

TRAPEZOIDAL TAPERED RING—KEY POSITION SELECTION IN CURVED TUNNELS

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ABSTRACT

The trapezoidal tapered ring method has made significant progress in recent years for shielded-TBM projects, excavating tunnels with high overburden, strict water tightness criteria, and multiple curve alignments. The selection of compatible tapered rings is critical for successful advancement of the tunnel, assuring efficient installation of rings, as well as prevention of ring damage and excessive leakage. Using experience from the Arrowhead Tunnels Project, this paper describes guidelines for ring selection in tunnel curves, geometric analyses that comply with criteria principals, and provides techniques developed to determine the appropriate relative key position.

INTRODUCTION

The Arrowhead Tunnels Project, a component of the Inland Feeder Program, consists of two tunnels, the Arrowhead West Tunnel (AWT) (6.6-km long) and the Arrowhead East Tunnel (AET) (9.3-km long). The Inland Feeder Program is a 69-km system of tunnels and pipelines, which will convey water from the East Branch of the State Water Project in San Bernardino to the Colorado River aqueduct and the Eastside Transmission Pipeline in San Jacinto. It is a major component of the Metropolitan Water District of Southern California's (Metropolitan) Capital Improvement Program. Metropolitan is the largest water wholesaler in Southern California, and provides service to more than 16 million people in the Southern California area.

Both tunnels will be excavated in igneous and metamorphic rock with highly variable ground conditions beneath the San Bernardino National Forest. The majority of the tunnels will be below the groundwater surface and exposed to over 240-m of head. In order to achieve a sufficient amount of cover under deep canyons, and to

place the alignment in more competent rock away from major faults, the tunnel alignment had to include a total of 5 horizontal curves.

The Arrowhead Tunnels project has been awarded to the J.F. Shea/Kenny Joint Venture to finish both tunnels. A U.S. Forest Service's (USFS) special use permit restricts groundwater inflows as a measure to protect the groundwater resources. Specific construction measures designed to meet this permit include two new tunnel boring machines (TBMs); pre-excitation probing and grouting; a bolted, gasketed, pre-cast concrete segmental initial lining, with an internal diameter of 4.88-m and thickness of 330-mm; and an impervious welded steel or steel reinforced concrete pipe final lining. The bolted and gasketed initial lining will limit inflows in the advancing tunnels, significantly reducing sustained groundwater discharges from the portals.

The continuous concrete segmental lining is used as a thrust block for advancing the shielded TBM's. The lining also provides initial ground support directly behind the advancing TBM's. One of the main factors that impacts the advance rate of tunnel excavation is the efficiency of segmental lining installation, which is complicated by negotiation of curved alignments. The use of the tapered trapezoidal segmental lining system gives the benefit of being able to build both straight and curved tunnel alignments using only two types of rings, a left and right ring. Installing the rings with different key positions allows for flexibility to build to a desired alignment and adjust to minor TBM steering changes.

ANALYSIS DURING DESIGN PHASE

For designing the geometry of the segmental lining rings to negotiate curves prior to manufacturing, the tapers of each ring, the variation of taper for each key position, the arc lengths of each segment, and angles of the radial joints relative to the longitudinal length of the tunnel need to be designed for specific key issues to ensure installation efficiency.

First, for each curve, the required taper per ring, T_r , to negotiate the curve must be determined. The taper is equal to the difference in the distances in width of the ring along the tunnel from one side to the other, $L_{\text{left},r} - L_{\text{right},r}$, where $L_{\text{left},r}$ and $L_{\text{right},r}$ are the lengths of the ring in plan view for the left and right side at springline, respectively, as shown in Figure 1. The required taper is a function of the radius of the curve, the external diameter of the segmental ring, and the average length of each ring. The arc angle of each segmental ring relative to the arc of the curve, α_r , is a function of the same factors as the taper, also shown in Figure 1. The following equations can be used:

$$\alpha_r = 2 * \tan^{-1} (L_o / (2 * r)) \quad (1)$$

$$L_{\text{left},r} = (2 * r + D_{\text{ext}}) * \tan (\alpha_r / 2) \quad (2A)$$

$$L_{\text{right},r} = (2 * r - D_{\text{ext}}) * \tan (\alpha_r / 2) \quad (2B)$$

Where

L_o = average length per ring

r = radius of curve

D_{ext} = external diameter of segmental ring

Second, the variation of taper of the ring for each possible key position must be determined. The number of possible key positions is equal to the number of bolts across the circumferential joint. For each key position, the actual taper is a function of the maximum taper, as discussed below. It is recommended that one to two positions away from the maximum taper should then be set equal to the required taper, T_r ,

