

Research Article

Selection of the Key Segment Position for Trapezoidal Tapered Rings and Calculation of the Range of Jack Stroke Differences with a Predetermined Key Segment Position

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It is generally accepted that selecting the key segment position for trapezoidal tapered rings and controlling the shield machine advancement are challenging tasks for shield tunneling projects. In this work, we propose a method for calculating the key segment position based on the shield tail gap, jack stroke difference, and lining trend. To calculate all possible key segment positions other than that corresponding to the straight joint configuration, the shield tail gap that remains after segment assembly and the jack stroke difference corresponding to the advancement of the segmental lining and lining trend were computed; then, values and importance coefficients were assigned to these factors according to current operating conditions. To ensure that the segmental lining can be assembled successfully with the calculated key position, we established a model to calculate the change in the shield tail gap before and after shield machine advancement based on the spatial relationships of the shield machine, the currently installed segmental rings, and the segment to be installed. Further, we propose a method for calculating the range of jack stroke differences when the predetermined “permitted shield tail gap” and key position are provided. The method is based on the change in the shield tail gap calculated with the above model and the positional relationship between the shield machine’s actual axis and the designed tunnel axis after the current segmental ring has been assembled. The calculated range of jack stroke differences may then be used to control the advancement of the shield machine. We validated the viability of our methods by using the data of Phase 1 works on Line 2 of the Ningbo Rail Transit system.

1. Introduction

In the field of urban tunnel construction, shield tunneling has become the preferred method, as it causes minimal ground disturbance and allows for fast construction. The trapezoidal tapered ring is a tunnel lining method that is becoming increasingly popular because of its cost-effectiveness, simple construction, and adaptability for a wide range of radius curves [1]. However, a tapered ring has many potential key segment positions (or key positions), which makes their selection a challenging task. If the key positions are not selected correctly, the segments will not fit the designed tunnel axis. This can cause the shield machine to deviate from the designed tunnel axis or damage the

segmental lining. In addition, the advancement of the shield machine directly affects segment installation. If the advancement of the shield machine is not controlled as per operating conditions, it may become impossible to install the segmental ring with its calculated key position, which will subsequently affect the quality of the construction. Therefore, studies on selecting the key position and controlling shield machine advancement with a predetermined key position are very important for engineering applications.

A number of important research findings have been obtained in China and abroad about the key position selection for trapezoidal tapered rings and shield machine advancement. In studies on technologies for the construction of tapered rings, Song used the least-squares method to

optimize the selection of the segment posture [2]. Li et al. created an algorithm for calculating the coordinates of the key position on planar and vertical curves, a bisection algorithm for calculating the ideal key positions of a tunneling route, and a computational geometry algorithm for a spatially arbitrary point rotating around an arbitrary axis [3]. Zhao et al. optimized the design of the ring thickness, overall ring deflection, ring segmentation/joint positioning, and segment assembly methods [4]. Song et al. analyzed the principles that underlie the design of ring segmentation, key position, and ring dimensions [5]. Zhang et al. used the coordinate system transformation theory to derive a method for segment typesetting that is based on the positional parameters of segment erectors in segment assembly processes [6]. Hu proposed a classification method based on a restrained support vector machine, which can regulate the position of the key segments by utilizing historic engineering data [7]. Zhang et al. calculated the advancement of the segmental lining in different directions and analyzed the influencing factors that need to be considered in the layout design for universal segmental lining combined with actual construction experience [8]. Besides, Li and He simulated segment lining with the beam-spring model and calculated loads acting on segment lining with the load-structure model [9]. Yang et al. chose three test sections with different geological conditions to study the segment internal force during the construction of the shield tunnel [10]. Chen and Mo analyzed a tunnel with 9 segment rings by the three-dimensional finite element method [11]. The loads include injected pressure, jacking force, and squeezing action of the tail of shield machine. The analytical results indicate that during the construction stage, the difference of loads along longitudinal direction causes various displacements and stress distributions in different segment rings.

