Optimization Potential for Pipe Umbrella Supported Tunnels due to Recent Technical Developments

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Abstract

Pipe umbrella support systems have been used successfully for tunnelling in challenging ground conditions since the 1970's. Due to further developments of drilling machinery, this pre-support system is used at shallow, urban tunnels in weak ground conditions on a regular basis. The umbrella pipes are installed stepwise subparallel to the tunnel alignment by connecting pipes to each other. These connections are the weakest link of the support system so recent developments in this field influence the system performance as well.

Both, the developments of machinery and connection types have a major influence on pipe umbrella design for tunnelling. This does not only include simple parameters like installation length or tube dimension but also connection times or in general installation times. So, a pipe umbrella design five years ago is not very efficient regarding installation and construction time respectively as well as utilized material compared to today's technical possibilities. Supplementing these technical points, a defined grade of mechanization or even automation increases the safety on site as well.

Therefore, this article explains optimization possibilities for pipe umbrella supported tunnels with simple examples to show cost-optimized design principles regarding time and material.

Key words

Pipe Umbrella, Canopy Tube, Umbrella Arch, Installation Length, Squeezed Coupling, Automation,

1 Introduction

Pipe Umbrella systems are categorized in the group of pre-support measures in tunneling. They are predominantly used in soft ground to ensure a safe and stable construction process. Pipes with an outer diameter from 90 to 170 mm are drilled at the outer perimeter of the tunnel from the actual face to the front. These tubes then form an umbrella over the working area during excavation, stabilize the surrounding ground and protect the workers. Typical areas of application are: shallow, urban tunnels; tunnels in fluvial or marine deposits or talus, fault zones, tunnel portals, and the recovery of collapsed tunnel sections.

The support method provides a high degree of flexibility and can be adapted to the encountered conditions. Principles of this method are quite easy, hence the potential regarding optimization possibilities is rarely used even though material costs, construction time, and safety issues are important facts all around the world.

2 Technical Developments

Due to technical developments of drilling machinery over the past decades, the pipe umbrella support method is one of the pre-support concepts that is increasingly used in conventional tunneling and has even been included in TBM support systems. Additionally,

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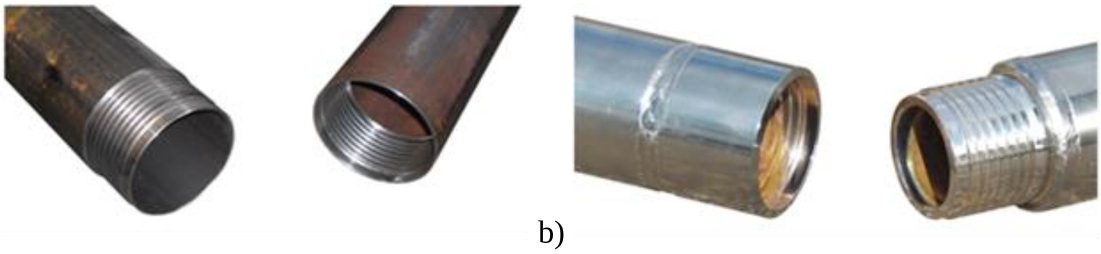
research investigations showed that standard thread connections are the weakest link in the support system (Volkmann & Schubert, 2008).

2.1 Drilling Machines

At the beginning of this support system only special machines installed the support members. In the 1990's further developments of conventional tunnel drilling machines allowed to installed pipes with a certain length as well. Since that time the hydraulics as well as the top hammers of tunnel drilling machines got stronger and quicker. This ensures in today's tunneling, that pipes with an outer diameter of 139.7 mm can be drilled at nearly the same speed as pipes with an outer diameter of 88.9 mm. Due to the same developments, the installation depth could be increase from 9.0 m in the 1990's up to 30.0 m and more nowadays. So, the limiting factor for recurrently installed pipe umbrella support systems is no longer the power of the drilling machine but the accuracy of the pipe alignment after installation. To ensure the necessary accuracy, it can be stated that recurrently installed pipe umbrellas should not be longer than 18.0 m nowadays.