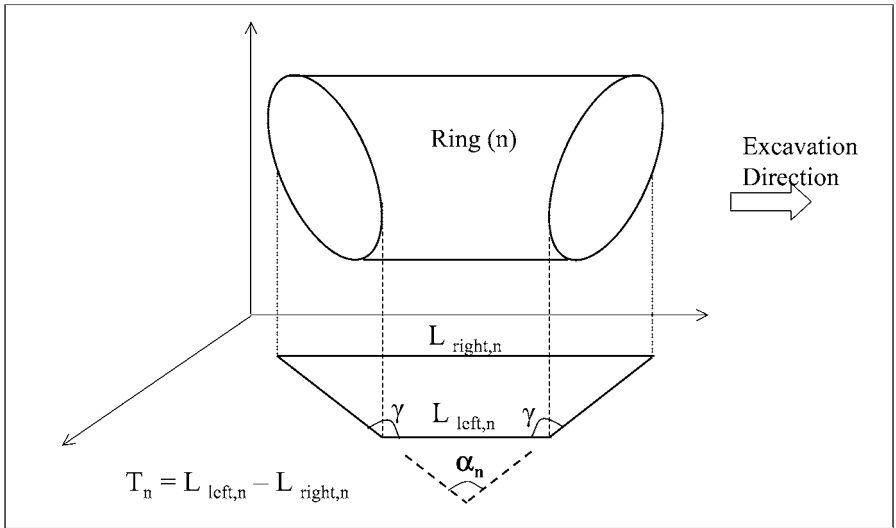


Figure 1. Tapered segment in plan view (α , γ and T)

determined above, to assure that at least one position will provide the exact required taper, and yet leave room for having larger tapers if needed.

Third, the arc lengths and radial joint angles then should be chosen to allow the maximum possible adjacent installation positions that do not cause cruciform joints. Cruciform joints, where four joints come together, are typically the weak points in a gasketed system from a sealing standpoint.

ANALYSIS DURING CONSTRUCTION PHASE

Analysis Purpose

Predicting clearances between the TBM tail shield and the segmental ring ahead of the present position can provide a guideline for future ring selection. Maintaining sufficient clearances is critical to prevent binding of the segments within the shield. This binding often results in delays in ring erection and advancement of the TBM, as well as damage to the segmental lining. Damage often occurs as spalling and cracking, which results in leakage, as well as create zones of structural weakness.

Two methods developed for the Arrowhead Tunnels project predict clearances between the outside edge of the segment and the inside surface of the shield, and aid in the selection of subsequent rings. Up-to-date information is necessary to ensure the accuracy of clearance prediction for subsequently built rings. These methods augment the TBM guidance system, which typically provides possible upcoming ring combinations. Although clearances need to be maintained in both the vertical and horizontal directions, the majority of curves on tunnels are in the horizontal direction where horizontal clearances are more critical, including all five curves on the Arrowhead Tunnels. The methods discussed in this paper are for horizontal clearances only. Between the two methods, input data is applied differently for predicting clearances, focusing either on the clearances themselves, or on the installation of the segment as a whole in order to select subsequent rings.

Common Input Requirements for the Two Methods

For the trapezoidal tapered ring system used on the Arrowhead Tunnels, there are 22 different installation positions, left ring or right ring, at each of 11 different key locations. The key positions are numbered clockwise in order to simplify the installation. Each installation position has a different taper, which is a function of the whether the ring is a left or right ring, and the key position. The maximum taper for the project was set at 38-mm, which occurs for a key position of R1 for turning right-hand curves, and key position L11 for turning left-hand curves. Based on equations above for T_r and α_r , for a typical curve radius (r) of 365.85-m, average segment length (L_o) of 1524-mm, and external diameter of the segmental ring (D_{ext}) of 5537-mm, values of 0.239 degrees and 23.1-mm are calculated, respectively.

Each installation position has a distinctive set of parameters, T_n , α_n , and γ_n , with n denoting the n th ring in a sequence of rings being built, that are used in the analysis methods. The angle (γ) between the base and the side ribs is the key angle used in one of the analysis methods discussed below. These parameters are also shown graphically in Figure 1. T_n is equal to the difference between the length of the ring in plan view on the left side minus the length on the right side, $L_{left,n} - L_{right,n}$. Values of $L_{left,n}$ and $L_{right,n}$ will depend on the amount of rotation of the ring away from the position that yields the maximum taper. The values for α_n , and γ_n are determined as follows:

$$\alpha_n = 2 * \tan^{-1} (T_n / 2 * D_{ext}) \quad (3)$$

$$\gamma_n = 90^\circ + \alpha_n / 2 \quad (4)$$

For positive values of T_n and α_n , the rings will negotiate a curve to the right; negative values indicate a ring for a curve to the left. In a similar fashion, values of γ_n greater than 90 degrees are the same as T_n and α_n with positive values, and γ_n less than 90 degrees is the same as T_n and α_n with negative values. The taper in plan view of each of the 22 installation positions was then determined, as shown in Table 1. These tapers neglect a slight reduction in the segment length due to shortening of the rings from vertical tapers.

The installation position used is mainly dependent on the position of the TBM, the minimal clearances and the sequence of previously installed rings, in order to maintain line and grade, and to avoid cruciform joints to assure proper sealing of the lining system. The input required for both methods is similar, including radius of curve; left and right clearances for previously built rings, between the segment and the inside surface of the tail shield; TBM position relative to the theoretical alignment for previously built rings; and TBM position relative to the theoretical alignment for future rings to be built.

