THE PIPE UMBRELLA SUPPORT SYSTEM - AN OVERVIEW

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INTRODUCTION

The increasing population in metropolitan areas requires an associated upgrade of the infrastructure. A major part of this infrastructure is located underground, especially in congested urban areas. Regional infrastructure projects also include essential tunnel sections. A safe and economic construction is always desirable, which often results in cost-intensive and time-consuming pre-support methods such as ground freezing or jet-grouting to protect surrounding infrastructure from excavation-induced damage.

Over the last decades, technological developments have led to an increased use of the so-called "Pipe Umbrella Support 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). The support concept perfectly fills the gap between conventional spiling (short forepoling) and cost-intensive pre-support systems such as ground freezing or jet-grouting techniques. This method of supporting potentially unstable ground ahead of the face and in the working area provides a high degree of flexibility as well as safety related to the excavation process, and can be easily adapted to the encountered conditions.

DEFINITIONS / STATE OF THE ART

In their book "Tunneling with Steel Support", Proctor & White (1964) discussed the use of wooden "spiles" as a forepoling method for traversing weak and ravelling ground. Since this time several slightly different concepts have evolved, all with the goal of providing additional support above and directly in front of the heading to minimize instabilities. Concurrent with the technical adaptations the terminology has also evolved but some pre-support methods are not distinguished from each other by clear definitions or different names are used for the same system. There are 5 primary concepts of pre-support technology installed from the tunnel that are utilized in modern tunnelling:

- The simplest forepoling method is the installation of spiles from the last arch to the face before the excavation takes place. Normally spiles have diameters up to 50 mm (rock bolts or tubes) and are either pushed or drilled into the ground at the perimeter of the later excavated tunnel with minimal spacing (figure 1). Spiles usually have a length of 3 m to 4 m and are used to suppress local failures in the just excavated span by their shear resistance. This system is in general called forepoling, while the term spiling is commonly used in German speaking countries.
- Pipes with a diameter lower than 200 mm (not exactly defined) can be installed using either special machines (e.g. Cassegrande drilling rigs) or a normal drill jumbo. This system requires the widening of the cross section resulting in a saw tooth shaped profile. Their lengths can vary, but they are typically 12 m, 15 m or 18 m long. After grouting the inner annulus and the annular gap the excavation advances under the supporting pipes. This system is named differently worldwide as mentioned above.

Figure 1. Spiles installed through the lattice girder to the face in every excavation step.

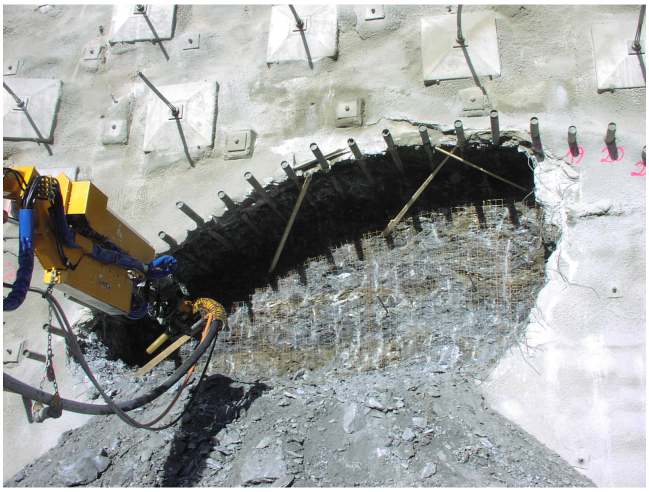

Figure 2. Pipe umbrella support system at a portal situation (Birgl tunnel, Austria).

- Pipes with a diameter up to 1 m or 2 m can be drilled with special equipment or installed with micro-TBMs, on the outer side of the designed excavation profile from a starting shaft. After filling them with grout the excavation can be done under a very stiff supporting umbrella - mostly called pipe roof support.
- Jet grouted columns installed from the tunnel can be used to create a canopy surrounding the excavation profile. These columns can be either overlapping, creating a closed often watertight canopy, or non-overlapping.
- Freezing of the ground is the most costly and time intensive pre-support method. Using this system the ground water is used to produce an ice-umbrella acting as support for the following excavation.