2.2 Pipe Connections

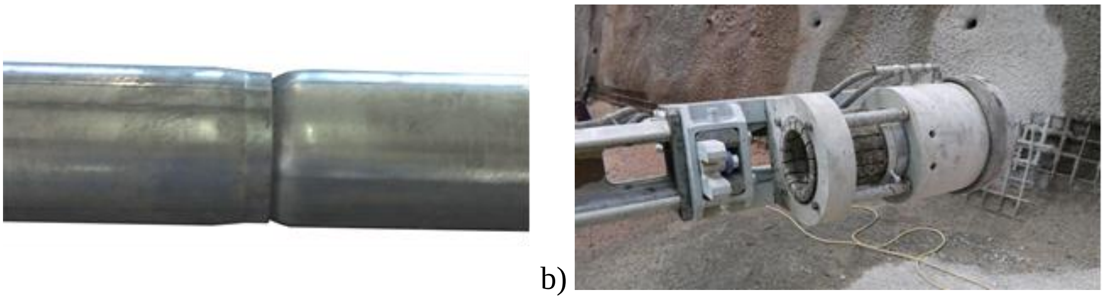
When the pipes are used as pipe umbrella, the bending behavior is crucial, and therefore laboratory tests have been carried out to determine the dominating support properties. The bending tests show the influence of filling grade, injection holes or connections on the load bearing capacity of the pipes (Volkmann, 2017). It turned out that the connection type has a crucial influence on the supporting effect of this support system. Due to this fact new connection types were developed in addition to the standard thread connection, which show differing perfomance characteristics (Volkmann, 2013; Volkmann et al., 2015).
Three different connection types are available on the market these days.
Very common is a **standard threaded connection** (Figure 1). Standard threaded connections are generally not well suited for connecting pipe umbrella pipes. By mechanically removing a certain portion of the steel tube for a thread, the effective cross-section is reduced. This fact drastically decreases the load-bearing capacity and stiffness in the connection area.
As a result of problems when using standard threaded connections during construction, the so called **nipple coupling** (Figure 1) was developed. Nipple connections consist of threaded connection fittings, which are pressed and welded into the ends of standard pipes. This connection type provides an elastic design load as well as stiffness properties equal to an un-weakened pipe.



a) b)

Fig. 1 a) standard threaded connection and b) nipple coupling

The latest development in the field of pipe connections is the **squeezed connection** (Figure 2), this connection type results from the attempt to provide a tough and easy-to-connect alternative to conventional threaded systems. By means of the squeezed connection, non-threaded pipe ends are mechanically connected in terms of force-fitted squeezing using a boom-mounted press (Figure 2).



a) b)

Fig. 2 a) squeezed connection and b) squeezing console mounted on a drill boom

3 Optimizations Potential due to Connection Types

The major difference between the standard threaded connection and the nipple coupling on one side and the squeezed connection on the other is the existence or non-existence of a thread in the connecting section. This difference results in an acceleration of connection time for each connection. The example in Table 1 calculates this advantage in time for the squeezed connection. Here it is assumed that the pipe umbrella support consists of 30 pieces of 12 m long pipes, which are installed in 3 m pieces. A common drilling machine performs the installation with two arms and a basket so only half of the pipes can be taken for calculation because the other half is installed parallel in time. Although this example deals with a relatively short pipe umbrella support the time that can be saved sums up with nearly 2 hrs per installation. So, this difference only results from connecting times necessary for 8 m of tunnel excavation.

Tab. 1 Comparison of cycle times for a threaded connection and a squeezed connection.

Type	**Length of Pipe Umbrella**	**Number of Pipes (half side)**	**Number of Connections**	**Single Connecting Time**	**Single Delay Time ***	**Number of Difficult Connections ***	**Connecting Time**	**Total Delay Time ***	**Total Delay Time**	
	[m]	**[#]**	**[#]**	**[min]**	**[min]**	**[%]**	**[min]**	**[min]**	**[min]**	**[%]**
Standard thread connection	12.0	15	45	3.5	10.0	5	157.5	22.5	180	100
Squeezed connection				1.5	-	-	67.5	0	67.5	37.5
						Time Savings:	**90.0**		**112.5**	**>60.0**

*Experience: 5 % difficult connections (outliers) which require additional handling time

As already mentioned the bending behavior is crucial for the performance of pipe umbrella support systems and its main factor is the mechanical properties of the connection type. The three mentioned connection types result in different strength and stiffness properties in the connecting section but during design, a required elastic bending moment is the result of static calculations. So varying pipe dimensions in combination with different connection types result in the same requested bending moment (Volkmann, 2016).