In studies on shield machine advancement, Xu et al. developed a method for calculating the thrust force of Earth pressure balance (EPB) shield machines and investigated the factors that affect this force based on the excavation mechanisms of these machines [12]. Dai divided the total buoyancy force experienced by the rings behind the shield machine into static and dynamic components based on the assumptions of ideal simultaneous backfill grouting and negligible changes in grout characteristics [13]. The static component is generated by the envelopment of the liquid grout, while the dynamic component changes with the ground conditions and buried depth of the tunnel. Formulas to calculate these buoyancy force components were also derived. Li et al. experimentally studied how Earth pressures inside and outside the soil chamber are correlated with changes in the cutter disc torque and thrust, as well as factors that influence this correlation [14]. In addition, they studied the effects of the cutter disc's opening ratio on the total thrust of the shield machine and the torque of the cutter disc.

In addition to the above studies, a large amount of basic research has been performed on selecting segmental linings, calculating the key position, axial line fitting, and the mechanical properties of segmental linings [15–28]. Although a number of important results have been obtained, the vast majority of studies on tapered rings have focused on

segment measurement, structural optimization, correcting the segment typesetting process, or the selection of segment types. Studies on controlling shield machine advancement have been relatively scarce.

In most of the above studies, the distance between the fitted center of the segment assembly plane and the target point of the designed tunnel axis was often the sole consideration to calculate the key position. Other operating conditions were simply overlooked. Furthermore, many of the proposed methods cannot fully prevent the occurrence of straight joints, which reduce the applicability of the calculated key position. Even after the key position of the segment to be installed has been determined, a mature and reliable method for controlling shield machine advancement toward the next segmental ring does not currently exist. Consequently, ring assembly in the calculated key position may be impossible under certain circumstances. In this work, we constructed a model for calculating the change in shield gap before and after shield machine advancement, and we propose a method for calculating the key position based on the shield tail gap, jack stroke difference, and lining trend. These methods are based on the spatial relationship between the shield machine, current segmental ring, and ring to be installed as well as a careful review of the existing literature. We also established a method for calculating the range of jack stroke differences for shield machine advancement to the next ring when the key positions are fully determined and a “permitted shield tail gap” has been defined. This method is based on the positional relationship of the shield machine's actual axis with the designed tunnel axis after the current ring has been assembled.

2. Calculation of Key Positions in Tapered Rings

2.1. Factors That Affect the Key Position Calculation. The shield tail gap, jack stroke difference, and lining trend were selected as the most important factors for calculating the key position based on actual field conditions and spatial relationships between the segmental lining, shield machine, and designed tunnel axis during shield machine advancement.

2.1.1. Shield Tail Gap. The segment is assembled into a ring at the shield tail and then ejected. However, the shield machine always deviates slightly during the tunneling process. Therefore, a gap between the shield housing and the outer surface of the segment (i.e., the “shield tail gap”), as shown in Figure 1, is necessary to ensure that the next ring can be safely assembled. The shield tail gap is defined as the shortest distance from the outer ring at the front end of the assembled segmental ring to the inner ring of the shield housing.

In theory, there is an ideal value for the shield tail gap in the top, bottom, left, and right directions. However, during the tunneling and assembly processes, the shield tail gap changes because of the jack stroke difference and advancement corresponding to each key position. The shield tail gap (a_2) after the segmental ring assembly consists of two parts: the shield tail gap of the previous segmented ring a_1 and the change in the shield tail gap d :

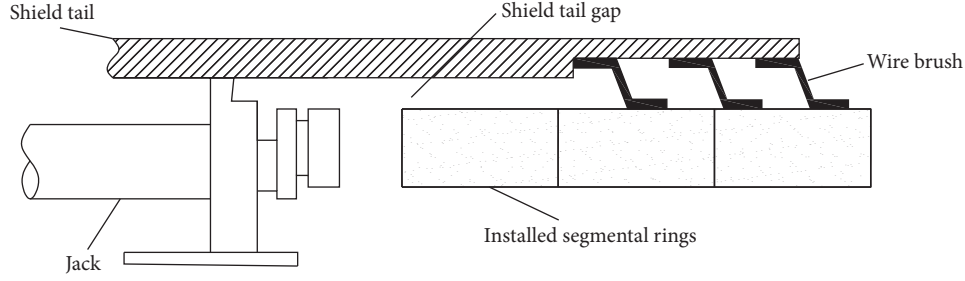


FIGURE 1: Schematic diagram of the shield tail gap.

