Verification of design relevant parameters for new pipe umbrella support systems

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ABSTRACT: Since the 90s pipe umbrellas have been used regularly to support tunnel headings in difficult ground conditions. During this time, the rules for design have continuously improved, but there are still problems to determine the equivalence of alternatively offered, new systems. For this reason, common connection types for pipe umbrella support systems are described and their characteristic design parameters, their advantages and disadvantages reviewed. Two different design approaches will be introduced and discussed. Different connection types or staggered connections / joints are assessed regarding their influence on the load-bearing capacity. The results of laboratory tests are discussed, and the necessity of a statistical evaluation shown. Having these results presented in a laboratory test report or a certificate issued by the producer in hand, it is possible to define for an owners representative whether alternative connection types are adequate or not.

Keywords: pipe umbrella, canopy tube, design approach, connection types, laboratory bending tests.

1 INTRODUCTION

Increased use of pipe umbrella systems – also called canopy tube system – began in the 1990s. An important reason for this was that the pipe umbrella ideally filled the gap between cheap pre-support systems like spiles and much more expensive and time-consuming pre-support systems like horizontal jet grouted columns, freezing technologies, or pipe jacking. In the beginning, the pipes were drilled into the ground by special machines, but systems were soon developed that allowed regular tunnel drilling machinery to drill in pipe umbrella pipes with a length of 12 m or more.

While at the beginning of the 2000s the design of pipe umbrellas was often based on experience, the knowledge about this system increased rapidly through scientific investigations at that time. Among other things, the behavior of the pipes in the ground was measured every minute during construction with inclinometer chains, and laboratory tests were carried out on the material as well as on the pipes, including their weakening. All this data was then used in three-dimensional numerical calculations and back-calculations to examine various influencing factors.

As a result, the geotechnical mode of action could be described (Volkmann & Schubert 2007) and the decisive design parameters determined. Based on this knowledge, not only rules for the correct execution of three-dimensional numerical calculations in the design phase could be defined (Volkmann et.al. 2006) but also comprehensible and easily verifiable analytical calculation approaches (Volkmann & Schubert 2010). Due to the system-immanent properties and the detailed knowledge of the support effects, the pipe umbrella system is used in almost every urban tunnel construction project and generally in projects with poor ground conditions nowadays.

2 PIPE UMBRELLA FEATURES

A pipe umbrella consists of steel pipes typically with outer diameters of 114 mm to 168 mm nowadays, which are drilled into the outer perimeter of the face in advance direction. During the subsequent advance, the pipes support the ground on the outside of the excavated area. This creates safe and stable tunneling conditions in the "unsupported" working area at the heading. In weak ground conditions even unsupported drill holes tend to deform and create unwanted deformations as well as stress relaxations therefore most pipe umbrella pipes are installed in self-drilling mode, which means that the supporting pipes follow directly behind the drill bit during installation.

So a pipe umbrella pipe consists of a starter unit including a drill bit and steel tubes connected to the started unit. In general, the steel tubes are additionally equipped with injection holes to grout the annular between the pipes and the ground after installation, but this feature do not decrease the load bearing capacity of the system. Connections do, however, so the connections between tubes are the most important feature regarding load bearing capacity of a pipe umbrella. During the last 2 decades 3 different connection types became accepted in worldwide tunneling business. All of these with different characteristics, advantages, and disadvantages.

2.1 Standard Threaded Connection

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 (figure 1a), the effective cross-section is reduced. This fact drastically decreases the load-bearing capacity and stiffness in the connection area. At most standard pipe umbrella dimensions the maximum elastic moment (design value) of the regular pipe is at the level of the ultimate moment (failure) of the standard threaded connection at laboratory conditions. Hence, to achieve certain given pipe umbrella design parameters, an over-dimensioning of the un-weakened pipe section is a practical way – though highly inefficient – to overcome this limitation.

The main advantage of this connection type is the constant inner diameter that allows to install measurement instruments or perform double packer injections without constraints.

