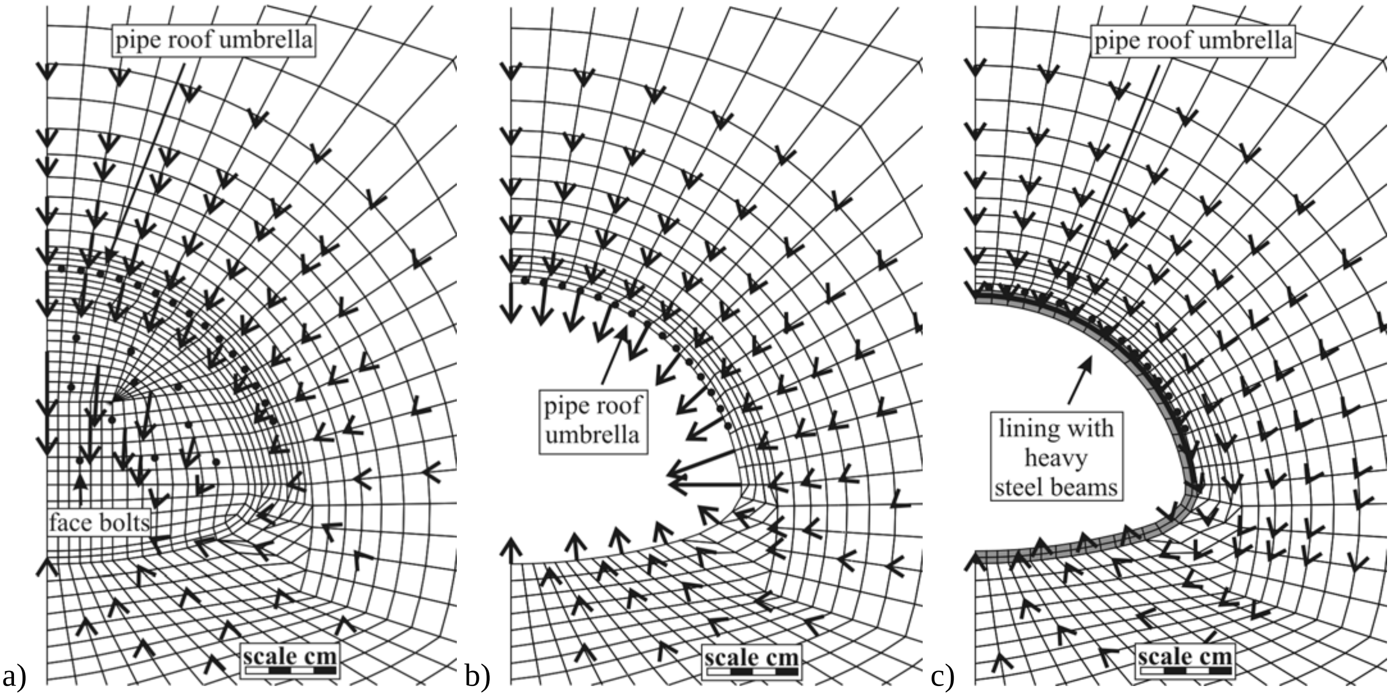

Figure 3. Three cross sections displaying the displacement vectors normal to the tunnel axis; a) 2 m ahead of the face, b) in the unsupported span, c) 2 m backwards in the supported section (one excavation round only).

4.3 *Normal excavation rounds*

The foundation effect of the stiffer shotcrete ring disappears with distance. The data from two case histories display that the following rounds of excavation induce a uniform settlement characteristic. This characteristic contains the magnitudes and positions of the measured settlement values relative to the face and the three-dimensional behavior in the already supported sections (Figure 4 for example). It depends on the strength- and stiffness contrasts between the ground and the installed support.

4.4 *Last meters*

Depending on the ground quality and the height of the tunnel, the effectiveness of the pipe roof foundation ahead of the face decreases with decreasing length. This decrease in effectiveness is associated with an increase of the settlements ahead of the face. Therefore, when the pipe roof support system is used to minimize displacements caused by the excavation a new pipe roof should be installed before the foundation effectiveness decreases. When the pipe roof system is only applied to increase the stability of the unsupported span, it is no problem to excavate further rounds as long as the stability of the face is guaranteed.

