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Use of Pipe-Roof Umbrella Supports for Tunnelling in Difficult Grounds – A Review

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ABSTRACT

Pipe-roof umbrella support systems are increasingly being used during tunnel construction through river bore material, very poor, loose, highly jointed and weathered rock masses. The pipe-roof umbrella system is also commonly used while tunnelling in low-cover zones. At the tunnel portals, this is the most preferred tunnelling technique. The pre-support technique not only provides safe working space below the umbrella, but also helps in controlling the ground settlement and deformations in the tunnel. With increase in tunnel construction lately, use of pipe-roof umbrella technique has also increased without much knowledge about the ground support interaction associated with pipe-roof system of support. Thus, the paper aims to review the design and application of pipe-roof support system. In the end, the importance of monitoring the pipe-roof system is highlighted for design evaluation and improvement.

Keywords: Pre-support; Spiles; Pipe-roof Umbrella; Coverage angle; Pipe length; Pipe diameter; Pipe spacing; Overlapping

1. INTRODUCTION

The rise of population in large cities, density of transportation, and need for storage capacity have led, inevitably, to an increased use of underground structures in modern days. For the reasons of overpopulation and the lack of space, tunnels have a significant role in the development of urban areas. In urban areas tunnels are being designed at shallow depths where the ground generally consists of sedimentary soil and/or highly weathered rock mass. Similarly, sometimes because of space limitations or because of the unavailability of any alternative, the tunnel portals are fixed through river-borne material. Tunnelling through these types of loose ground and weathered & poor rock masses are associated with large displacements, which may lead to ground surface settlement. In order to control ground settlement (i.e., to restrict ground surface settlement), which is of paramount importance, so that the minimum disturbance is caused to surface structures, pre-supports are used. In addition, often varying geological conditions can lead to complications with respect to tunnel excavations. In such conditions also, for safe tunnelling, pre-supports in the form of pipe-roof umbrella are used. In India also, most of the tunnels through the difficult ground are being excavated using the pipe-roof umbrella support system. Some of these are tunnels of Rishikesh-Karnaprayag rail link project, Bhanupalli-Bilaspur rail project tunnels, various highway tunnels in challenging and fragile terrain of Himalaya etc. Author has worked in many such tunnels as a design and proof-check consultant and the experiences gained in these projects have also been incorporated in this paper.

Difficult grounds including the weak rock masses (or granular material with low cohesion) that are encountered during excavation (whether foreseen or unexpected) can require additional and innovative means of temporary pre-support measures to prevent failure of the ground. In these conditions, the ground limitations control the entire design process, which may require time and cost-intensive additional support systems. Due to its time and cost-effectiveness in comparison with other pre-support methods (ground freezing, jet grouted columns, or pipe jacking), the pipe-roof umbrella arch method, though less stiff, is often preferred and used in tunnel construction. The pipe-roof umbrella arch method (UAM) or the pipe umbrella system helps in achieving short-term stability during tunnel construction by preventing collapse of the tunnel face under unfavorable ground conditions such as soil with poor self-standing and/or weathered soil with a shallow cover. It is important to note that in flowing, ravelling grounds or in water-charged river-borne material, soil and poorer rock masses, pre-grouting is recommended before the use of pipe-roof pre-supports. Accordingly, the pre-grouting shall be designed, which is not covered in the paper.

The pre-support system helps in increasing the stability in the working area by transferring loads of overlying formation/strata in the longitudinal direction and decreases excavation-induced deformations. These facts have led to an increase use of the pipe-roof umbrella method without much knowledge about the ground support interaction associated with this system of support (Volkmann and Schubert, 2007).

The pipe-roof umbrella method is generally applied in the crown (above spring level) of a tunnel, in weak ground conditions in conventional as well as mechanised tunneling, by installing a series of large diameter steel tubes in an arch or a ring form from the current working face out to a distance in the range of 12 m to 15 m in front of the working tunnel face. Thus, providing the stability and safety in the working area. The pattern of pipes is arranged in a manner so that it outlines the tunnel extents (Fig. 1). This method consists of installing, prior to the excavation of a length of tunnel, a series of pipes, either parallel to the tunnel axis or at a certain angle with it. By injecting grout through the pipes, the ground in between the pipes is stiffened and the pipes are connected, creating a kind of 'umbrella' above the area to be excavated. Therefore, the success of the pipe-roof umbrella system depends to an extent on the grouting of the ground around the pipes. This arrangement creates a stiff layer of ground and allows safe excavation even in the poor ground conditions.

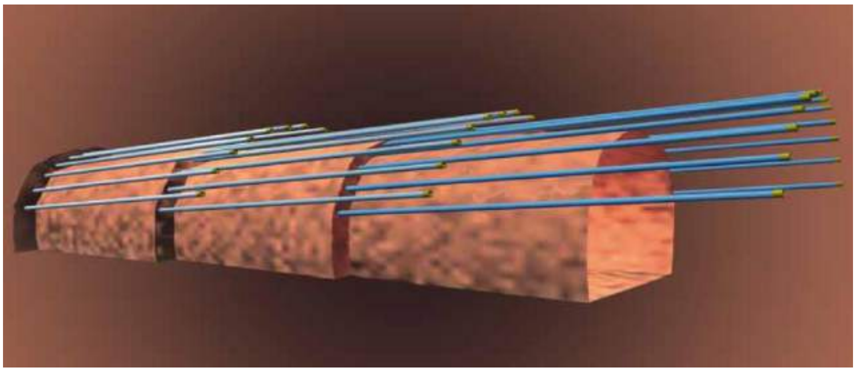


Figure 1 - Schematic presentation of pipe-roof umbrella method (Atlas Copco, 2011)

as forepoles, spiles, pipe umbrella etc. and briefly described in Section 2, Table 1. One of these is the pipe umbrella system that is also referred to as “Umbrella Arch Method”, “Pipe Fore-Pole Umbrella”, “Long-Span Steel Pipe Fore-Piling” and “Steel Pipe Canopy” in literature (Volkmann and Schubert, 2010). Pipe umbrella system has been termed and used as ‘pipe-roof umbrella’ by the author.