$$a_2 = a_1 + d. \quad (1)$$

The total change in the shield tail gap d consists of changes in the shield tail gap that are caused by jack stroke differences d_1 and the key position of the segment to be installed d_2 :

$$d = d_1 + d_2, \quad (2)$$

where

$$d_1 = \pm \frac{\Delta s B}{D_j}. \quad (3)$$

$$d_2 = \begin{cases} \pm \frac{\delta B}{2D_r} \cos\left[\frac{\pi}{8}(N_1 - 1)\right] \\ \pm \frac{\delta B}{2D_r} \sin\left[\frac{\pi}{8}(N_1 - 1)\right] \end{cases} \quad (4)$$

Here, Δs is the stroke difference of the jack (mm), B is the width of the segment (mm), D_j is the diameter of the jack (mm), D_r is the segment diameter (mm), δ is the taper of the tapered ring (mm), and N_1 is the key position of the segment to be installed. Equations (4) calculate the vertical and horizontal changes, respectively, in the shield tail gap. d_1 and d_2 are positive for shield tail gaps at the top and right sides of the segmental ring and negative for gaps at the bottom and left sides.

The shield tail gap of the previous segmental ring is obtained using an automated measurement system. The above equations are then used to calculate the postassembly shield tail gap. If the postassembly shield tail gaps in the top, bottom, left, and right directions are greater than permitted, this position may then be selected for ring assembly. If the postassembly shield tail gaps do not meet the above criterion, then this position cannot be selected for ring assembly.

2.1.2. Jack Stroke Difference. The jack stroke difference can vary significantly during the tunneling process of a shield machine. If the jack stroke difference is very large, the segmental rings will be subjected to excessively large force differentials, and the attitude of the shield machine also becomes difficult to control. Therefore, the effects of the jack stroke difference should be considered when selecting the key position for the next segmental ring. Because the

advancement of the segmental ring (due to the selected key position) should match the intended advancement of the designed tunnel route, the advancement of each possible key position should be calculated in the horizontal and vertical directions by using (5) and (6), respectively. A threshold value may then be defined for the jack stroke difference according to the operating conditions. A key position should not be selected if the resulting postassembly stroke difference exceeds this threshold value.

$$\Delta r_v = -\delta \cos\left[\frac{\pi}{8}(N_1 - 1)\right], \quad (5)$$

$$\Delta r_l = \delta \sin\left[\frac{\pi}{8}(N_1 - 1)\right]. \quad (6)$$

2.1.3. Lining Trend. During the advancement of a shield machine, the assembled segments should fit the designed tunnel axis in both distance and angle. The lining trend is defined as the distance and angular deviations of the segment axis from the designed tunnel axis. Hence, the main objective when selecting the key position is to minimize the distance and angular deviations between the segment axis and the designed tunnel axis to ensure that the segmental rings are closely aligned with the latter axis.

It is easy to observe that distance deviations induced by the key position are equivalent to changes in the shield tail gap. Therefore, distance deviations can be calculated with equations (4). Angular deviations induced by the key position in the vertical and horizontal directions may be calculated with (7) and (8), respectively:

$$\arcsin\left\{\frac{\delta}{2D_r} \cos\left[\frac{\pi}{8}(N_1 - 1)\right]\right\} \approx \frac{\delta}{2D_r} \cos\left[\frac{\pi}{8}(N_1 - 1)\right], \quad (7)$$

$$\arcsin\left\{\frac{\delta}{2D_r} \sin\left[\frac{\pi}{8}(N_1 - 1)\right]\right\} \approx \frac{\delta}{2D_r} \sin\left[\frac{\pi}{8}(N_1 - 1)\right]. \quad (8)$$

Because the key position should be selected to minimize distance and angular deviations between the segment axis and designed tunnel axis, the lining trend needs to be minimized. This is performed by calculating and comparing the distance and angular deviations induced by different possible key positions in various practical settings.

2.2. Segment Position Selection and Software Development. Visual Basic was used to develop an automated position selection program to calculate key positions for segmental ring assembly. After the shield tail gap, jack stroke difference, and lining trend are measured or calculated, each candidate key position is assigned a value based on the principles of key position selection. This value indicates the “selectability” of a candidate key position according to the previously described conditions. Candidate key positions that are suitable for selection have a value of 1, while positions that cannot be selected have a value of 0.

2.2.1. Shield Tail Gap. The shield tail gaps are calculated in the top, bottom, left, and right directions after the assembly of the next segmental ring. If the gaps in all directions are greater than some defined limit, a value of 1 is then assigned to this candidate key position. If the gap in some direction is less than the limit, a value of 0 is then assigned to the candidate key position.