In table 2 all three connection types are compared with the goal that the resulting elastic bending moment is about 20 kNm. The necessary wall thicknesses differ from 4.0 mm to 10.0 mm. As a result, the inserted material varies with the same factor. When replacing a standard thread connection by a squeezed connection the pipe wall thickness can be decreased from 10.0 mm to 6.3 mm. These pipes safe one third of material resulting in a more economic support design as well as in an easier handling on site during construction.

Tab. 2 Comparison of necessary pipe types including connection types for an elastic moment of ~20.0 kNm

Pipe Type	Coupling Type	W		I		M_{el}*		M_{pl}*	Weight
	[m]	[cm³]	[%]	[cm⁴]	[%]	[kNm]	[%]	[kNm]	[kg/m]
139.7x6.3	squeezed	58.4	100	344.0	100	**20.7**	**100**	>40.0	20.7
139.7x10.0	cut thread	53.6	92	345.3	100	**19.0**	**92**	n/a	32.0
139.7x4.0	nipple	56.2	96	392.8	114	**20.0**	**97**	n/a	13.4

* Values must be proven by the manufacturer with certificates.
M_{el} … maximum bending moment [kNm] in the elastic material range.
M_{pl} … Maximum bending moment [kNm] when using plastic reserves of the steel material.

4 Optimization Potential due to Longer Pipe Umbrellas

Due to the stronger machines the possible installation length changed over the last two decades. At the turn of the millenium a typical pipe umbrella was 12 m long and had a foundation length in the ground of at least 3 m. This results in only 8 m of excavation under one pipe umbrella because pipe length is lost at the installation point etc. Nowadays a pipe umbrella can be installed with a length of 18 m in most ground conditions without any problems. So, 14 m can be excavated under protection of one pipe umbrella.

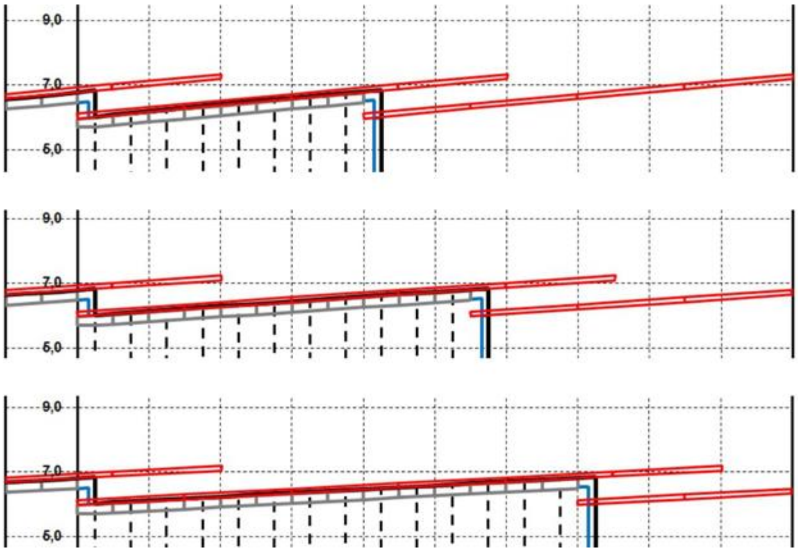


Fig. 3 A longitudinal sketch of 12 m, 15 m, and 18 m pipe umbrellas

As can be seen in Figure 3, the overlap in the longitudinal direction is constant. In this example the axial distances are constant as well, while the parameters shape of sawtooth, pipe length, inclination, and number of excavation steps change. Due to the ratio between installed pipe length and overlapping length, material consumption can be decreased by increasing the installed pipe length. The change from 12 m to 15 m decreases the necessary pipe quantity by nearly 10 % while a change to 18 m results in savings of nearly 15 %, when using a standard threaded connection (139.7 x 10.0). This saving can be combined with a squeezed connection (SC) leading to a smaller pipe dimension (139.7 x 6.3) without losing support performance. In this case 45 % of steel pipe consumption can be saved resulting in 640 kg of steel per running meter of excavated tunnel. Additionally, there is a small decrease of excavated material by the decrease of the saw-tooth profile, which must not be mucked out or refilled by shotcrete.