2.2 Nipple Coupling

As a result, the so-called nipple coupling was developed. Nipple connections consist of threaded connection fittings, which are pressed and welded into the ends of standard pipes (figure 1b). This connection type provides an elastic design load as well as stiffness properties equal to an un-weakened pipe. By using this connection type, default design parameters are constant over the entire length of installed, connected pipe umbrella drills.

2.3 Squeezed Connection

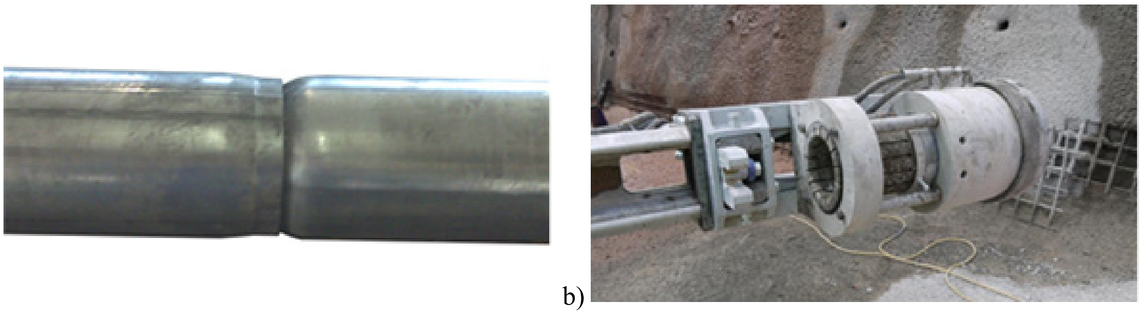
The latest development in the field of pipe connections is the squeezed connection, this connection type results from the attempt to provide a tough and easy-to-connect alternative to conventional threaded systems. By means of the squeezed connection, non-threaded pipe ends are mechanically connected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

In detail the pipes are delivered to the side with one reduced end that fits into the other unedited end. So, after feeding an extension tube with its drill steel to the boom the drill steel is conventionally screwed together, and the smaller pipe end is simply moved into the regular pipe end at the squeezing console position. Then the squeezing unit is activated by remote control and the pipes are squeezed together after a 2-second-long squeezing process (figure 2a). This squeezing process creates a force-fit connection. So, there are on one hand fewer rotating parts, which increases safety and simplifies handling and on the other hand there is no thread, which increases the system security and decreases the coupling time for the installation process.

This connection type has the advantage that design values of a default pipe can be used because plastic hinges are created by activating plastic reserves of steel.

a) b)

Figure 1. a) standard thread connection and b) nipple coupling.



a) b)

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

3 TECHNICAL CHARACTERISTICS

Note: All values mentioned in this document are without safety factors and only valid for DSI Underground products.

A grouted default tube with an outer diameter of 139.7 mm and 8.0 mm of wall thickness is used as reference, since it represents 100% of elastic bending moment. With a defined stiffness without any weakening. Test results for this default tube are presented by black lines in figure 3. Its analytically calculated elastic design moment is 36.6 kNm and its ultimate bending moment is > 75 kNm (5% quantile value).

The standard threaded connection – red line – has the lowest resistance against bending. The ultimate load for this group of samples is 31.9 kNm (5% quantile value). This is lower than the elastic 36.6 kNm from above. Its analytically calculated transition from elastic loading to plastic loading is at 13.8 kNm. This analytic calculation does not include the influence of notches in the thread or allowed tolerances during steel tube production. So, the effective value is lower.

The nipple connection is defined as strong and as stiff as the default tube in the elastic loading area. As can be seen in the diagram – blue lines – this is correct and can be proven by laboratory tests. So, the elastic load bearing capacity of the nipple connection is 36.6 kNm as well, confirmed by an analytical calculation. The ultimate bending moment for the nipple connection is >53.1 kNm (5% quantile value).