2.2.2. Jack Stroke Difference. The jack stroke differences are calculated in the horizontal and vertical directions after the assembly of the next segmental ring. If these stroke differences fall within a certain limit, a value of 1 is then assigned to the candidate key position; a value of 0 is assigned otherwise.

2.2.3. Lining Trend. Distance and angular deviations in the horizontal and vertical directions after the assembly of the next segmental ring are calculated. If the values of these deviations fall within a certain range of limits, a value of 1 is then assigned to the candidate key position; a value of 0 is assigned otherwise.

The above limits should be selected rationally according to actual operating conditions. In special circumstances (e.g., an excessively large jack stroke difference), a larger value should be assigned to the selectable key positions. This is because the attitude of the shield machine is very poor in this instance, and the jack stroke difference needs to be corrected in a timely manner. A larger value is thus assigned to the selectable key positions. In this case, all selection factors other than the jack stroke difference may be neglected until it has been reduced to an acceptable value.

Each candidate position has three assigned values V_{1i} , V_{2i} , and V_{3i} , which correspond to the shield tail gap, jack stroke difference, and lining trend, respectively. The overall value of each candidate position is the sum of these factors multiplied by their corresponding importance coefficients I_{1i} , I_{2i} , and I_{3i} .

The overall value of each position is

$$J_i = V_{1i}I_{1i} + V_{2i}I_{2i} + V_{3i}I_{3i}, \quad (9)$$

where J_i is the overall value of a candidate position; V_{1i} , V_{2i} , and V_{3i} are the values associated with the shield tail gap, jack stroke difference, and lining trend, respectively; I_{1i} , I_{2i} , and I_{3i} are the important factors associated with the shield tail

gap, jack stroke difference, and lining trend, respectively; and i represents a candidate position.

The importance coefficients are selected as follows. The shield machine operator selects the importance coefficients of the factors according to his or her judgment of the current situation; certain factors may be assigned larger values if a problematic situation is encountered. For example, if the shield tail gap is currently very poor while the jack stroke difference and lining trend are satisfactory, a larger importance coefficient is assigned to the shield tail gap. The degree of importance, therefore, depends on the judgment and selection of the shield machine operator.

The above calculations can be used to calculate n selectable candidate key positions for the next segmental ring by using the key position of the previous segmental ring. The overall calculated values of these n positions are then compared, and the next ring is then assembled with the key position having the greatest overall value. The Visual Basic programming language was used to write a program that performs our key position calculations.

3. Calculating the Range of the Jack Stroke Differences in Tapered Rings

Even after the key positions are fully determined, assembling the segments in the calculated key positions during the tunneling process may not be possible, or the segments may simply break after being assembled. This is caused by a lack of theoretical research on the advancement of shield machines toward the next ring. To address this issue, we propose a method for controlling the advancement of a shield machine by calculating the range of Jack stroke differences needed to reach the next ring.

3.1. Calculation of the Shield Tail Gaps before and after Shield Machine Advancement. The shield tail gap is the most important factor for determining whether a segment can be assembled successfully. If the shield tail gap is too small, the shield tail will interfere with the segment during shield machine advancement. A minimal level of interference will increase resistance against the advancement of the shield machine, whereas a severe level of interference can lead to dislocations or damage in the segmental ring that will subsequently induce tunnel leakage or surface settlement. Because the shield tail gap has a significant impact on the advancement process, this factor was selected as the controlling index for calculating Jack stroke differences.

3.1.1. Shield Tail Gap after the Current Ring Has Been Released from the Shield Tail at the End of the Shield Machine's Advancement. Figure 2 illustrates the calculation of the shield tail gap after a segmental ring is released at the end of the shield machine's advancement. The contact between the installed segmental ring and jack is the datum plane, and the manually measured shield tail gap of the previous segmental ring after the advancement of the shield machine is a_1 . If the shield tail gap after the current segmental ring is released from the tail is a_3 and all shield machine displacements