As previously mentioned the support concept of pipe umbrella systems perfectly fills the gap between the simple and short forepoles and the more complex pre-support concepts. Due to that fact and due to the technological developments pipe umbrella support systems evolved from a special measure to a conventional measure in tunnelling. Since that happened, this support system is not only used to drive through difficult fault zones but it is also commonly used in urban areas to decrease subsidence and increase the safety or as additional measure at tunnel portals (figure 2) where the stress situation is always ambiguous.

Current trends indicate that measures such as pipe umbrella systems are more often used in mechanized tunnelling and are commonly considered during the design stage. For this application the pipe umbrella system has been expanded beyond its original version using steel tubes. Here steel tubes are often combined with drainage pipes or GRP-pipes. This opens additional options to improve, drain and support the ground around and ahead of the later TBM excavation.

GEOTECHNICAL BEHAVIOR

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 second step, the pipe is installed in the unsupported hole (Volkmann 2004).

The internal forces of the pipes are almost zero after the installation, comparable with other passive support measures (rock bolts). The stress transfer, due to the previous excavation steps, has an influence on the ground and on the previously 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 support effect of the pipes. The displacements are mainly caused by the excavation process during tunnelling so the three-dimensional displacement characteristic control the activation of the support effect after the installation of the pipe umbrella.

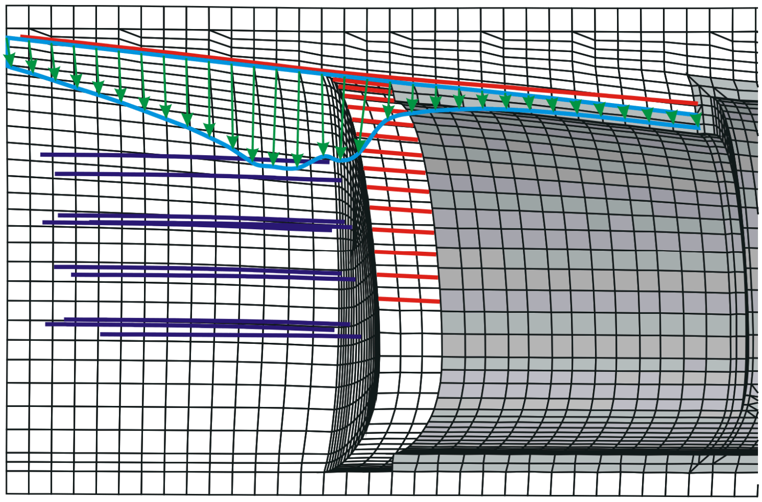

Figure 3. This longitudinal section displays the vertical and longitudinal displacements in the crown (one excavation round only).

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 support effect of the pipe umbrella therefore depends on both the ground properties as well as on the time dependent strength and stiffness properties of the lining (shotcrete, steel beams). Figure 3 shows the vertical deformations in the roof section of one excavation round in an ideal back calculation. The on-site measurements show similar results for each single excavation round – a typical deformation characteristic in weak ground tunnelling supported by pipe umbrellas. Because of the good correlation between on-site measurements and numerical calculations (figure 4) the following support effects can be concluded as quoted in Volkmann and Schubert (2007).

Pipe gap in the unsupported span

The axial distance of the pipes and the diameter of the pipes define the remaining gap between the pipe umbrella pipes. A local arching effect 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.

Radial support effect

The pipes bend primarily at two positions with on-going excavation under the pipe umbrella. One position is about 3 m to 5 m ahead of the face. The second one is about 1 m to 2 m behind the face. These sections indicate the positions where the pipes transfer the loads to the ground and the lining. In between the pipes are loaded. The loads are only transferred in the longitudinal direction and the pipe umbrella support does not create any arching perpendicular 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 perpendicular to the tunnel axis (Volkmann et al. 2006). Both simplifications could lead to an underestimation of the displacements and/or to an overestimation of the stability conditions.

A pipe umbrella system therefore supports the face region, the unsupported span, and sometimes a short zone at the beginning of the lining. The support effect decreases the risk of possible failures associated with the tunnel face in these critical sections.