The analytical calculation results in an elastic load bearing capacity of 23.6 kNm for the squeezed connection – green lines –, corresponding to 65% of the default value. The working line of the sample confirms this value. The ultimate load bearing capacity is 64.0 kNm, far higher than the elastic 36.6 kNm.

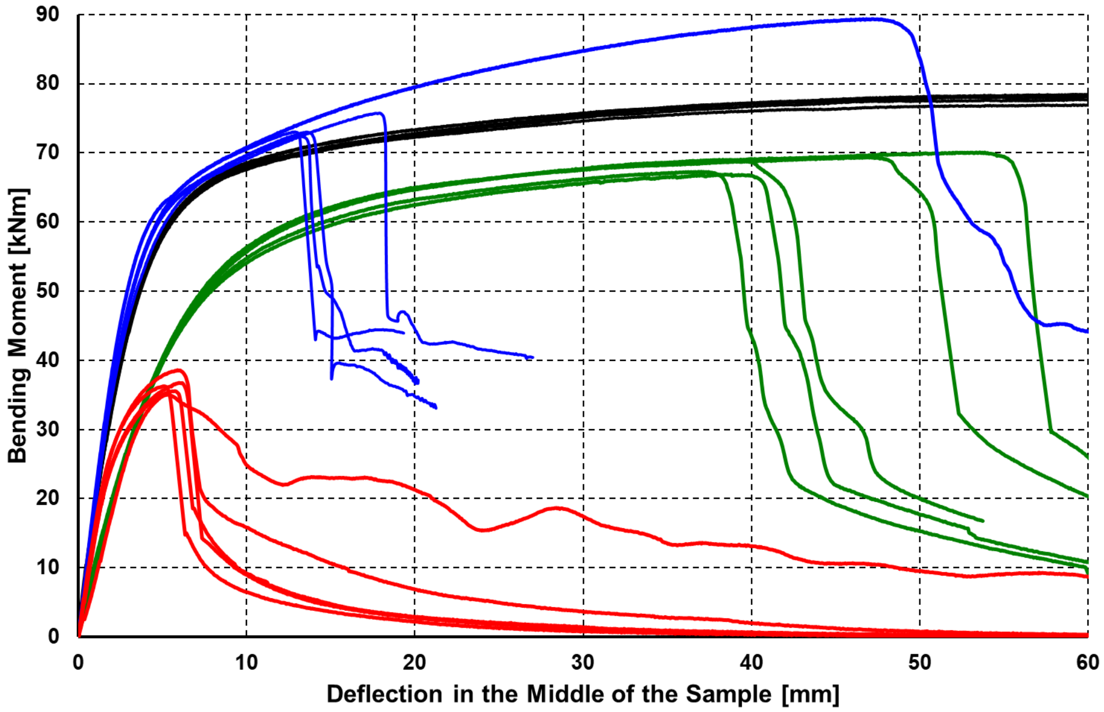


Figure 3. This diagram shows laboratory test results of bending tests for 139.7 mm pipes. The tests were always performed with 5 samples & these were equipped with different connection types.

Table 1. Summary of discussed characteristic values for 139.7x8.0 and a "historical" alternative for staggered joints.

type	component	OD [mm]	ID [mm]	steel grade	W [cm^3]	I [cm^4]	M_{el}* [kNm]	M_{ult} [kNm]
139.7x8.0	tube	139.7	123.7	S355	103.1	720.3	36.6	75.8 lab
	threaded connection				38.9	252.6	13.8*2	n/a
	nipple coupling				103.1	720.3	36.6	53.1 lab
	squeezed connection				66.5	380.6	23.6	64.0 lab
139.7x12.5	tube		114.7		146.0	1,020	51.8	n/a
	threaded connection				58.7	368.1	20.8*2	n/a

* all values are calculated with minimum values, which are stated in steel standards
*2 notches and steel tube production tolerances are not considered but will decrease this value

3.1 Resume of technical characteristics

Canopy pipes and respective connections must be tested to prove its technical characteristics. Even when products from different suppliers look obviously similar, only laboratory tests verify its quality. Laboratory test reports or certificates issued by the producer declare the performance of relevant design parameters before installation and can be used to compare different options on an adequate technical level.