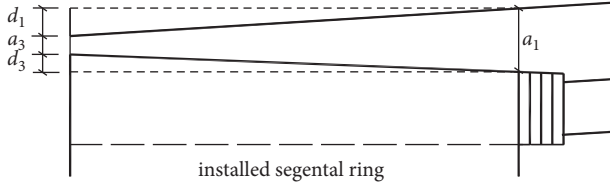


FIGURE 2: Diagram of the shield tail gap upon the release of a segmental ring at the end of the shield machine's advancement.

caused by other factors are negligible, the following equation may then be obtained from the geometric relationship between the shield machine and segmental lining:

$$a_3 = a_1 - d_1 - d_3, \quad (10)$$

where d_1 is calculated from Equation (3) and d_3 is the change in the shield tail gap caused by the installed segmental ring. The vertical and horizontal components of this change may be calculated using equation (11), respectively:

$$d_3 = \begin{cases} \pm \frac{\delta B}{2D_r} \cos \left[\frac{\pi}{8} (N_1 - 1) \right] \\ \pm \frac{\delta B}{2D_r} \sin \left[\frac{\pi}{8} (N_1 - 1) \right] \end{cases}, \quad (11)$$

where N_2 is the key position of the installed segment. All other symbols retain their previous definitions.

3.1.2. Shield Tail Gap at the Segment after the Next Segmental Ring Has Been Fully Assembled. Further constraints may be applied to the jack stroke difference by considering the shield tail gap after the next segmental ring has been assembled. The shield tail gap after the assembly of the next segmental ring (a_2) can be calculated using equations (1)–(4).

The vertical top-side shield tail gap is taken as an example here. Substituting (3) and (11) into (3) and (10) and (4) into (1) yields

$$a_3 = a_1 - \Delta s \frac{B}{D_j} - \frac{\delta B}{2D_r} \times \cos \left[\frac{\pi}{8} (N_1 - 1) \right], \quad (12)$$

$$a_2 = a_1 + \Delta s \frac{B}{D_j} + \frac{\delta B}{2D_r} \times \cos \left[\frac{\pi}{8} (N_1 - 1) \right]. \quad (13)$$

3.2. Calculating the Range of Jack Stroke Differences with Predetermined Key Positions. A reasonable range of values for the shield machine's jack stroke difference may be acquired by applying constraints based on the shield tail gap. Determining the range of jack stroke differences is effectively a method for controlling shield machine advancement that is compatible with segment typesetting schemes.

Boundary conditions are added to (12) and (13). The shield tail gap when the current ring is released from the shield tail (a_3) and the shield tail gap after the next segmental ring is assembled (a_2) should not be smaller than ε (i.e., $a_2 = a_3 \geq \varepsilon$). By setting $a_2 = a_3 = \varepsilon$, the range of the jack stroke

difference Δs , which is represented by $[x_1, x_2]$, may then be calculated with equations (12) and (13). The minimum requirements of the upper shield tail gap on the top side are satisfied when $\Delta s \in [x_1, x_2]$. The range of Δs for the shield tail gap on the bottom side, which is represented by $[x_3, x_4]$, may be calculated in the same way. The results of $[x_1, x_2] \cap [x_3, x_4]$ are then denoted as $[x_{\min}, x_{\max}]$. When all other factors are negligible, $[x_{\min}, x_{\max}]$ is the vertical range of jack stroke differences that satisfies the minimum shield tail gap. Similarly, the horizontal range of jack stroke differences that satisfies the minimum shield tail gap may be calculated by using the minimum shield tail gaps on the right and left sides of the shield tail.

To further minimize the calculated range of jack stroke differences, the positional relationship between the actual axis of the shield machine and the designed tunnel axis needs to be considered. The initial stroke difference in the vertical direction after the current segmental ring is assembled is denoted as Δs_0 , and the height deviations of the shield machine and shield tail are denoted as h_1 and h_2 , respectively. These height deviations are positive if the shield machine is above the designed tunnel axis and negative if the shield machine is below the designed tunnel axis. The goal is to keep the shield machine moving along the direction of the designed tunnel axis.

When $\Delta s_0 \in [x_{\min}, x_{\max}]$, the following values define the vertical range of jack stroke differences that satisfies the minimum shield tail gap:

When $h_1 < h_2$, $\Delta s \in [x_{\min}, \Delta s_0]$;

When $h_1 > h_2$, $\Delta s \in [\Delta s_0, x_{\max}]$;

When $h_1 = h_2$,

If $h_1 > 0$ and $h_2 > 0$, then $\Delta s \in [\Delta s_0, x_{\max}]$;

If $h_1 < 0$ and $h_2 < 0$, then $\Delta s \in [x_{\min}, \Delta s_0]$;

If $h_1 = h_2 = 0$, then $\Delta s = \Delta s_0$.