In the paper, a review is presented related to development in the design of pipe-roof umbrella support system along with the selection of different design parameters.

2. NOMENCLATURE OF DIFFERENT PRE-SUPPORT ELEMENTS

Table 1 highlights the nomenclature of various pre-support elements with respect to the tunnel height (H_e) and the length of forepoles or pipes (L) proposed by Tuncdemir et al. (2012) and Wittke et al. (2006). A comparison of support elements (Table 1) illustrates different types of supports that exist in literature based on $L < H_e$ and $L > H_e$.

The support or pipe length (L) divides the nomenclature in Table 1. In general terms, for $L<H_e$, what Tuncdemir et al. (2012) define as a forepole (Fp), Wittke et al. (2006) name as a spile (Sp). Further, for $L>H_e$ also different terms for similar support are used; one uses umbrella (UA) while the other uses Pipe Umbrella.

Table 1 - Nomenclature of pre-support elements and design parameters (Oke et al., 2014)

Design Parameters	Typical Excavation Type: Metro tunnel (H_e = *6.87m) (Tuncdemir et al., 2012)	Typical Excavation Type: Highway tunnel (H_e = *8.85-14m) (Wittke et al., 2006)
$L<H_e$	***Forepoles***	***Spiles***
Length	3-4m (sometimes 5m); may be more as per the requirements	3-6m (12m if grout injected)
Angle	5°-10°	5°-15°
Overlap	1/4-3/4 of length (generally ½)	0.8-1.2m
Spacing	No reference	Max 30cm
Size (diameter)	32-38.1mm	23-28mm
$L>H_e$	***Umbrella***	***Pipe Umbrella***
Length	9-16m (sometimes 5m)	15-30m (12m if grout injected)
Angle	6°-8°	5°
Overlap	1/4-3/4 of length (generally ½)	Min 3m
Thickness	*3.65mm	8-25mm
Spacing	*30cm	30-50cm
Size (diameter)	114mm	76-200mm

*Notation: H_e - height of excavation; L – Length of forepoles/spiles; * - Not generalized values, values from selected authors published case studies*

Furthermore, a comparison of the other design parameters of Table 1, forepoles (Fp) and spiles (Sp) are generally installed at greater angles, smaller size, and with closer spacing than the larger UA and Pipe Umbrella elements. These differences exist because the selection of shorter support elements is usually based on structural (geological) failure type and/or availability of proper installation equipment. The selection of longer support is commonly based on preventing complete failure of the tunnel face, or to minimize the convergence of the tunnel in order to minimize surface settlements. Therefore, the failure mechanism and the risk of convergence will dictate the appropriate composition of the UA support elements (Oke et al., 2014).

According to Oke et al. (2014), there is confusion in terms of nomenclature of supports (forepoles, spiles, umbrella or pipe umbrella) given in Table 1. To overcome this confusion, Oke et al. (2014) divided these pre-support elements in three categories based on their physical properties,

(i) Spiles (Sp) - metallic longitudinal members shorter than the height of the tunnel (H_e);
(ii) Forepoles (Fp) - metallic longitudinal members. As per the site requirement, Fp may be longer than the height of the tunnel H_e; and
(iii) Grouted pipes (G) - a pipe support element that consists of grout.

The main contrast between spiles, forepoles and grouted pipes are that the systems vary in their respective stiffness, costs, and time commitment for installation. Category (iii), i.e. grouted pipe-roof pre-support elements are mainly discussed in the paper. However, spiles and forepoles are briefly discussed in following paragraphs.

Spiles (Sp) are generally installed when the geological structure itself controls a possible local failure of the portion of the tunnel. Further, Sp are inserted at a range of angles of 5° to15° (sometimes may even up to 40° depending upon the requirement) to the horizontal plane of the longitudinal axis of the tunnel excavation in order to achieve adequate structural control and proper embedment (Oke et al., 2014). It is suggested that the centre to centre spacing of Sp be <30 cm. In addition, such spacing is stipulated as a safety requirement which protects the workers from spalling/reveling or large wedge-type failures from falling between the individual support elements. The overlap of the Sp is directly linked to the potential problematic reoccurring rock mass structure that may be present within the tunnel profile. Typically, the overlap is half of the overall Spile length but ranges from 1/3 to 2/3 of the Spile length. The size of the Sp normally matches standardized rebar with diameters ranging from 25 to 50.8 mm. Figure 2a shows typical installation of spiles through lattice girder support in every excavation step.

Forepoles (Fp) are installed when a difficult and/or weak material is present for a large portion of the tunnel alignment and where there is a large potential for multiple geological structures of unfavourable orientation/structures to contribute to a possible failure. As previously mentioned, Fp have a larger diameter than Spiles (Sp). The stability of the face of the tunnel is derived by the fact that the Fp are long enough to embed themselves past the empirically derived Rankine active line, as shown in Fig. 2b. This design length is generally in agreement with Wang (2012), Fang et al. (2012), and Wittke et al. (2006).