For shielded TBM's, maintenance of adequate shield-ring clearances is the most important factor for subsequent ring selection. The clearance measurements should be taken at the end of the TBM shove, prior to the next ring selection. The measurements for the gaps between the extrados of the ring and the intrados of the shield surface should be made at four different locations: Invert, crown and each springline, as shown in Figure 2.

Local Method

The first approach, described as the "Local Method," utilizes measured clearances, then projects these clearances ahead using the tapers of subsequently built rings, as well as the steering of the TBM. In order to improve the accuracy of the prediction, the trend of previously built rings relative to the steering of the TBM can be used as an initial correction factor. In addition to the common information to both

Table 1. Characteristic parameters for Arrowhead Tunnels rings (α , γ and T)

Ring Type	Key Position	L _{right} (mm)	L _{left} (mm)	Taper (mm)	$\gamma(i)$ (deg)	α (deg)	Curve Direction
Right	1	1505	1543	38	90.1971	0.394	RIGHT
Right	2	1508	1540	32	90.1658	0.332	RIGHT
Right	3	1516	1532	16	90.0819	0.164	RIGHT
Right	4	1527	1521	-6	89.9719	-0.056	LEFT
Right	5	1536	1512	-24	89.8709	-0.258	LEFT
Right	6	1542	1506	-36	89.8109	-0.378	LEFT
Right	7	1542	1506	-36	89.8109	-0.378	LEFT
Right	8	1536	1512	-24	89.8709	-0.258	LEFT
Right	9	1527	1521	-6	89.9719	-0.056	LEFT
Right	10	1516	1532	16	90.0819	0.164	RIGHT
Right	11	1508	1540	32	90.1658	0.332	RIGHT
Left	1	1540	1508	-32	89.8342	-0.332	LEFT
Left	2	1532	1516	-16	89.9181	-0.164	LEFT
Left	3	1521	1527	6	90.0281	0.056	RIGHT
Left	4	1512	1536	24	90.1291	0.258	RIGHT
Left	5	1506	1542	36	90.1891	0.378	RIGHT
Left	6	1506	1542	36	90.1891	0.378	RIGHT
Left	7	1512	1536	24	90.1291	0.258	RIGHT
Left	8	1521	1527	6	90.0281	0.056	RIGHT
Left	9	1532	1516	-16	89.9181	-0.164	LEFT
Left	10	1540	1508	-32	89.8342	-0.332	LEFT
Left	11	1543	1505	-38	89.8029	-0.394	LEFT

methods, additional input can be used to improve the accuracy of the prediction, including TBM position and ring clearances as far as three rings behind the present ring to be built; rotation of the rings in the tangential direction, relative to the theoretical positions (“clocking”); stepping of rings relative to previously built rings; and use of shimming material on the circumferential joint to provide additional taper to the rings. Stepping and shimming may not be known until after the rings are installed, at which time it may be too late to make accurate predictions. However, general trends can be incorporated into this method.

The following equations make up the basis of the Local Method. If correct signs are maintained, these equations are valid for both left curves and right curves.

$$C_{left,n} \cong C_{left,n-1} + \delta_{c,n} + (L_o + T_n / 2) * \sin \psi_n - \delta_{d,n} + \delta_{s,n} \tag{5}$$

$$C_{right,n} \cong C_{right,n-1} - \delta_{c,n} - (L_o - T_n / 2) * \sin \psi_n + \delta_{d,n} - \delta_{s,n} \tag{6}$$

Where: ψ_n = Angle of longitudinal joint plane relative to a reference plane perpendicular to the initial theoretical alignment, as described below.

Figure 3 shows how each of the other terms, δ_c , δ_d and δ_s , are determined, as well as providing sign conventions for each term.

The term $\delta_{c,n}$ is the net offset due to a curved alignment for Ring n compared to the previously built Ring (n - 1), or $\Delta_{c,n} - \Delta_{c,n-1}$. The offset of a curved alignment from