5 BASIC GROUND DISPLACEMENT

The numerical results shown in the Figures 3a, 3b, 3c, and 4 are calculated with the program “Fast Lagrangian Analysis of Continua in three dimensions” (FLAC-3D). The geometric conditions, used for this example, simplify those from the project Trojane tunnel (Slovenia). The selected section, with a crown cover of 15.0 m, was supported by a pipe roof system to help minimize surface displacements within a major fault zone (UCS << 1.0 MPa) where distress to surface structures had been observed. The input parameters were determined by laboratory tests (ground, pipes); as well as taken from literature (ground, shotcrete) (Zlender 2003, Aldrian 1991, Müller 2001). Further information on these calculations can be found in Volkmann et al. 2006. The displacements displayed in the Figures 3a, 3b, 3c, and 4 result from excavating only one 1.0 m long excavation round.

5.1 *Radial displacements*

The displayed cross sections are 2.0 m ahead of the face (Figure 3a), in the middle of the unsupported span (Figure 3b), and 2.0 m backwards in the supported section (Figure 3c). All three figures display that the orientation of the incremental displacement is almost normal to the shape of the tunnel in the area where the pipe roof is installed.

The maximum displacement vector in Figure 3a is about 3.0 cm but is situated in the area excavated later. The maximum displacement in the zone where the pipes are installed is 2.1 cm.

The displacement vectors in the unsupported span (Figure 3b) have nearly the same magnitude (2.0 cm) and are practically uniform around the upper section of the tunnel perimeter. The displacements only increase to 3.3 cm in the region below the installed pipes (lower sidewall).

Due to the very stiff support system in the supported section behind the face, the displacements

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decrease to 0.5 cm only 2.0 m behind the unsupported span (Figure 3c).

5.2 *Distribution of displacements in the longitudinal direction*

Elastic numerical calculations normally result in 30 % of the total displacements ahead of the face (Steindorfer 1998). When the stress level is higher than the strength of the ground near the tunnel the displacement distribution changes considerably, resulting in significantly higher displacements ahead of the tunnel face. The strength weakening characteristics of the material associated with the post peak behavior control these changes. This fact agrees with the measured data from the Trojane tunnel where up to 80% of the total displacements occurred ahead of the supported section in the tunnel.

Figure 4 exemplifies a calculated displacement distribution in the longitudinal section. The calculated values increase to 2.5 cm approximately 1.0 m ahead of the face while the displacement vectors in the supported section are lower than 0.5 cm. The settlement values start decreasing with distance to the face ahead of the position where the maximum amount occurs.

This example displays that the displacements are orientated against the excavation direction in the sections ahead of the face, except the last 2.0 m ahead of the face. This area moves vertically or slightly in the excavation direction. In the unsupported span and in the first supported meter the displacements are orientated towards the face. The previously supported region again displaces against the excavation.

6 GEOTECHNICAL BEHAVIOR

The internal forces of the pipes are almost zero after the installation, comparable other passive support measures (rock bolts). The stress transfer, due

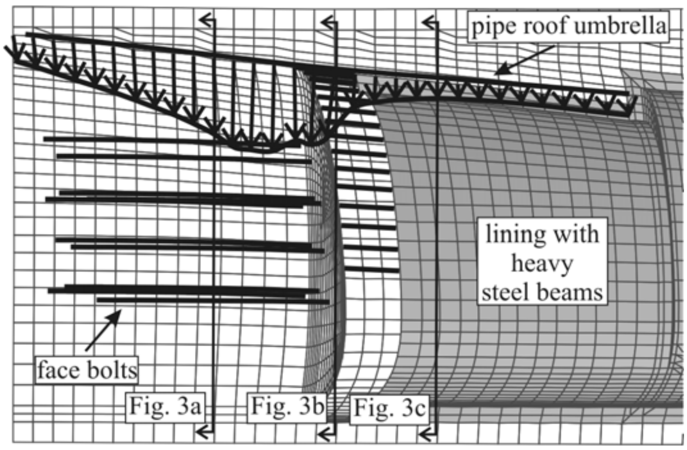

Figure 4. This longitudinal section displays the vertical and longitudinal displacements in the crown (one excavation round only).

to the previous excavation steps, has an influence on the ground and on the already installed support. The newly installed pipes are not affected by previous activities, whereas every construction process after the installation that causes a stress transfer starts to activate the supporting effect of the pipes. The displacements mainly develop by the excavation process during tunneling so the three-dimensional displacement characteristic rules control the activation of the supporting effect after the installation of the pipe roof.