Figure 2a - Spiles installed through the lattice girder (Volkmann and Schubert, 2011)

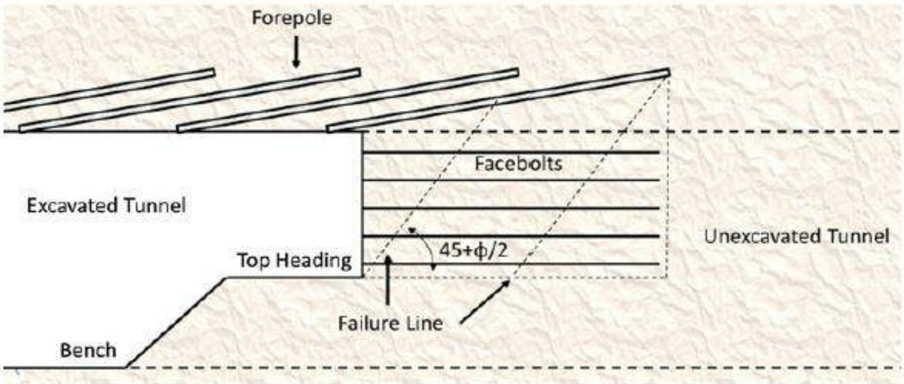


Figure 2b - Illustration of the Rankine failure line of a double overlap forepole (Oke et al., 2014)

Another consideration for the forepole length is that it exceeds the ensuing plastic region around and ahead of the face within the weak rock regions. In addition, the angle of installation is shallow and typically between 3° and 8° from the horizontal in the longitudinal direction of the tunnel alignment. The typical theoretical drilling accuracy is ±2 % relative to the forepole length (Oke et al., 2014). The centre to centre spacing of the Fp is within the range of 30–60 cm, however, the spacing is defined by the requirement to create an individual arching effect in between two sets of Fp (overlapping influence of support elements). The overlap of the Fp range between 0 and 1/2 of the forepole's length. The range usually depends on the use of additional pre-support methods that aid in the prevention of collapse of the face, such as face bolting. If the overlap of the successive forepole's umbrella is greater than ½ of the forepole length, it is referred to a double overlap forepole (Fig. 2b) as there will always exist two layers of support between the tunnel wall and surrounding rock mass. Depending on the rock mass quality and ground condition, sometimes pre-grouting may also be required alongwith spiles and forepoles.

3. IMPORTANT CONSIDERATIONS OF PIPE-ROOF UMBRELLA

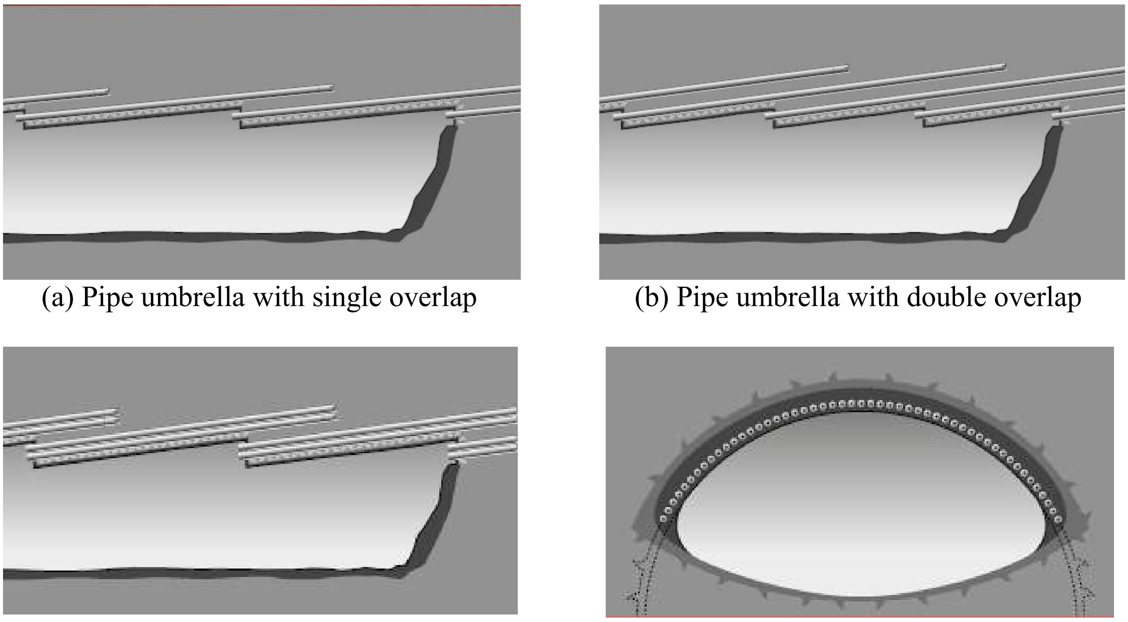
Contrary to rock tunnelling, certain aspects need particular consideration while tunneling through weaker ground where pipe-roof umbrella is required (Aagaard et al., 2017):