Longitudinal support effect

The stiffness of a steel pipe is much higher than the stiffness of ground that needs additional support by a pipe roof system during tunnelling. The relative movements in the longitudinal direction

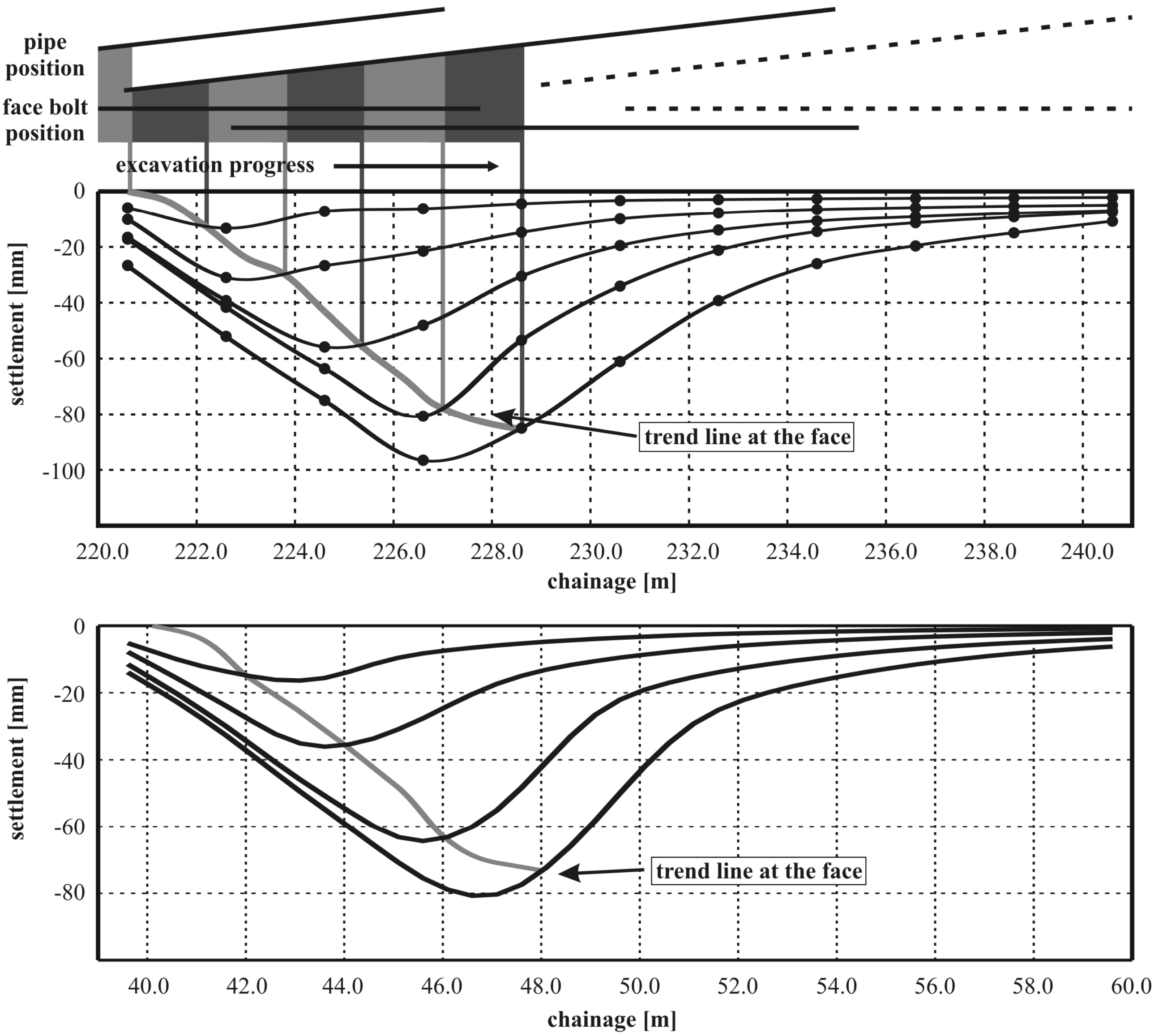

Figure 4. This deflection curve diagrams demonstrate measured settlement values from the Trojane tunnel (upper diagram) and results of a three-dimensional numerical calculation (lower diagram) after every second excavation round.

therefore create a third support 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.