Experience shows that two different approaches for the design calculations exist. There is a pure elastic approach (EL-EL) and an approach that allows locally (connections) to use plastic reserves of steel (EL-PL). The second approach usually uses higher safety factors (e.g., 1.3) for the connections since there are anyhow a lot of uncertainties in the surrounding ground. So, the regular steel tube is in both approaches the elastic reference. In case of the EL-EL design approach this value is decreased depending on the chosen connection type. The highest decrease must be done by using a standard thread connection. For the EL-PL approach it must be proven that the connection does not fail before the elastic reference moment plus determined safety factor. With the example of table 1 and an exemplary safety factor of 1.3 this would mean that the 5% quantile value for the ultimate moment of the connection must be higher than 47.6 kNm. So this approach would work for the nipple coupling as well as for the squeezed connection but not for a thread connection.

Anyhow, it cannot be recommended to load a thread connection in the plastic range because laboratory values do not include the negative influence of construction problems like non perfect screwing of threads or damages on threaded connections due to the construction environment. By experience these events happen at more than 5% of connections leading to the suggestion that a standard threaded connection should only be used up to the analytically calculated elastic bending moment.

In figure 3 can be seen that similar samples do not fail at the same load level. To counter this fact, design parameters are never determined by single laboratory tests. A group of samples is tested, and the results are evaluated by means of statistic. A 5% quantile value is calculated, and this value is taken for further design calculations to ensure stable and safe construction conditions as well as finalized buildings.

4 STAGGERED CONNECTIONS / JOINTS

Staggered tube connections have been a temporary solution before higher quality connections were developed before 2010. This solution was developed to decrease the weakness of the weakest point (standard threaded connection) by increasing the number of weaknesses in the support system. When it was used correctly it was used in combination with an increase of pipe dimensions (wall thickness and/or outer diameter). This idea was eliminated by newer, more effective connection types because the risk for failures of the entire support system was still too high, and it was more economical to use new, well developed connection types.

Figure 4 (Volkmann & Krenn 2009, Figure 4) was modified with 2 blue lines. Both lines have a length of 1.5 m corresponding to the distance between 2 staggered pipe connections. The reduction of the maximum bending moment due to the longitudinal extension has only a minor effect. In the case presented, we have a reduction of the maximum bending moment to 81% in front of heading and to 87% in the already supported section. This means that in this arbitrarily selected example, a reduction of only 13% can be achieved by staggered connections. The evaluation of further cases would certainly lead to both higher and lower values. Due to the existing scatter, however, it can be assumed that a 5% quantile value of the reduction, calculated from several back calculations, will be well below 10% of reduction. Thus, the reduction of the design moments that can be achieved with certainty by staggering pipe connections can be classified as low.

Nevertheless, a typical way to find an adequate pipe dimension would be a re-calculation. This document discusses 139.7x8.0 pipes with an elastic bending moment of 36.6 kNm. So, 2 pipes have an elastic bending moment of 73.2 kNm. This value must be replaced by the elastic bending moment of one default tube and its standard threaded connection. Using a pipe dimension of 139.7x12.5 mm the elastic bending moment of the default tube is 51.8 kNm and 20.8 kNm for the standard threaded connection (table 1). Both elements together would have an elastic bending moment of 72.6 kNm – comparable to the requested moment of 73.2 kNm so by increasing the wall thickness from 8.0 mm to 12.5 mm and using staggered connections it would be fine as well, but un-economical because the necessary steel volume as well as the used CO_2 increases to 156%.