- The ground frequently needs some treatment in advance of the excavation process, such as de-watering, grouting or support measures ahead of the tunnel face.
- It is common practice to subdivide the excavation section into top heading, bench and invert instead of a full-face excavation. In case of limited stand-up capacity (and time) of the soil, a further subdivision of the top heading face may be necessary.
- The advance length is a very important parameter to control the short-term stability. The advance length is connected with the stand-up time of the soil and the pre-support measures used. Common advance length in soil is around 1.0 m to 1.5 m.
- The perimeter of the excavation mostly required additional support measures, such as spiles, forepoles, pipe-roof umbrella or grouting. In case of very cohesive soil (clayey soil), it may also be possible to excavate a limited length without such measures.
- The tunnel face may require systematic support, such as face bolting in combination with a layer of mostly reinforced shotcrete. This is necessary to prevent face collapse and to avoid detrimental effects of moisture causing progressive loosening of the soil in the face.
- As mentioned earlier, the umbrella method is generally employed under the following conditions:
  - The existence of a shallow overburden above a tunnel,
  - The need to restrict ground surface settlement,
  - Poor ground conditions, and
  - At tunnel portals to make an entry (Fig. 2c), and

Figure 2c - Installation of a portal pipe-roof umbrella (Volkmann and Schubert, 2011)

4. PIPE-ROOF UMBRELLA CONFIGURATION

There can be different configurations of pipe-roof umbrella as per the ground requirements as shown in Figs. 3a to 3c. Pipe-roof umbrella with single overlap (Fig. 3a) is mostly used. However, under very poor ground conditions and where almost no surface settlement is allowed pipe-roof umbrella with double overlap (Fig. 3b) or double pipe-roof umbrella (Fig. 3c) are used. Figure 3d shows the tunnel cross-section below the pipe-roof umbrella along tunnel roof in the crown portion. In case double pipe-roof umbrella is required, it is suggested to use second row of pipes staggered to first bottom row of pipes.



(a) Pipe umbrella with single overlap (b) Pipe umbrella with double overlap

(c) Double pipe umbrella (d) Tunnel cross section below pipe umbrella

Figure 3 - Different configurations of pipe-roof umbrella and excavated tunnel cross section below the pipe-roof umbrella (DSI, 2019)

5. DESIGN APPROACH

5.1 Load on Pipe-Roof Supports and Interaction with Ground

In order to clarify the effect of umbrella arch method (UAM) on the tunnel reinforcement, vertical stress distributions at tunnel crown in both cases (tunnel excavation using UAM and without using UAM) are compared, as shown in Fig. 4. In the case where the UAM is not employed (Fig. 4a), due to the rapid decline of vertical stress to zero in excavation face (Point A), concentrated stress is induced ahead of the excavation face and zero stress continues along the unsupported section (Muraki, 1997). Further, vertical stress increase is expected by installing tunnel supports in specified distances beyond the excavation face. In the case of deploying UAM (Fig. 4b), the umbrella arch structure covers the unsupported tunnel section and carries the ground pressure. The Mohr-Coulomb failure envelope is also shown in Figs. 4a and 4b to better evaluate the stress state of the soil element. The initial stress condition for a soil element far from the excavation face is demonstrated as a dashed-line Mohr circle. During the tunnel excavation procedure, as the tunnel face approaches the soil element, an increase in the Mohr circle radius is witnessed due to the increase in the major principal stress. Hence, in the case without using UAM, in a close distance from the soil element, Mohr circle is tangent to the Mohr-Coulomb failure envelope, and consequently, the soil failure occurs. In contrast, when the UAM is deployed, the major principal stress is not increased considerably; hence, the Mohr circle is not tangent to the Mohr-Coulomb failure envelope, leading to failure prevention. Consequently, implementing the UAM could enhance the stability of tunnel excavation face by controlling the increases in major principal stresses in soil elements during excavation (Muraki, 1997).

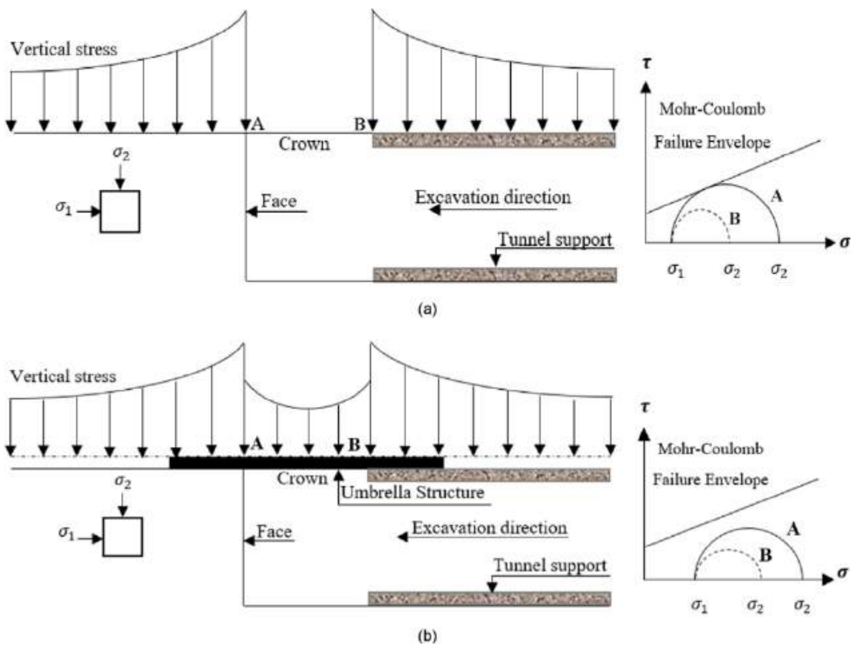


Figure 4 - Stress condition in tunnel excavation face, when (a) umbrella arch method is not employed, and (b) umbrella arch method is employed (Muraki, 1997). σ_1: minor principal (horizontal) stress, and σ_2: major principal (vertical) stress

The pipe-roof umbrella supports the rock mass and the tunnel face predominately by transferring the overburden load by the longitudinal beam action through the interaction of the support and surrounding ground condition. Thus, in this method the pipes are designed to carry longitudinal loads only (Lukic and Zlatanović, 2019).