If $\Delta s_0 \notin [x_{\min}, x_{\max}]$, the requirements of the shield tail gap need to be prioritized to ensure that the segmental lining does not break or crack. Hence, the constraints imposed by the need to fit the designed tunnel axis are abandoned in this instance, and the value of Δs_0 remains within $[x_{\min}, x_{\max}]$.

The range of jack stroke differences in the horizontal direction may be calculated in a similar manner. The Visual Basic programming language was used to write the software for calculating the range of Jack stroke differences.

4. Case Study

4.1. Project Overview. Project TJ2101 (Phase 1 in Line 2 of the Ningbo Rail Transit system) covers the section from Lishe Station up to Yinzhou Avenue Station. Shield tunneling was used to construct this section. The design lengths of the up and down lines were 1463.318 and 1445.695 m, respectively. The running tunnel has a minimum buried depth of 5.8 m and a maximum buried depth of 21.6 m. Most of the tunnel is situated in (2) 2 gray silty clay, (4) 1 silty clay, (5) 1 clay, and (5) 1a sandy silt clay. The soil layers are therefore weak and unstable, so they are prone to uneven settlement and large deformations.

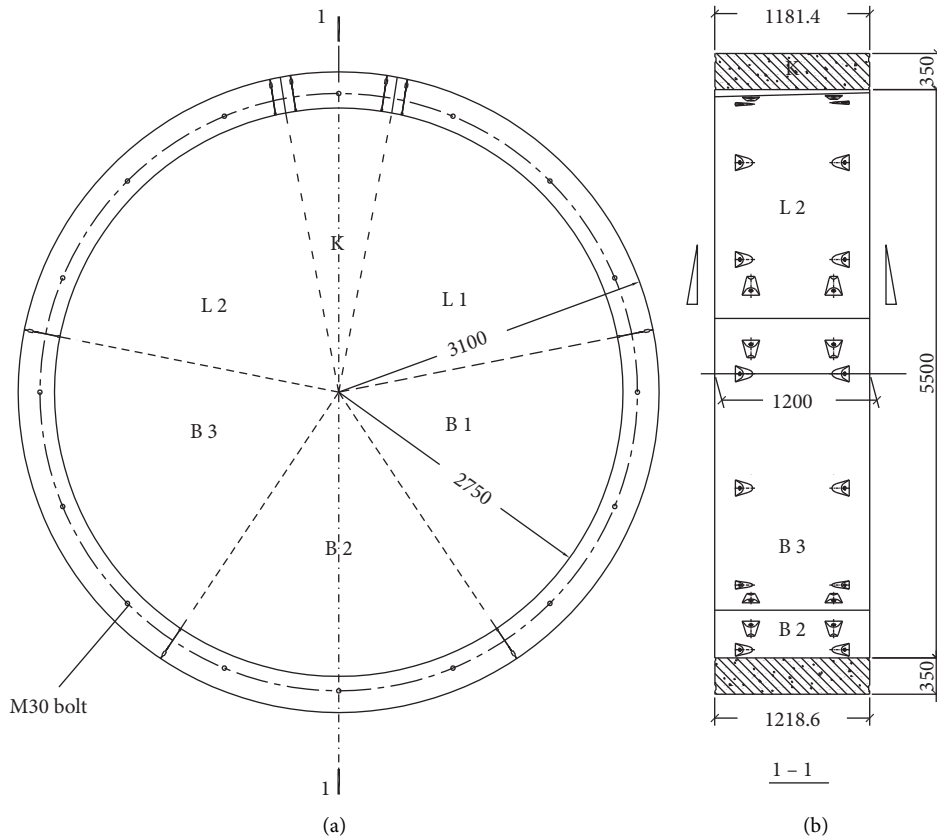


FIGURE 3: Schematic of a tapered ring (dimensions: mm). (a) Front view and (b) sectional view.