Main design parameters

To achieve stability the first design parameter is the axial distance in between the installed pipes. Due to the saw tooth shaped profile the relevant point for the design is at the end of the pipe umbrella field where the next pipe umbrella is installed. This distance is determined such that the ground can create local arches between the pipes.

Depending on the expected loads and the supported span the structural properties (outer diameter and wall thickness) of the pipes must be chosen. The bending of the pipes creates the radial support effect so the second moment of the area defines the activation speed of the support effect by bending. Pipes with a larger diameter activate a more powerful support effect at similar

displacements compared to smaller diameters. The pipe wall thickness, on the other hand, defines the critical moment and/or the maximum bending.
Last but not least the overlap in the longitudinal direction must be determined. This value is dependent on the ground conditions, the height of the front excavation, the stability conditions of the face and additional measures like face bolts or a face stabilisation wedge.

ADDITIONAL POINTS FOR TENDER DOCUMENTS

Installation method

As mentioned above pipe umbrella systems can be installed by the pre-drilling as well as the cased-drilling method. The weaker the ground gets the more important it is to define the installation method because even the small holes for the pipes create deformations similar to a tunnel.
The development of settlements was observed on site during installation for both methods in comparable ground conditions (Volkmann & Schubert, 2006). Figure 5 presents the results of the horizontal inclinometer measurements. Each line in these diagrams presents the measured settlements after the installation of a finished pipe umbrella. The installations performed with the cased drilling system induce small settlements. The results for the pre-drilling system vary dependent on the ground conditions observed during the following excavation and show values of 30 mm to 40 mm.
The difference in the observed settlements is mainly caused by the stress redistribution due to drilling holes for the pipes. The pipe that follows immediately behind the drill bit supports the drill hole from closing, while the deformations occur unhampered in pre-drilled holes. Consequently as soon as subsidence rules the design a cased-drilling method should be defined in the tender documents for weak ground conditions.

Pipe Couplings

When installing a pipe umbrella with conventional jumbos the pipes are installed piece by piece and connected to each other on the boom before drilling. The quality of this connection has an important influence on the bearing capacity of the system. The tests of grouted samples with standard thread connections (red) identified this usually used connection type as the weakest link in pipe umbrella pipes (figure 6). The picture in figure 6 at the bottom shows this connection type after failure in the bending test. The flexural strength and the failure load are lower, compared to the test result of the regular pipe (black).
This induces a reduction in the performance of pipe umbrella support systems during tunnelling. A new connection type called "threaded nipple coupling" was developed to solve this problem. This connection type (green) shows a comparable flexural strength to the grouted regular pipe and a higher load at rupture. This connection compensates the weakest link and increases the

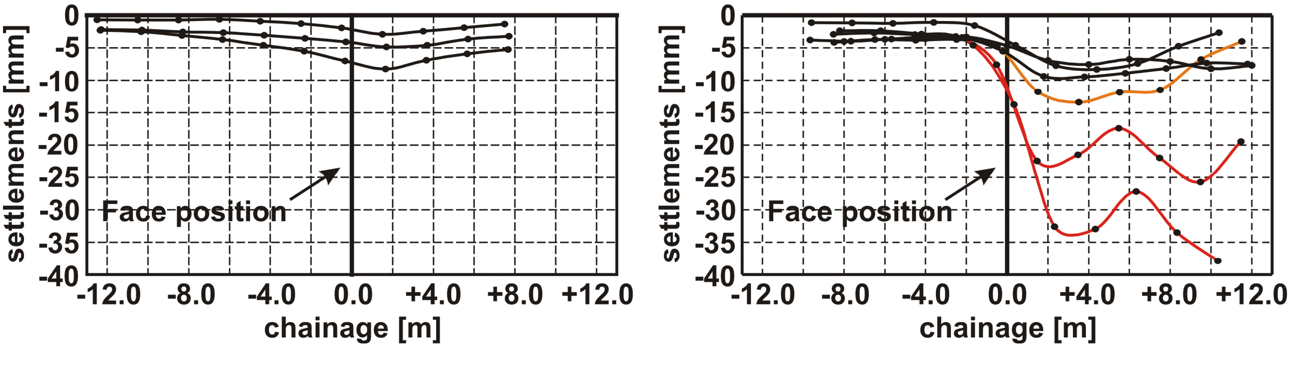

Figure 5. Measured settlements during pipe umbrella installations by the cased-drilling (left) and the pre-drilling method (right)