Pipes of umbrella are primarily loaded by bending. Therefore, the relevant design parameter is the maximum elastic moment of the system. The benchmark criterion is the performance of the weakest link, which usually is the pipe connection.

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.

The internal forces of the pipes are almost zero after the installation, comparable to other passive support measures like rock bolts (Volkman and Schubert, 2011). The stress transfer, due 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 following construction process that causes a stress transfer starts to activate the supporting effect of the pipes. The spatial displacement characteristic developing during excavation controls the activation of the supporting effect after the installation of the pipe umbrella (Lukic and Zlatanović, 2019).

5.2 Loading Model and Optimum Design Parameters

Pipe-roof support load model proposed by Volkmann and Schubert (2010) is shown in Fig. 5. Each pipe is found in the ground (ahead of the face) as well as on the lining (behind the face) in the longitudinal and radial direction (Fig. 5). The strength and stiffness of the pipe umbrella system, therefore, depend on both the ground properties as well as on the time-dependent strength and stiffness properties of the lining (shotcrete, steel beams).

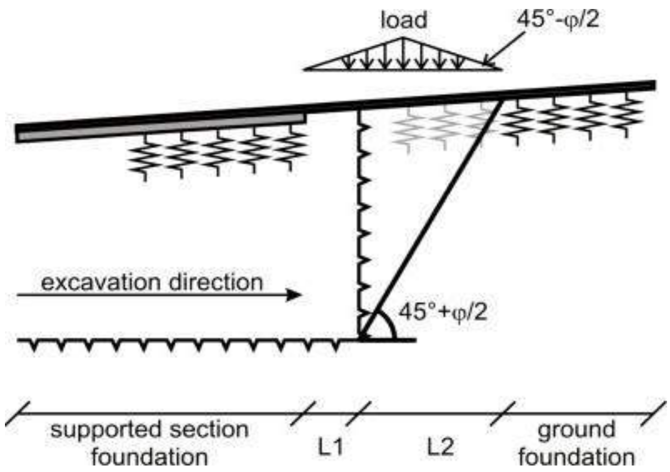


Figure 5 - Pipe roof support model showing the load and the foundation ahead and behind the face (Volkmann and Schubert, 2010) [L1 - Unsupported span; L2- Disturbed ground foundation)

The definition of the load acting on each pipe is one of the key features. It is dependent on ground properties, the axial distance between single pipes and the supporting length. In this case the shape of the load is described by the back-calculated equivalent dead load body. The supporting length is composed of two parts; L1 and L2. L1 is the excavation step length plus a working area that is necessary during construction (usually 0.3–0.5 m). Figure 5 shows the most conservative version for L2. This length could be reduced, if required, by the chosen way of construction sequence or additional face support.

The model in Fig. 5 is for shallow excavations. Thus, it is questionable whether the mechanical response will be the same for deep excavations that are dealing with squeezing ground conditions. It was determined that the loading condition was not gravity-induced when the overburden was greater than $1.2D_t$ (D_t is width of the tunnel). Volkmann and Schubert (2010) proposed that their back-calculated stress conditions are based on slices of ground that are 'squeezed out' by the longitudinal stress component over the entire length of the supported section. The disturbed-ground foundation that Volkmann and Schubert (2010) proposed in Fig. 5 is a conservative response and they suggested that it can be reduced if additional support is installed (e.g. core reinforcement) or an alternative construction sequence is chosen.

The optimum overlapping length regarding settlements can be defined when the abutment length ahead of the face is known. Whenever the actual length falls below this value during construction, the effectiveness of the pipe umbrella system decreases and the loads cannot be fully transferred to less loaded sections (Volkmann and Schubert, 2010). This leads to an increase in settlements at the end of a pipe-roof umbrella field.

When using a pipe umbrella system, the mode of action can be divided in 3 main parts (Fig. 6), the local arching effect in the open span, the radial support effect, and the longitudinal load transfer (Volkmann & Schubert, 2010). The spacing between pipes is defined by the requirement of developing a local arching effect, as shown in Fig. 6a. Immediately after the excavation, the tunnel perimeter is subdivided in smaller open areas because of the prior installed pipes. The shortest length for an arching is no longer the length of an excavation step; it is the distance between the pipes now. Due to this fact the local arching effect can be created much easier in critical ground conditions.

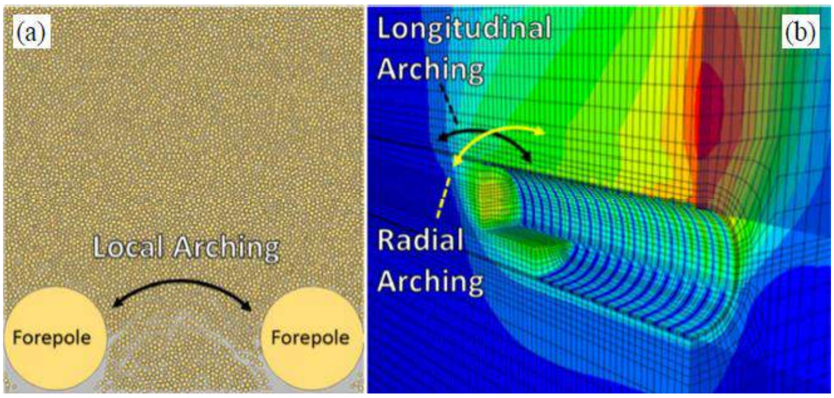


Figure 6: - Illustration of arching, (a) Local arching and (b) Longitudinal arching and radial arching (Oke et al., 2014b)

In order to be effective in the longitudinal direction, the embedding of the forepole element requires sufficient distance (length) from the disturbed ground region. This embedment ensures that there will be sufficient longitudinal arching, which is the transfer of stresses at the tunnel face to the support system (in front of the face) and to the stable ground (ahead of the face), as illustrated in Fig. 6b.