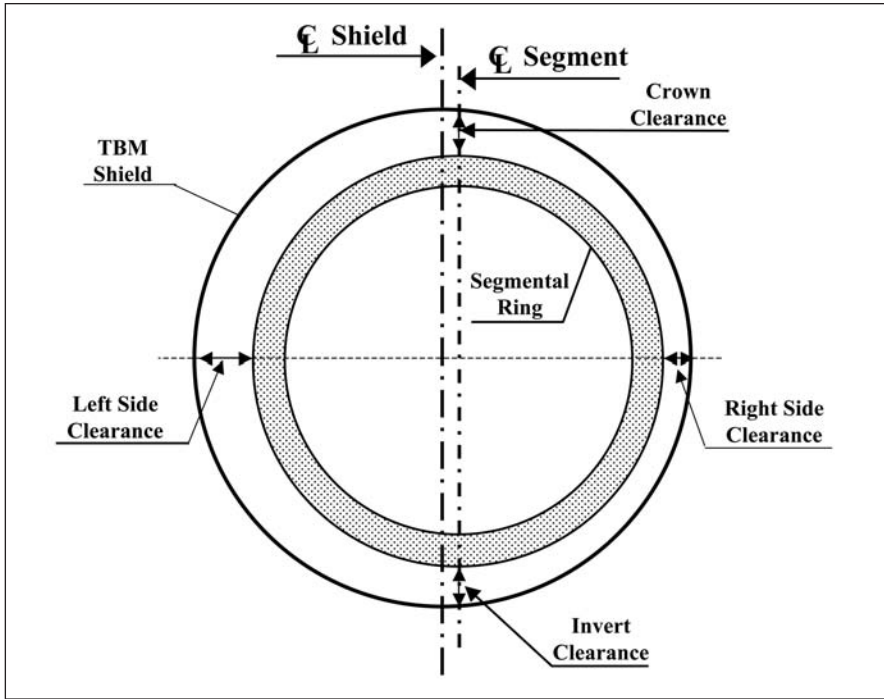


Figure 2. Clearances readings at the TBM's tail shield (looking in direction of tunnel drive)

a straight alignment for Ring n ahead of the present position, $\Delta_{c,n}$, is calculated by the following equation:

$$\Delta_{c,n} = r * (1 - \cos (n \times \alpha_r)) \tag{7}$$

The term $\delta_{d,n}$ is equal to the net offset due to TBM steering effects for Ring n from a previously built Ring (n - 1), $\Delta_{d,n} - \Delta_{d,n-1}$. The term $\Delta_{d,n}$ is equal to the offset of the actual TBM alignment from the theoretical alignment for Ring n. The term $\delta_{s,n}$ is equal to the net offset due to ring stepping for Ring n from a previously built Ring (n - 1).

The term ψ provides the angle of the planar surface of the previously built ring relative to an initial reference plane, upon which the subsequent ring is then built. This angle is a function of the angle of arc length (α_{n-1}) of the previously built ring; the directional tendency of the TBM and previously built rings; and the net thickness of shims ($t_{s,n}$), if used. See Figures 4 to 6 for description of terms ψ , $\Delta\psi_{Shield}$, and $\Delta\psi_{Segment}$, determined by following equations:

$$\psi_1 \equiv (\alpha_o / 2) + \sin^{-1} (t_{s,1} / D_{ext}) + (\Delta\psi_{Shield} + \Delta\psi_{Segment}) \tag{8}$$

$$\psi_n \equiv \psi_{n-1} + \alpha_{n-1} + \sin^{-1} (t_{s,n} / D_{ext}) \tag{9}$$

$$\Delta\psi_{Shield} \equiv \sin^{-1} ((\Delta_{d,-1} - \Delta_{d,-3}) / 2 * L_o) \tag{10}$$

$$\Delta C_{left} = C_{left,-1} - C_{left,-3}; \Delta C_{right} = C_{right,-1} - C_{right,-3} \tag{11}$$

$$\Delta C_{Avg} = (\Delta C_{left} - \Delta C_{right}) / 2 \tag{12}$$

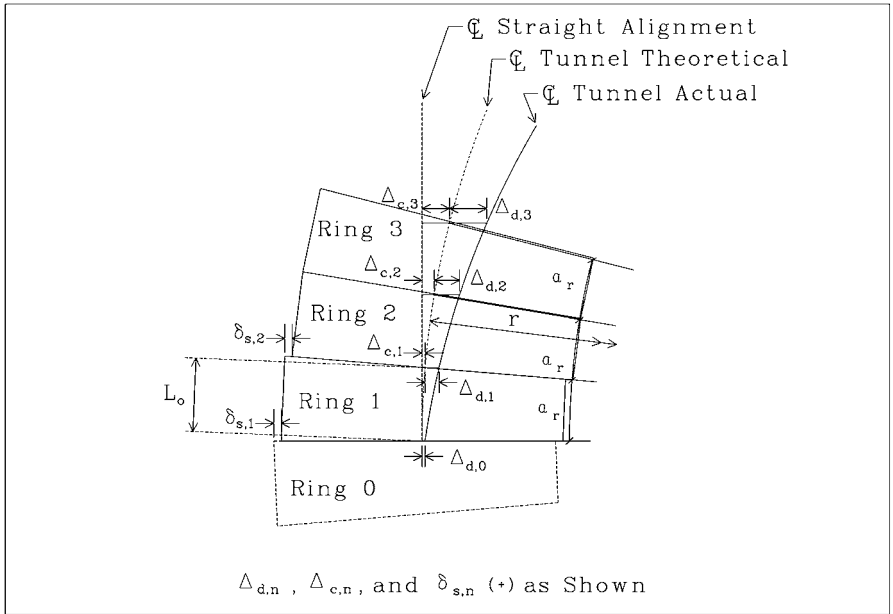


Figure 3. Ring curvature (δ_c), shield drift (δ_d), and ring step (δ_s)

$$\Delta\psi_{\text{Segment}} \equiv \sin^{-1} (\Delta C_{\text{Avg}} / 2 * L_0) \tag{13}$$

Where:

- $\Delta\psi_{\text{Shield}}, \Delta\psi_{\text{Segment}}$ = Correction Factors for angle ψ_1 , accounting for TBM steering tendency or tendency of previously built rings, for two previous rings, respectively
- $\Delta C_{\text{Left}}, \Delta C_{\text{Right}}$ = Net difference in clearance for two previously built rings, for left and right side
- ΔC_{Avg} = Average difference between left and right side of ring clearances

Global Method

The second approach is called the “Global Method.” The basis of this method is building segments in plan view, relative to the shield’s movements. Based upon the segment geometry, the projection of a tapered ring on a two-dimensional horizontal plane generates an isosceles trapezoid, as shown in Figure 7. The angle (γ) between the base and the side ribs is the key angle used in the Global Method, as discussed above, and as shown in Table 1.