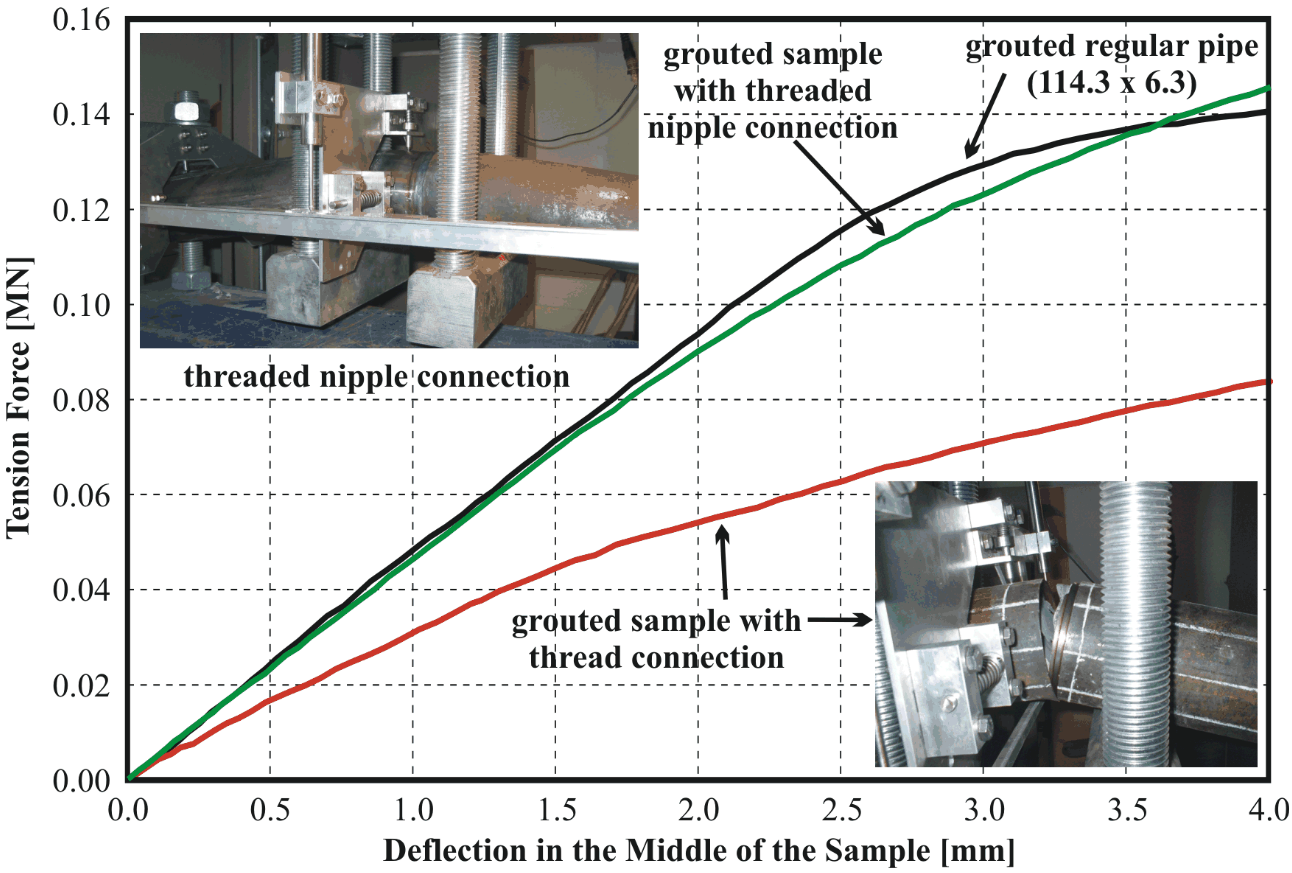

Figure 6. Bending test results of different connection types

effectiveness of the pipe umbrella pipes when they are installed piece by piece.
Depending on the design calculations the correct connection type must be specified otherwise workers may be injured.