Similar loading model (as in Fig. 5) was considered by Wang (2012) who has used an analytical approach based on Pasternak elastic foundation beam theory for pipe-roof reinforcement. A systematic parameter study was conducted by Wang (2012) to study the effects of important design parameters such as pipe diameter, pipe length, and overlap length on the mechanical behavior of pipe-roof reinforcement. Oke et al. (2014b) carried out detailed numerical analyses and highlighted that the stresses are first redistributed at the side walls, causing great deformations. Further, as the coverage angle increases, the stresses are transferred away from the excavation walls to below the excavation due to the support, decreasing the convergence of the side walls further, which explains why the coverage angle has a greater impact on the global response.

The results of the study by Wang (2012) and other researchers are summarized in the following paragraphs to highlight the specifications of various design parameters.

6. PIPE-ROOF UMBRELLA DESIGN PARAMETERS

The design parameters associated with the pipe-roof umbrella support elements primarily consist of the following (Fig. 7):

- Pipe diameter,
- Pipe length (L),
- Spacing between support elements,
- Coverage angle of pipe-roof umbrella,
- Overlap of successive steps of umbrella supports, and
- Grouting (not covered in this paper).

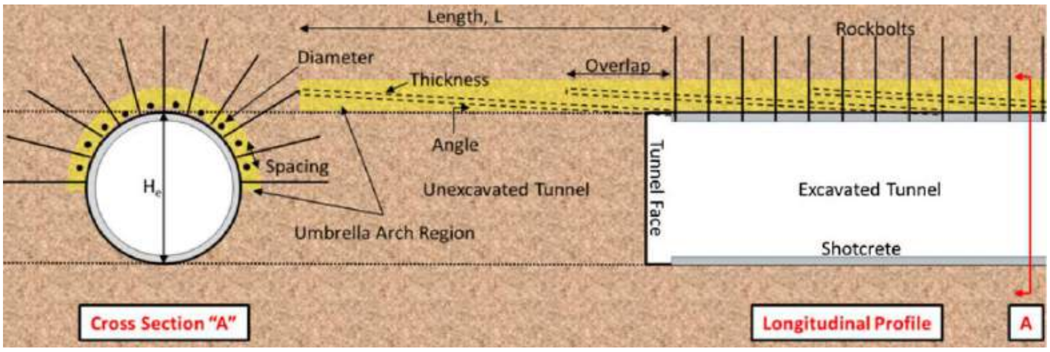


Figure 7 - Pipe-roof umbrella arch showing various design parameters. The yellow-shaded region defines the zone where the umbrella arch is installed. H_e is height of excavation (Oke et al., 2014)

Each design parameter with its influence in the design of pipe-roof pre-support umbrella is presented in the following paragraphs.

6.1 Pipe Diameter

Diameters of the pipes range from 70mm to 200mm. The study of Wang (2012) indicated that a more effective and efficient pipe-roof reinforcement system is required when tunnel is excavated under high overburden pressure. The vertical deformation of the pipe (ω) under high overburden pressure is larger than that under low overburden pressure. The study also showed decrease in ω with increasing pipe diameter (D), but the decrease tends to level off at D=159mm in all the studied cases. This means that any further increase in the pipe diameter would have insignificant contribution to limiting the vertical deformation of the pipe. Similarly, the effect of the elastic characteristics of the soil, excavation length and stiffness of support on the ω-D relationship is obtained. With the increase of the elastic characteristics of the soil, the vertical deformation of pipe is decreasing.

An important conclusion from the study is that the ω-D curves practically merge into one curve when exceeding certain values of the pipe diameter, suggesting that any further increase beyond the particular values of the pipe diameter would yield to no extra benefit in terms of reducing the vertical deformation of the pipe. Such limiting values represent the critical values of pipe diameter for a given tunneling condition. The study showed that the vertical deformation of the pipe can be reduced by 70% when the pipe diameter is varied from 108mm to 159mm, but reduced by 10% when the pipe diameter is varied from 159mm to 300mm, and the curves tends to level-off when the pipe diameter is varied from 300mm to 600mm. Thus, the results suggest that the critical value of the pipe diameter is 159mm.

Pipes used for a pipe-roof umbrella support system not only have a certain outer diameter and wall thickness but also have some additional features, which may influence the strength and stiffness parameters of the installed support.

6.2 Pipe Length

Wang (2012) observed that as the length of the pipe increases, the vertical deformation of the pipe at tunnel face decreases. The vertical deformation of the pipe increases with the increase of overburden pressure and excavation length, but decreases with the increase of the elastic characteristics of the soil and the stiffness of the support. However, pipe length longer than 9m is not likely to contribute reducing deformation. This indicates that the part of the pipes far beyond failure zone does not give any significant structural benefit. The results suggest that the critical value of the pipe length is in around 9m (i.e. 1.5h, where h is the height of tunnel), if the pipe length is more than 1.5h, structural advantages due to an increase in pipe length may not be significant.