The relative horizontal displacement of the tail shield ($\Delta\text{shield}_{(n+1)}$) is described as follows:

For a right curve:

$$\Delta\text{shield}_{(n+1)} \equiv Ds_{(n+1)} - Ds_{(n)} + [r (1 - \text{Cos } \phi)] \tag{14}$$

For a left curve:

$$\Delta\text{shield}_{(i+1)} \equiv Ds_{(n+1)} - Ds_{(n)} - [r (1 - \text{Cos } \phi)] \tag{15}$$

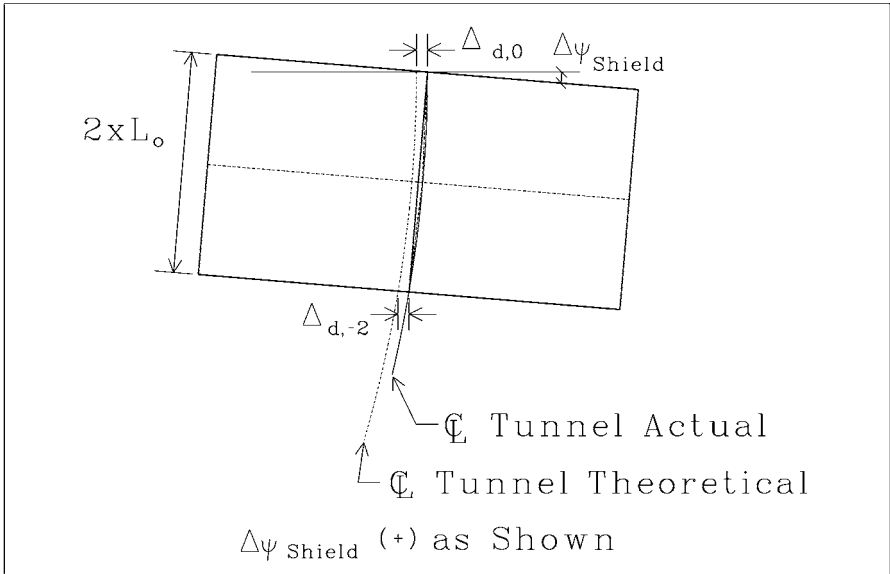


Figure 4. Shield correction factor ($\Delta\psi_{Shield}$)

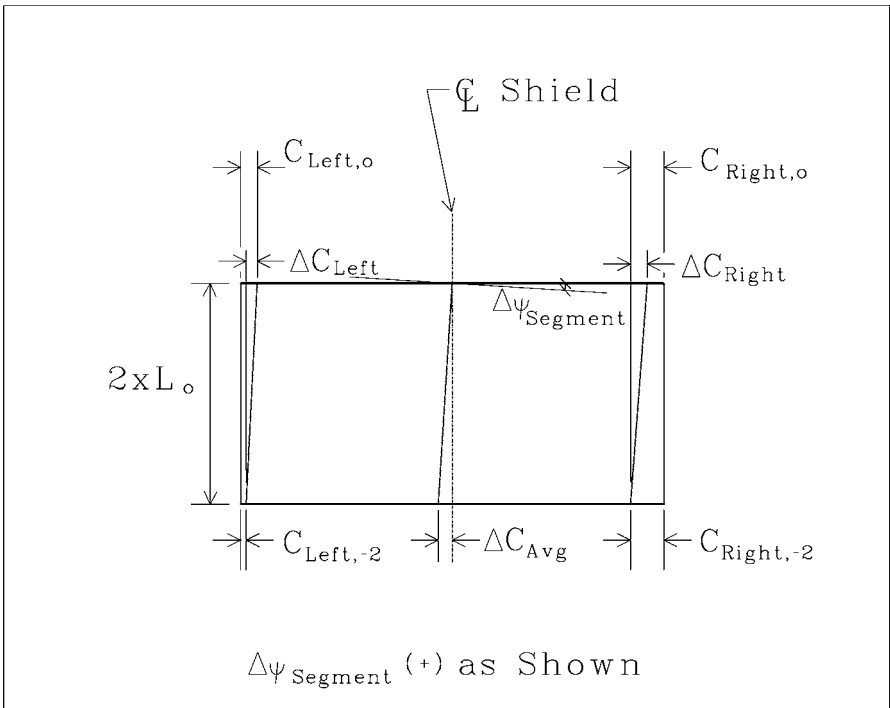


Figure 5. Segment correction factor ($\Delta\psi_{Segment}$)