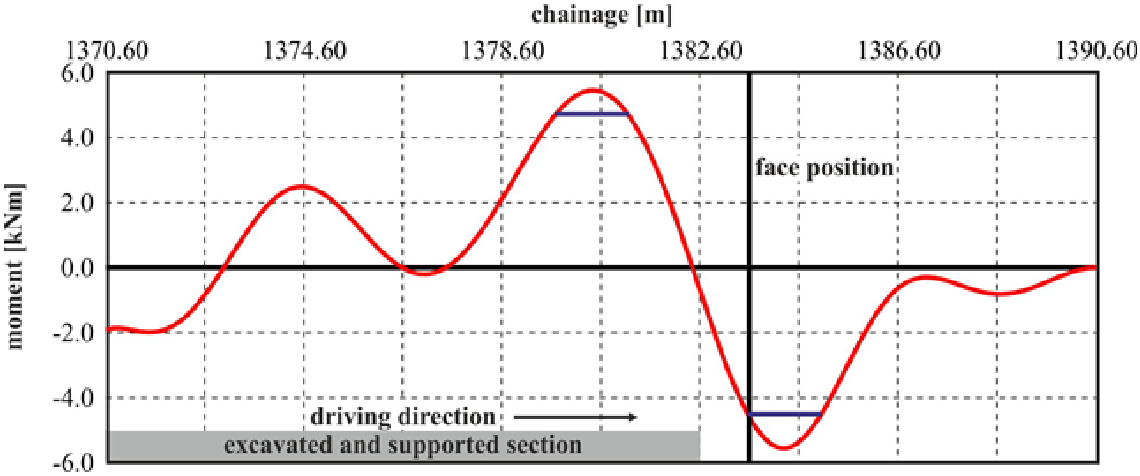


Figure 4. shows the bending moment of a back-calculation (modified).

5 CONCLUSION

Since the 90s pipe umbrellas have been used regularly to support tunnel headings in difficult ground conditions. During this time, the rules for design have continuously improved. The mode of action as well as design rules are well known but there are still problems to determine the equivalence of alternatively offered, new systems. One main reason for this fact is the continuously ongoing development of new pipe connections, which are decisive for the load-bearing capacity of the entire system.

The 3 most common pipe umbrella connections were presented with their technical characteristics and documented with a numerical example. Pros and cons were presented, showing clear economic and safety benefits for newer connection types. 2 common design approaches were shown and here as well, advantages for the nipple coupling and the squeezed connection can be seen in the application. The verification of the equivalence of alternative connections can only be made through appropriate evidence through statistically evaluated laboratory tests, which are documented in appropriate reports.

Finally, the topic “staggered joints” was discussed, clearly showing that this method is neither effective nor useful nowadays because state-of-the-art connection types do not need this measure.

REFERENCES

Volkmann G.M., Button E.A. & Schubert W. 2006; A Contribution to the Design of Tunnels Supported by a Pipe Roof. Proc. 41st U.S. Rock Mechanics Symp., American Rock Mech. Assoc., June 17-21, Golden, CO.

Volkmann, G.M. & W. Schubert 2007. Geotechnical Model for Pipe Roof Supports in Tunneling. In Proc. of the 33rd ITA-AITES World Tunneling Congress, Underground Space - the 4th Dimension of Metropolises, Volume 1. eds. J. Bartak, I.Hrdina, G.Romancov, J. Zlamal, Prague, Czech Republic, 5-10 May 2007, Taylor & Francis Group, ISDN: 978-0-415-40802. app. 755-760

Volkmann, G. M. & F. Krenn, 2009. Back-Calculated Interacting Loads on Pipes of Pipe Umbrella Support Systems Proc. of the ITA-AITESWorld Tunneling Congress 2009, SafeTunnelling for the City and for the Environment, May 23–28 2009, Budapest, Hungary; ISBN: 978 963 06 7239

Volkmann G.M. & W. Schubert 2010. A load and load transfer model for pipe umbrella support. In Proc. of EUROCK 2010, Lausanne, Switzerland, 15-18 June 2010