Though there may not be any structural benefit of longer pipes, but the cycle of installing the pipes of umbrella pipe-roof support is a time taking process. Hence, to reduce the construction time, it is suggested to use longer pipes, may be 12 to 15m if there is no practical difficulty in installing these longer pipes and grouting through these pipes. With the length of pipe, the space between two adjacent pipes away from the tunnel face increases. Because of the increased space between the pipes, the ground material in between may not grout and therefore the ground reveling and failure may start. Therefore, while selecting the pipe length, there shall be proper understanding of change in the space between pipes, grouting of ground material in between the two adjacent pipes and formation of local arch to avoid raveling or failure of ground material in between the pipes.

In design practice, the length of pipe is defined at the crown, and generally the pipe length at the spring line is taken as that of the crown. If active failure condition is assumed at the tunnel face, the pipe length at the spring line can be reduced (wang, 2012).

6.3 Spacing Between Two Adjacent Pipes

The distance between pipes is governed by grouting pressure (Wang, 2012), groutability of the ground material and the development of local arching effect between two adjacent pipes. The spacing shall be able to prevent the raveling type of failure between two adjacent pipe elements.

Radial and longitudinal supporting effects of pipe-roofs are also influenced by the number of pipes. This design parameter and the diameter of the pipes define the remaining space in between the pipe-roof pipes. The results of the analyses of Oke et al. (2014b) illustrate a slight difference in reduction of surface settlement with the effect of spacing in comparison to the coverage angle. It is found that the coverage angle has a greater influence than the spacing of the forepole element on the global response of the system. Further, it is also apparent from raw data, however, that the 40 cm spacing is capable of controlling settlement more effectively than spacing with an equivalent coverage angle of up to 160°, indicating an optimum spacing value of 40cm.

The spacing of the pipe-roof or also written as forepole in the paper) element, however, is not constant due to the angle of installation of the forepole elements. The forepoles at the Driskos tunnel project were installed at an angle of 5.73° at a centre to centre spacing of 30cm, which would result in a spacing of 36 cm after 8 m of excavation (the location of the installation of next section of forepole elements), Fig. 8. An even greater spacing allowance could exist (44 cm) if the calculation included the 0.5% average deviation of drilling (Oak et al., 2014b). In such condition, when the spacing between the pipes is increased because of deviation in drilling or because of the angle of pipes or because of larger pipe length, it is suggested to insert spiles between two adjacent pipes.

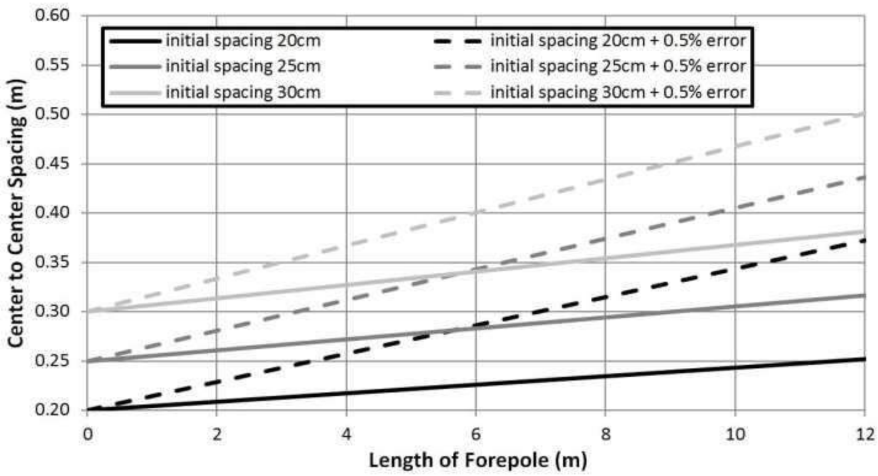


Figure 8 - Spacing assessment based on a 12 m length of pipe-roof (forepole) element, with forepole installation angle 5.73° (Oak et al., 2014b)

Sometimes the space between two adjacent forepoles increases because of the hole deviation during the drilling. The deviation of drilling hole has been experienced much in river borne material with small to medium size boulders. Hence, one shall be cautious while working in such grounds.

6.4 Coverage Angle

The pipe-roof elements coverage angle is defined by the failure mechanism more than the mechanical response of the system. For gravity-driven failures, the pipe-roof element only requires a coverage around the crown (~120°) of the excavation face to protect the workers working underneath. For subsidence-driven failure mechanisms, it is more common to employ 180° coverage above the face of the tunnel, i.e. complete roof above spring level (Oke et al., 2014b). Similarly, Song et al. (2013) stated that 120° is optimal for weathered rock and 180° for soil. For tunnel in moraine coverage angle of 120° has been used (Aagaard et al., 2017). For squeezing ground conditions, Hoek (2001) suggested an increase of the coverage angle from 120° to 180° for severe to very severe squeezing conditions, respectively. The coverage angle mainly depends upon the ground type, tunnel size and depth of tunnel from surface. In deeper tunnels, surface settlement may not be main issue, but there are other issues like high support pressure. The pipe-roof umbrella coverage, sometimes, can extend upto the invert level. For example, In India, in a rail tunnel of around 8m diameter through river borne material and having overburden less than 3D, pipe-roof umbrella has been used upto the invert level.