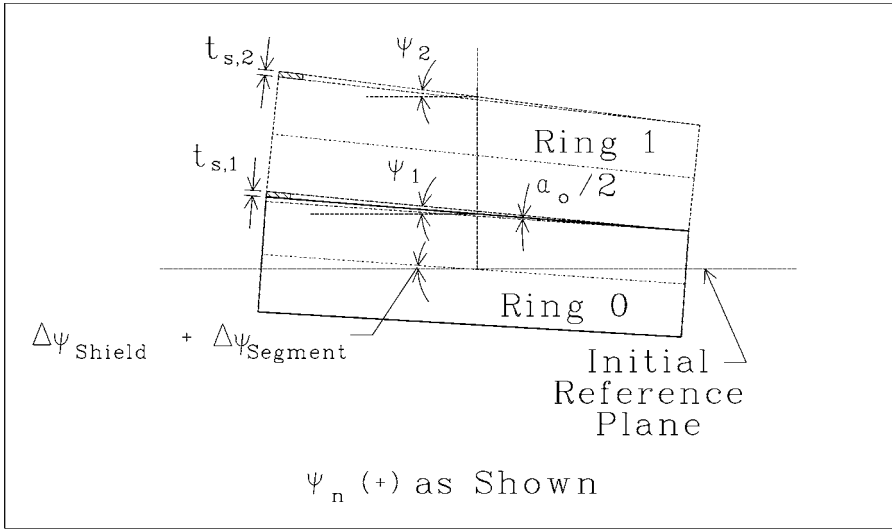


Figure 6. Segment build angle (ψ_1 and ψ_n)

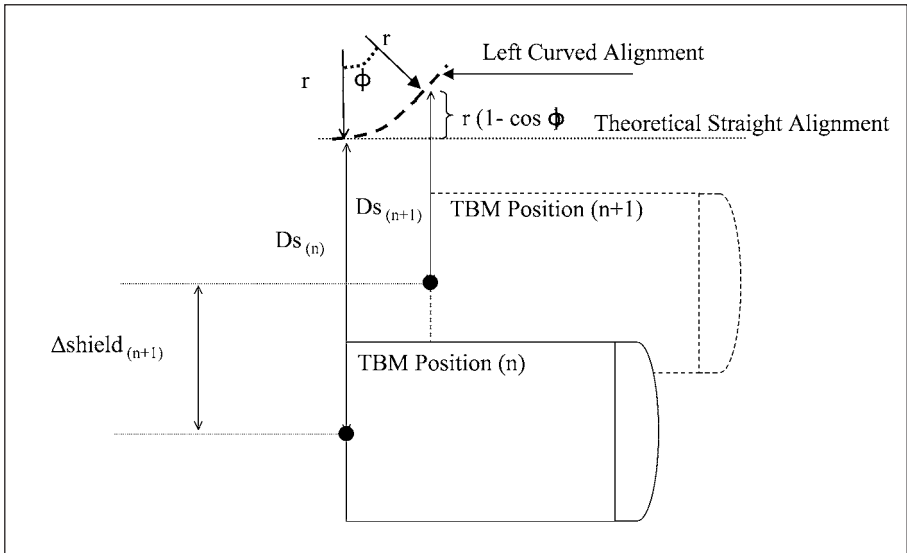


Figure 7. Example of a relative horizontal displacement of TBM's tail shield in a curved alignment

Where:

$\Delta s_{\text{shield}}_{(n+1)}$ represents the horizontal differential displacement of the tail shield between two consecutive positions

$Ds_{(n)}$, $Ds_{(n+1)}$ are the distances of the tail shield to the target alignment for two consecutive TBM positions

φ is the angle between consecutive projected tail shield positions on the curve

Positive values for $\Delta s_{\text{shield}}_{(n+1)}$ occur if a subsequent shield position (n + 1) moves to the right with respect to the previous shield position (n). The signs for $Ds_{(n)}$ and $Ds_{(n+1)}$ are the same as the one used by the TBM guidance system (i.e., negative values for left of the target, or positive for right of the target). In order to evaluate angle (φ), the following approximation can be used:

$$\varphi \cong \text{Sin}^{-1} (L_o / r) \quad (16)$$

To clarify the key principals of the Global Method, a projected baseline ring is described. A rectangular coordinate system is positioned in which the origin (0,0) is located at the back right corner of the initial baseline ring, as shown on Figure 8.

Two shield locations are the basis for the initial values for the analysis, which are derived from five values tied to the baseline ring and the relative movement of the shield. The five values consist of the key position of the baseline ring, distances from the backside of the tail shield to the target line for the two consecutive TBM positions (i.e., $Ds_{(0)}$ and $Ds_{(1)}$, respectively) and the measured clearances on the right side of the baseline ring at the initial and subsequent shield positions, (i.e., C_{PreBase} and $C_{\text{right},0}$, respectively). Once the above values have been obtained, the geometric values of the isosceles trapezoid, ($L_{\text{right},0}$), ($L_{\text{left},0}$) and ($\gamma_{(0)}$), can be determined, as discussed above. The relative initial displacement of the tail shield ($\Delta s_{\text{shield}}_{(1)}$) can be determined based on the alignment type, per equations [14] to [15]. The angle ($\beta_{(0)}$), which is the angle between the right side of the baseline ring and the x-axis, is initially adjusted by the following equation based on geometrical relations:

$$\beta_{(0)} = \text{sin}^{-1} (\Delta Y_{\text{right},0} / L_{\text{right},0}) \quad (17)$$

$$\Delta Y_{\text{right},0} = C'_{\text{right},0} - \Delta \text{Shield}_{(1)} - C_{\text{PreBase}} \quad (18)$$

Where: C_{PreBase} is the measured right clearance of a ring prior to the baseline ring.