Each pipe is founded in the ground (ahead of the face) as well as on the lining (behind the face) in the longitudinal- and radial direction. The strength and stiffness of the pipe roof therefore depend on both the ground properties as well as on the time dependent strength and stiffness properties of the lining (shotcrete, steel beams).

6.1 *Radial supporting effect*

Figure 5 displays the calculated result of the ground pipe interaction after every 2nd excavation step. The pipes bend primarily at two positions with ongoing excavation steps under the pipe roof as long as the pipe foundation effectiveness does not decrease ahead of the face. One position in this example is 3.0 m ahead of the face. The second one is 1.0 m behind the face. These sections indicate the positions where the pipes operate as support and where the pipes transfer the loads to the ground and the lining. The supported section is between chainage 47.0 and 50 (for bottom line) while on both ends of this area the loads are transferred to the foundation regions. The position ahead of the face corresponds to the orientation change of the displacements in Figure 4. The loads are only transferred in the longitudinal direction and the pipe roof support does not create any arching normal to the tunnel axis. It is therefore necessary to model each pipe individually in the numerical simulation; because in numerical calculations both a stiffer homogenized region as well as the use of shell elements would additionally cause an arch effect normal to the tunnel axis. Both simplifications could lead to an underestimation of the displacements and/or to an overestimation of the stability conditions.

This pipe roof supporting effect is affected by the bending of the pipes so the second moment of the area defines the activation speed of the supporting effect by bending. Pipes with a larger diameter activate the supporting effect faster at similar displacements compared to smaller diameters. The pipe wall thickness, on the other hand, defines the critical moment alternatively the maximum bending.

This example displays that a pipe roof system supports the face region, the unsupported span, and sometimes a short zone at the beginning of the lining (fast excavation). The supporting effect decreases in