A Komatsu TM634PMX shield machine (Japan) was used for this project. This shield machine has a length of 8680 mm and an outer diameter of 6340 mm. The jack group consists of 22 cylinders and has a diameter of 5850 mm. The tapered ring has an inner diameter of 5500 mm, an outer diameter of 6200 mm, a thickness of 350 mm, and an annular width of 1200 mm. The segments were designed as doubly tapered segments with a maximum taper of 37.2 mm and a tapering angle of 20'37.59" for each segment. Each segmental ring was composed of six segments: one key segment (F), two countersegments (L1, L2), and three regular segments (B1, B2, B3). Each ring had a total of 16 possible key positions for segment assembly, and a tongue and groove construction was used for the joints of the segmental ring. The structure of the segmental ring is shown in Figure 3.

4.2. Example of Key Position Selection. The key positions selected by our program and actually selected during the project were compared. Twenty-five samples from a linear section of the down line were used, which corresponded to rings 104–116 and 129–140. This area of the tunnel was mainly excavated in a single stratum of (2) 2 gray silty clay, and no damage or leakage was observed in these 25 segmental rings. This implies that the shield machine operator chose the key positions of these segmental rings in a rational manner according to all operating conditions and factors. These selections may therefore be used as a reference for

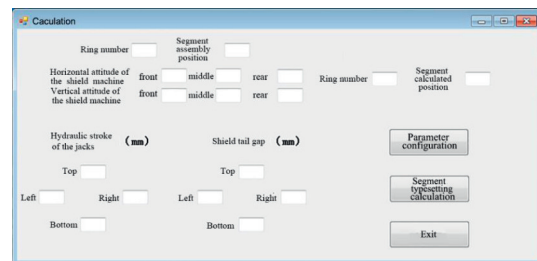


FIGURE 4: Data input interface.

comparison. The data input and parameter configuration interfaces are shown in Figures 4 and 5, respectively. Table 1 compares the actual key positions with those selected by our program.

The key positions computed by our program for these 25 segmental rings are very similar to the key positions that were actually selected. There are 17 instances where the same position was selected, which accounts for 68% of all selections. Therefore, the results of our program are highly reliable. Because the importance coefficients of the shield tail gap, jack stroke difference, and lining trend were set to 1 : 3 : 2 in all of the calculations, some of the calculated positions significantly differed from the actual positions used for segment assembly. Therefore, the importance coefficients need to be chosen according to the actual operating conditions prior to each calculation.

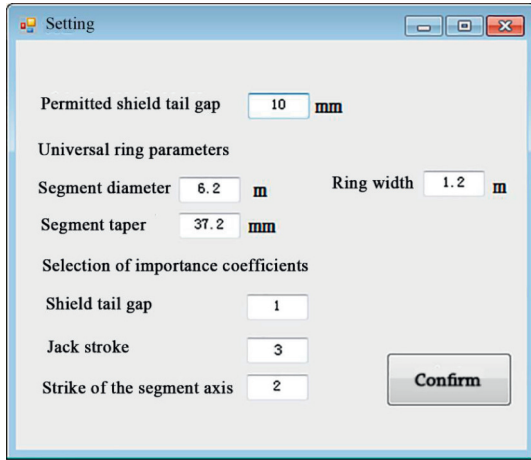


FIGURE 5: Parameter configuration interface.

TABLE 1: Comparison of the calculated and actual positions for segment assembly.

Ring number	104	105	106	107	108	109	110	111	112
Actual key position	13	5	13	5	13	5	13	11	13
Calculated key position	13	5	7	5	7	5	13	5	13
Ring number	113	114	115	116	129	130	131	132	133
Actual key position	5	3	5	13	5	13	5	13	15
Calculated key position	11	13	5	13	14	13	5	13	15
Ring number	134	135	136	137	138	139	140		
Actual key position	13	5	13	5	7	5	13		
Calculated key position	13	11	13	5	7	5	16		

4.3. *Example Calculation for the Range of Jack Stroke Differences.* In this case, the key position of the ring currently being assembled was assumed to be Position 5, while Position 13 was predicted to be the key position for assembling the next ring. The current shield tail gap (which may be measured by using a specialized instrument or manual measurements) was 20 mm on the top, 30 mm on the bottom, 18 mm on the left, and 33 mm on the right. The permitted shield tail gap was set to 10 mm. The current stroke difference of the shield machine was 15 mm in the horizontal direction and -20 mm in the vertical direction. The horizontal and vertical deviations in the attitude of the shield machine were 5 and -15 mm, respectively, at the cutter head and 15 and -30 mm, respectively, at the shield tail. Figure 6 shows the calculated range of jack stroke differences for a permitted shield gap of 10 mm. These ranges were 49 mm to -20 mm in the vertical direction and 15-56 mm in the horizontal direction. These ranges are clearly too large to be of any use for shield machine operators. This is because the attitude of the shield machine is currently in a good state, and the permitted shield tail gap was too small. Consequently, the range of jack stroke differences was not