$C'_{\text{right},0}$ is the measured right clearance of the baseline ring subsequent to the first full shove of the shield.

The angle $\beta_{(0)}$ is a vital factor in the determination of the following ring sequences, and thus should be carefully computed and checked. Using the above adjustments determined by the baseline ring, the first prediction for the next ring position can be made.

By advancing the shield a ring, the predicted ring-shield clearances at the leading edge of the installed ring, shown in Figure 8, can be computed. The influence of the previous shield movement should be added to the leading edge clearances, as follows:

$$C'_{\text{right},n-1} \cong C_{\text{right},n-1} + \Delta \text{Shield}_{(n)} \quad (19)$$

$$C'_{\text{left},n-1} \cong C_{\text{left},n-1} - \Delta \text{Shield}_{(n)} \quad (20)$$

Where: $C'_{\text{right},n-1}$, $C'_{\text{left},n-1}$ are right and left clearances of the previous ring (n - 1) after a full shove of the shield, respectively.

$C_{\text{right},n-1}$, $C_{\text{left},n-1}$ are right and left clearances of a previous ring (n - 1) prior to a full shove of the shield, respectively.

As a general guide for ring selection, the intention of selecting rings is to balance the leading-edge ring-shield clearances, which depends on the ring type options.

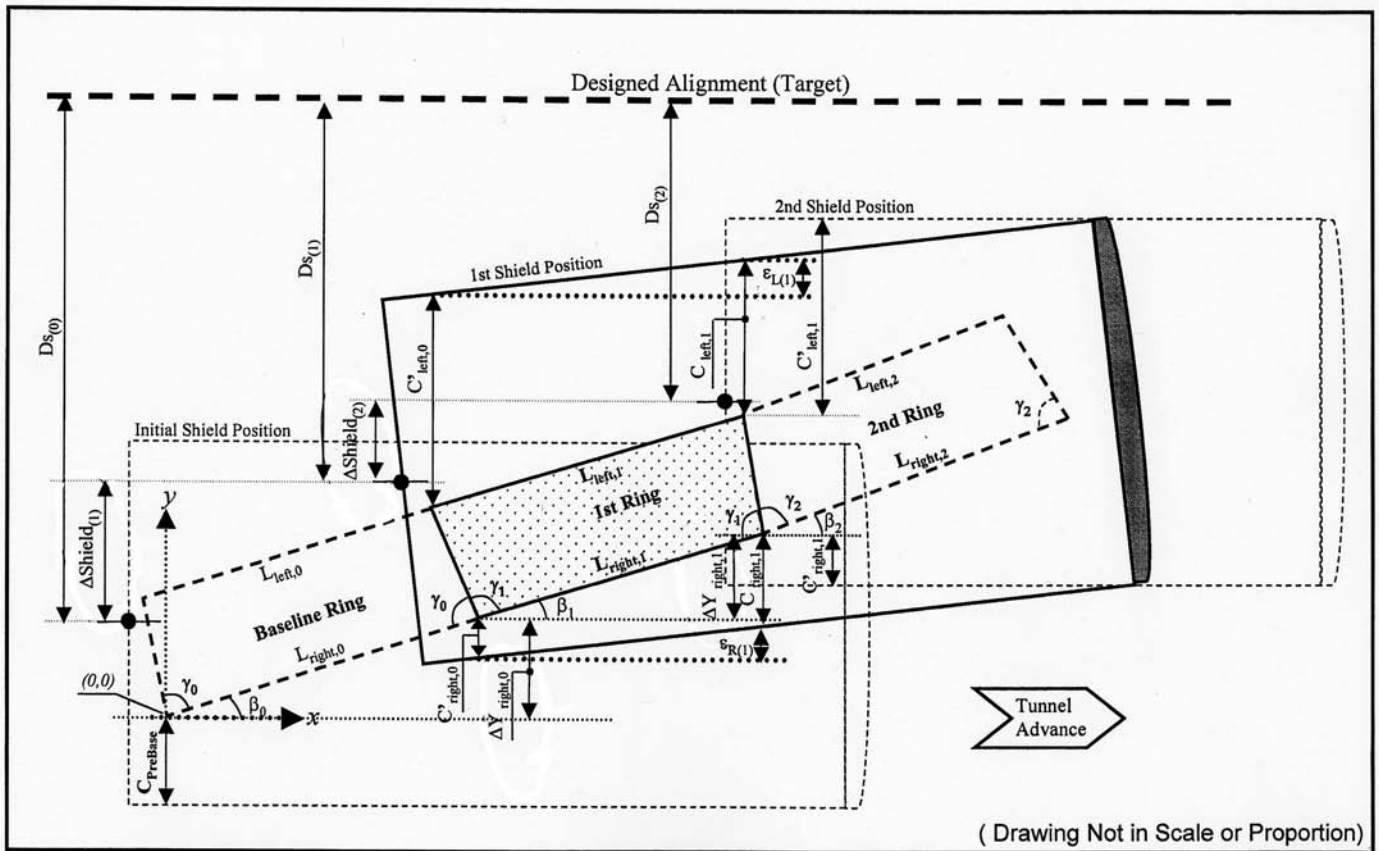


Figure 8. Plan view of shield sequence for the global method analysis

Hence, the difference between $C_{right,n}$ and $C_{left,n}$ should be minimal, where $C_{right,n}$ and $C_{left,n}$ are the predicted right and left clearances at the ring leading edge after installation and prior to shield movement. Consequently, the above clearances can be determined as follows:

$$C_{right,n} \cong C'_{right,n-1} + L_{right,n} * \sin \beta_{(n)} + \varepsilon_{R(n)} \quad (22)$$

$$C_{left,n} \cong C'_{left,n-1} - L_{left,n} * \sin \beta_{(n)} - \varepsilon_{L(n)} \quad (23)$$

Where: $\varepsilon_{R(n)}$, $\varepsilon_{L(n)}$ are the additional influence in clearance at the leading edge of ring (n) due to a tendency of the shield.

$\beta_{(n)}$ is the angle of the ring tendency in respect to the x-axis, as discussed above.

$\varepsilon_{R(n)}$, $\varepsilon_{L(n)}$ are determined by the projection of the shield tendency at the required location. Note that positive values occur if the front shield drifts to the right with respect to the tail shield position.

It should be emphasized that the calculation of the ring tendency angle ($\beta_{(n)}$) would be maintained by the following series:

$$\beta_{(n)} \cong 180^\circ * n - \gamma_{(n)} - 2*\gamma_{(n)} - 2*\gamma_{(n-1)} - 2*\gamma_{(n-2)} - \dots - 2*\gamma_{(1)} + \beta' \quad (n > 0) \quad (24)$$

$$\beta' = + (\beta_{(0)} - \gamma_{(0)}) \quad (25)$$

Since ($L_{right,n}$), ($L_{left,n}$) and ($\gamma_{(n)}$) are characteristic of a relative installation position, and have relationships between themselves, the value of ($\beta_{(n)}$) could be derived as follows:

$$\beta_{(n)} \cong \sin^{-1} [(C'_{left,(n-1)} - C'_{right,(n-1)} - 2*\varepsilon_{(n)}) / (2*L_o)] \quad (26)$$

Where: $C'_{left,(n-1)}$ and $C'_{right,(n-1)}$ are the new ring-shield clearances of the previous installed ring after a full shove.

Having found the required angle $\beta_{(n)}$, and as a result of deriving $\gamma_{(n)}$ from equations (24) and (25), the ring can be chosen as the closest ring that meets the recommended $\gamma_{(n)}$ angle.

RESULTS

Based on comparison of actual clearances measured in the first curve on AWT, which consisted of over 100 installed rings, the results of the two methods have been compared. The following conclusions can be made for the accuracy of the Local Method to predict clearances:

- Prediction of clearances for the first ring to be built were within 6-mm for 60% of the actual measured clearances, and about 90% of the rings analyzed were within 12.5-mm.
- Prediction of clearances for the second ring to be built were 12.5-mm for 70% of the actual measured clearances, and 85 to 90% of the rings analyzed were within 19-mm.

The following conclusions can be made for the ability of the Global Method to predict clearances:

- Prediction of clearances for the first ring to be built were within 8-mm for 60% of the actual measured clearances, and about 80% of the rings analyzed were within 12.5-mm.
- Prediction of clearances for the second ring to be built were within 10-mm for 60% of the actual measured clearances, and 85 to 90% of the rings analyzed were within 19-mm.

CONCLUSIONS

During the design phase for trapezoidal tapered bolted and gasketed segmental linings, selection of maximum ring tapers, as well as reduced tapers for various key positions, should be selected to meet the required parameters for the given curves on the project. Arc lengths of each segment, and angles of the radial joints relative to the longitudinal length should be selected to reduce the occurrence of cruciform joints, which are susceptible to leaking.

Both the Local and Global Methods can predict clearances with a reasonable degree of accuracy for the next ring to be built. In addition, clearances two rings ahead of the existing location can be estimated, but with a lesser degree of accuracy. Predictions beyond two rings in curved alignments have not been consistent to date, although general trends (increasing or decreasing clearances) can be predicted. Data from future curves may be used to refine and later combine these methods in order to improve accuracy. In addition, prediction of clearances for potential ring sequences is properly modeled for both methods, allowing certain ring sequences to be tested prior to implementation in the field. Using these methods, ring selection programs used by TBM guidance systems can be used to assure that the recommended sequences will maintain adequate clearances.

The key issue for the effectiveness of both methods is predicting initial correction factors ($\Delta\psi_{o,shield}$ and $\Delta\psi_{o,segment}$ for the Local Method, and $\beta_{(0)}$ for the Global Method). Minor adjustments in these factors can result in significantly different predicted clearances, especially more than two or three rings ahead of the present location.