Drill bit size

The geotechnical mechanisms used to define a maximum drill bit diameter are the same as for preferring a cased- drilling system in weak ground conditions. An oversized drill bit creates a bigger annular gap between the supporting casing pipe and the ground so deformations can be induced in weak ground conditions. These deformations are accompanied by an undesired stress relaxation around the later excavated tunnel section so the drill bit diameter should not be bigger than 1 cm to 1.5 cm of the following pipe.

Flushing method

The flushing method is an important point in weak ground conditions as well. Simply think about drilling a hole; the flushing media gets to the front inside the drill steel, comes out from the drill bit and gets back between the drill rod and the unprotected borehole walls. On the way back the flushing media gets in contact with the ground and transports the cuttings over the entire borehole length during drilling. Firstly, some ground types are sensitive to water, which negatively influences the quality of the later excavated ground. Secondly, the flushing media with the cuttings erodes the borehole walls, which may get more serious in weak ground conditions. By changing the flushing media to air the negative influence on the ground quality disappears but the erosion is still present. The best solution for sensitive ground conditions is the flushing system used by the cased-drilling method. This method flushes inside the casing pipe so the water only comes in contact with the ground at the drill bit's position, influencing the ground's properties in a very limited area without any erosion effects.

APPLICATIONS IN MECHANIZED TUNNELLING

Today, most tunnel metres are excavated by tunnel boring machines and the technical developments in this field have led to machines that can handle most ground conditions without major problems. Recent developments, however, show an increased acceptance of pipe umbrellas in continuous tunnelling. When required by the conditions of the project, special measures like pipe umbrellas are being taken into account during the design phase. Application areas are ground improvement or drainage of fault zones ahead of the TBMs or additional support in cases of instabilities in front of and at the cutting wheel.

In general the installed system is similar but the drilling machinery is not situated directly at the face. It is situated a few metres behind the cutting wheel depending on the machine type. Access to the ground is hampered by the cutting wheel as well as supporting shields so drilling channels must be utilized to install the tubes. The cutting wheel of a TBM is not able to cut and mug steel pipes so it is absolutely necessary that no steel pipe is installed ahead of the cutting wheel. This is basically not a problem because the GRP-system is designed for injection works so it can be applied for all kind of ground improvements in the later tunnel alignment. The application of the drainage system is also not a problem because drainage can also be performed above or under the tunnel alignment so the pipes are drilled outside of the later excavated ground.

Commonly, the pipe umbrella system is not used in combination with mechanized tunnelling because of the steel tubes although it can be used in cases of ground instability ahead of the cutting wheel or when advancing through a fault zone with limited extension in the tunnel alignment. The supporting effects that can be activated are comparable to those activated when using this system in SCL tunnelling. A safe application can be ensured by a combination of the pipe umbrella system and the GRP-system which can be connected by a coupling. In this case the steel pipes are installed first while the last meters are drilled with GRP pipes. This enables the TBM to move ahead after the installation and creates a static pipe umbrella support at the outside of the tunnel alignment that can be used for ground improvement the same way as GRP-systems (Volkmann et al., 2012).

CONCLUSIONS

The advantages of being reasonable regarding material costs and less time consuming during installation increased the use of pipe umbrella support systems over the last few decades. Parallel to this development a monitoring campaign, including settlement measurements ahead of the face at the tunnel level, facilitated the development of the geotechnical model for this support system. Using this knowledge design parameters of the pipe umbrella system were investigated and optimized in numerical calculations.

The results of the numerical and on-site 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 because the risk decreases that failures occur in the working area. Compared to the stiffness of the ground, the high stiffness of the steel pipes additionally influences the stress distribution ahead of the supported section positively. This effect and the radial support around the heading decrease the induced settlement amounts.

A cased drilling system should be used to prevent water saturation and flushing erosion of the ground during installation. For projects with subsidence limitations and strain sensitive ground, this system should also be preferred because the risk for installation induced deformations is lower.

The rapid and uncomplicated installation of pipe umbrella systems combined with the wide scope of application offer uncomplicated solutions in many difficult cases. This will result in an increasing use of pipe umbrellas in the future, both as an additional support measure and combined with grouting for ground improvement, as has already been shown by recent developments.

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