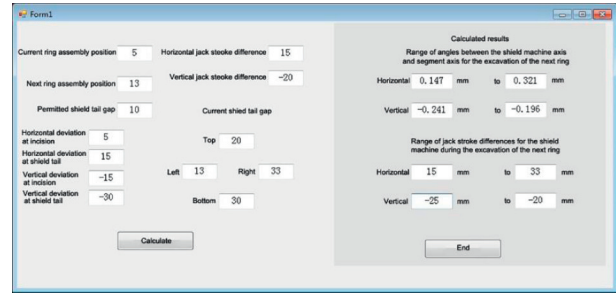


FIGURE 6: Calculated range of jack stroke differences when the permitted shield tail gap is 10 mm.

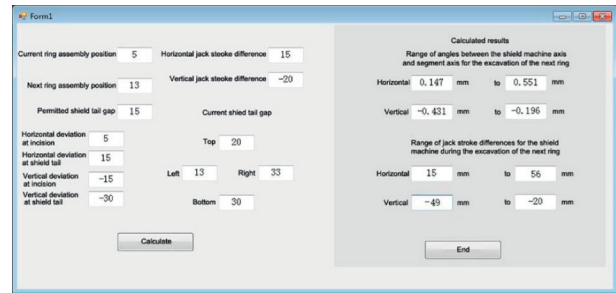


FIGURE 7: Recalculated range of jack stroke differences when the permitted shield tail gap is adjusted to 15 mm.

restricted in a meaningful manner. This calculation was therefore performed again with an adjustment to the permitted shield tail gap.

The permitted shield tail gap was adjusted to 15 mm, and the recalculated range of jack stroke differences is shown in Figure 7. The results were -25 to -20 mm in the vertical direction and 15-33 mm in the horizontal direction. The range of stroke differences was significantly reduced compared to the previous example, and this range is sufficiently precise for practical applications.

The case study showed that the calculated range of stroke differences is closely related to the permitted shield tail gap. Hence, the shield machine operator should select a suitable permitted shield tail gap according to the actual project conditions. The attitude of the shield machine may then be maintained in a good state by the operator using the range of jack stroke differences calculated by the program to control the advancement of the shield machine.

5. Conclusion

Based on a review of previous relevant studies, we propose a method for key position selection based on the shield tail gap, jack stroke difference, and lining trend. We also constructed a method for calculating the range of jack stroke differences with predetermined key positions and a user-defined permitted shield tail gap to ensure that a segmental ring can be safely installed in the calculated key position. Comparisons with a case study showed that the calculation results of our method are highly reliable.

Our automated key position selection program (based on our algorithm) accounts for the impacts of the three

most important factors for shield tunneling, and the importance coefficients of these factors can be adjusted according to actual operating conditions. This program is therefore viable for practical applications. When the program was used in an engineering application, the importance coefficients of the shield tail gap, jack stroke difference, and lining trend were found to affect the quality of the calculated results to some extent. Therefore, the shield machine operator should select importance coefficients for each factor according to the actual operating conditions.

The range of jack stroke differences was calculated by using the shield tail gap as the controlling index. The calculated ranges based on the permitted shield tail gap are sufficiently precise for practical applications, and the calculations are straightforward to perform. In the validation experiment, the range of jack stroke differences corresponding to a permitted shield tail gap of 10 mm was very large. Increasing the shield tail gap to 15 mm significantly reduced the range of Jack stroke differences to be sufficiently precise for practical requirements, which proved the viability of this method. Therefore, the permitted shield tail gap needs to be selected according to actual operating conditions in practical applications.

Segment floating often occurs during shield construction, especially under the condition of crossing soft soil layer. In this paper, we do not consider the influence of the segment floating on the key position selection as well as the calculation of jack stroke differences. This point will be studied with an emphasis on our future research.

Data Availability

All the data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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