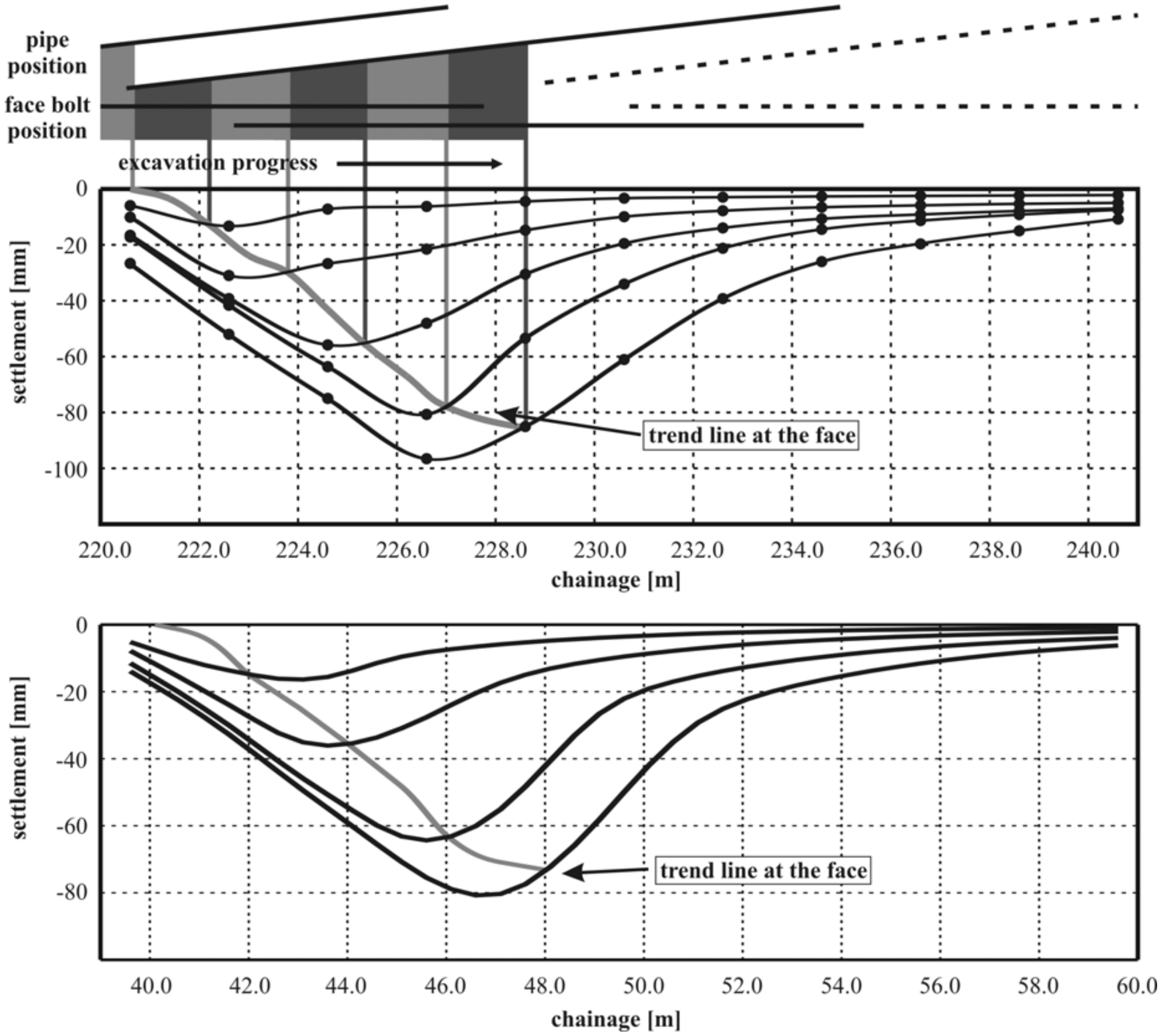

Figure 5. This deflection curve diagrams display measured settlement values from the Trojane tunnel (upper diagram) and results of a three-dimensional numerical calculation (lower diagram) after every 2nd excavation round.

these critical sections the risk against possible local or global failures associated with the tunnel face.

6.2 *Longitudinal supporting effect*

The stiffness of a steel pipe is much higher compared to the stiffness of ground that needs additional support by a pipe roof system during tunneling. The relative movements in the longitudinal direction therefore create a second supporting effect of pipe roof systems during excavation. The pipes are subjected to longitudinal compression. This influences the stress distribution ahead of the face positively so the displacements in the ground decrease ahead of the face.

This effect is affected by the area that can be used for the transfer of interaction forces so the outer pipe diameter defines the effectiveness of this supporting effect.

6.3 *Pipe gap in the unsupported span*

Both previously mentioned support effects are also influenced by the number of pipes. This design parameter and the diameter of the pipes define the remaining gap in between the pipe roof pipes. A local arching effect in between the pipes (Stöckl 2002) increases the stability in the unsupported span and decreases the overbreak volume as long as this local arch can be formed.

A comparison of calculated results can be found in Volkmann & Schubert 2006. Those results display both the effect of larger pipe diameters and different numbers of pipes on the displacement characteristic.

6.4 *Validation of numerical results*

Complex three-dimensional numerical calculations are influenced by all input parameters. These include geometric conditions, material properties, installed support systems, and time dependent changes of strength- and stiffness properties.

The comparison of the measured and calculated displacements (Figure 5) for this case history displays good agreement ahead of the face, in the unsupported and supported sections. This fact provides evidence that the relevant mechanisms, which occurred during the excavation of the Trojane tunnel, could be reproduced in the numerical calculations.

7 CONCLUSION

The advantages of being cheap and less time consuming during the installation, increased the use of Pipe Roof Support systems over the last decades even though neither formulas nor clear rules for the design of this pre-support system were determined. An intensive monitoring campaign, including settlement measurements ahead of the face at the tunnel level, enabled the determination of the geotechnical model for this support system. Using this knowledge design parameters of the Pipe Roof System were investigated in numerical calculations.

The results of the numerical investigations demonstrate that the pipe roof system supports the critical section around the heading by transferring the radial loads to both the ground in the front as well as the lining in the supported section. This support effect increases the safety in the working area against local or global failures.

Compared to the stiffness of the ground, the high stiffness of the steel pipes influences the stress distribution positively ahead of the supported section. This effect and the radial support around the heading decrease the settlement amounts.

Numerical calculations enable the adaptation of the pipe roof support system by a knowledge-based change of the design parameters: overlapping length, pipe dimensions, and number of pipes. So the calculated system behavior can be optimized with respect to the project requirements.

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