Oke et al. (2014b) studied the final displacement of three different points around the tunnel cavity for varying coverage angles while maintaining constant spacing (40 cm). The results find that the stresses are first redistributed at the side walls, causing great deformations. As the coverage angle increases, the stresses are transferred away from the excavation walls to below the excavation due to the support, decreasing the convergence of the side walls further, which explains why the coverage angle has a greater impact on the global response. The results of analyses show a slight difference in reduction of surface settlement with the effect of spacing in comparison to the coverage angle. It is found that the coverage angle has a greater influence than the spacing of the forepole element on the global response of the system.

Wu and Zhushan (2018) studied pipe-roof coverage angle (or the pipe arrangement area) and its impact on surface settlement in shallow tunnel through loess. They found that with increasing coverage angle, deformations show a decreasing trend. Maximum surface settlement drops quickly when area ranges from 120° to 150°. Specially, tunnel peripheral convergence declines sharply from 11.3 mm to 3.2 mm, and afterwards, there is no distinct reduction with pipe-roof area reaching 150°. So, as per Wu and Zhushan (2018), 150° should be adopted as the optimal parameter for the pipe-roof coverage angle. In such a case, requirements for maximum track settlement still could not be satisfied and other control measures need to be taken.

6.5 Overlapping Length

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 (see Fig. 7).

In Section 6.2 it is put in place that when L=1.5h, the reinforcement approximately extends to the theoretical Rankine active line (i.e. failure line) as illustrated in Fig. 2c, and any further increase beyond the particular values of the pipe length would yield no extra benefit. Thus, considering the repetitive nature of the pipe-roof reinforcement technique, the horizontal distance between the tunnel face and the failure line can be considered as a minimum overlap length (Le) required between two successive reinforcement installation cycles. Namely the critical value of overlapping length is ‘$h \tan(45° - \phi/2)$’. This implies that the excavation height (h) and the soil type (ϕ -friction angle) would have an influence on the overlapping length of the pipe. So, the overlapping length of pipe should be selected with due consideration of these factors, of course with some factor of safety. For example, (i) a pipe-roof umbrella with pipe length of 15 m and overlap of 3 m was used in Joberg tunnel, Norway (Aagaard et al., 2017); (ii) in Adit-3 of Rishikesh-Karnaprayag rail tunnel excavated through river borne material in India, a pipe-roof umbrella with pipe length of 12m and overlap of 4m was used. These two examples show that the overlap is from 20 percent to 33 percent of the pipe length.

7. PERFORMANCE MONITORING OF PIPE-ROOF UMBRELLA SYSTEM

In order to obtain a better understanding of this support system, in-situ measurements are generally performed using inclinometer chains installed parallel to the pipe-roof umbrella support. The measurements of the inclinometer chain were linked to the geodetic 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 and Schubert, 2010).

The impact of increasing the loading conditions across the entire support, as well as decreasing the loading conditions within the region of the overlap of the pipe-roof or forepole element, was found to capture the displacement profile more accurately.

Volkmann and Schubert (2006) illustrated through instrumentation of (pipe-roof) elements that it is possible to capture the influence of a weaker zone ahead of the tunnel face before it is actually excavated. Volkmann and Schubert (2006) were able to capture this weakness zone during the first segmented stage excavation. Their results showed the embedded end of the forepole element was displaced more than the forepole element near the tunnel face. Due to this early indication of a weaker zone, additional support was installed in order to proceed through the weaker zone without any problem.

The evaluation of these data sets helps not only in controlling construction processes, but also in understanding the geotechnical mechanisms around the heading when using pipe-roof umbrella systems.

8. CONCLUDING REMARKS

Use of pipe-roof umbrella pre-support and tunnel excavation system is becoming quite popular for tunnel excavation in difficult ground conditions. The system needs careful planning and execution. The author has covered the important issues related to the design of the pipe-roof elements with respect to different ground condition, depth of the tunnel, size of the tunnel and other conditions. The suggested values of these design parameters, as per the site condition and availability of the material, are as follows.

Diameter of pipes: The vertical deformation of the pipe reduced by 70% when the pipe diameter is varied from 108mm to 159mm. On further increase in pipe diameter, the rate of vertical deformations is practically negligible. Hence, the critical value of the pipe diameter is 159mm.

Length of the pipe: The optimum length of pipe shall be 12 to 15m, if there is no practical difficulty in installing these longer pipes and grouting through these pipes (Depending upon the availability of the drilling machine and the drilling pipe, the length may vary.)

Spacing between two pipes: The spacing of the pipe-roof is not constant due to the angle of installation of the pipe-roof elements. Moreover, the spacing increases with the length of the pipe-roof element. The spacing shall be such that the ground between the two pipes is properly grouted. In standard conditions, the centre to centre spacing shall be about 30-40cm. In tunnel sections where the spacing has increased because of practical reasons, spiles shall be used in between two pipe-roofs.

Coverage angle of pipe-roof umbrella: The coverage angle mainly depends upon the ground type, tunnel size and depth of tunnel from surface. Maximum surface settlement drops when coverage angle increases. In certain conditions, the pipe-roof umbrella have been used below the spring level also. However, the optimum coverage angle, in general, is found to be 150°.

Overlapping: Site-specific study shall be carried out to decide the overlapping length. However, in general, 20 percent to 33 percent of the pipe length is overlapped.

In addition to the above, the monitoring of pipe-roof shall be mandatory for design verification and for optimum use of the pipe-roof support system.

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