Tab. 3 Comparison of material for 12 m, 15 m, and 18 m long pipe umbrellas.

Pipe umbrella length	**Excavation length**	**Axial pipe distance**	**Maximum axial distance**	**Pipes installed**	**Pipe per rm tunnel**	**Steel per rm tunnel**		**Over-excavation**	**Over-excavation per rm tunnel**
	[m]	**[mm]**	**[mm]**	**[m]**	**[m]**	**[kg]**	**[%]**	**[m^3]**	**[m^3]**
12 m	8.0	400	456	360	45.0	**1,440**	**100**	70.4	8.8
15 m	11.0			450	40.9	**1,309**	**91**	95.3	8.7
18 m	14.0			540	38.6	**1,235**	**86**	120.1	8.6
18 m +SC	14.0					**799**	**55**		

The decrease of pipe length also results in a decrease of installation time because less meters must be drilled per running meter tunnel. Table 4 indicates the size of these time savings with the same adaptations as mentioned above. It can be shown that each increase of pipe length decreases installation times and an additional change from a standard treaded connection to a squeezed coupling (SC) again decreases the installation times due to the experiences presented in table 1. In the best case nearly half an hour can be saved per running meter tunnel.

Tab. 4 Comparison of installation times for 12 m, 15 m, and 18 m long pipe umbrellas.

Pipe umbrella length	**Excavation length**	**Pipes installed**	**Pipe per rm tunnel**	**No of couplings**	**No of couplings per rm tunnel**	**Installation time per rm***	**Saving per rm tunnel**
	[m]	**[m]**	**[m]**	**[#]**	**[#]**	**[min]**	**[min]**
12 m	8.0	360	45	90 (45)	11.3 (5.6)	**125**	**0**
15 m	11.0	450	40.9	120 (60)	10.9 (5.5)	**116**	**9**
18 m	14.0	540	38.6	150 (75)	10.7 (5.4)	**110**	**15**
18 m +SC						**97**	**28**

* Values are taken from Volkmann 2016, including manipulation times.

5 Optimization Potential Regarding Mechanization or Automation.

Now mechanization or automation of installation processes is not very common in tunneling. The only exception may be countries with health and safety standards at a very high level. In fact, doing the hard work over a shift long clearly leads to fatigue and exhaustion resulting in inefficiency and a higher risk for injuries. Today, nearly all manual processes can be performed by mechanization or automation units. This means that all processes after moving

the pipe plus the drill steel onto the basket can be mechanized and remote controlled. Resulting in significant advantages in both time and safety during the process as well as in subsequent tasks due to lower physical and mental fatigue.
The required grade of mechanization or even automation must carefully be defined for each project depending on regional regulations. When discussing automation units, safety issues are the main concern nowadays but other advantages like effeciency and time savings are getting more popular as well.

6 Conclusion

A large number of circumstances in tunneling call for additional pre-support measures to supplement the support concept. The Pipe Umbrella System is one of the increasingly used methods of pre-support because its application area starts at relatively hard ground conditions and is only limited by flowing or raveling ground conditions. The system is very flexible and adaptable to changing situations and can be installed by common drilling machinery. Its optimization potential is very often not used in worldwide tunneling therefore the discussed points are highlighted in the following.

For an exemplary 100m long tunnel, which is continuously supported by a pipe umbrella the potential for optimization results in;

- **64 tons of steel pipes** by changing from 12 m to 18 m long pipe umbrellas and a change from threaded connections to squeezed connections (Table 3).
- Nearly **47 hours of installation time** by doing the same changes as mentioned above (Table 4).

This proves that simple changes in the way of installing pipe umbrella systems like 18 m instead of 12 m long pipe umbrellas or alternative coupling types may have a major impact on material consumption and installation time.

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