Research on Key Technology of Integral Translation and Rotation of the Large-Diameter Shield and Steel Sleeve in the Underwater Tunnel of the Karnaphuli River, Bangladesh

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Abstract: The construction of the underwater tunnel of the Karnaphuli River in Bangladesh boasts the characteristics such as short time limit, small working shaft space and a large weight of the shield tunneling machine and etc.. Moreover, the translation and rotation of the shield tunneling machine are the key link of the entire construction, which also takes a longer time and is more difficult to achieve. The existing rotating technology of a shield tunneling machine and its applicable conditions were analyzed to conquer the difficulties like the tight time limit and the high mechanical level of disassembling and assembling of the shield tunneling machine in this project. The technology of integral translation and rotation of the large-diameter steel sleeve of the shield and the shield tunneling machine was proposed according to its characteristics and the present situation of confined working space. The technology mainly includes the design and application of the new steel ball base, the preparation of the working shaft space and its base, the leveling and translation of the shield tunneling machine, the translation of the shield machine, and its rotation at 180° in situ. The sliding friction between the sleeve base and the bottom plate of the working shaft is turned into rolling friction by the new steel ball base, which can effectively reduce the resistance of the translation and rotation of the steel sleeve. In a word, the working efficiency can be highly improved and the construction period can be shortened.

1. Introduction

In the construction of shield tunnel, the initiation, reception and rotation of the shield are the key links of the whole process. Among them, accidents are prone to happen during the process of the start and reception of the shield [1]. In terms of the key technologies in the process of shield launching and receiving, such as how to reinforce the end of the shield, shield tunneling parameters, tunnel portal sealing and so on, many scholars at home and abroad have made a raft of research [2-5]. And these technologies have become more and more mature. Due to the constraints of site space, resources and equipment, a single shield tunneling machine is always used to carry out multi-station and multi-section construction during the process of urban rail transit projects. Moreover, in the construction of large-
diameter highway tunnels, a single shield tunneling machine will be used to excavate two or more lines if the construction period is sufficient. Since the translation and rotation of a shield tunneling machine are applied to the actual construction more and more frequently, it is of great importance to complete the translation and rotation of a shield tunneling machine efficiently and quickly.

The translation and rotation of a shield tunneling machine are the key links in the construction of shield tunnels, which is also difficult to achieve and takes a long period of the entire process. However, it’s the key link that can ensure the second start of a shield tunneling machine. The commonly used methods of translation and rotation of a shield tunneling machine include lifting method and base shifting method [6-12]. The lifting method can be divided into integral lifting and separated lifting. The latter is mainly suitable for small and medium-sized shield tunneling machines while the latter needs to dismantle, lift and reassemble a shield tunneling machine. Construction technologies of both the methods are mature, but large lifting equipment is needed and the construction period will be longer. The traditional base shifting method is that the turning of a shield tunneling machine will be achieved by the jacking base of a hydraulic cylinder after the steel bracket receives it. This method is simple in construction and it’s widely used. However, the problem is that a large friction resistance exists between the bracket and the base plate, which means greater thrust is required. The success of the above-mentioned cases has accumulated experience for the translation and rotation technology of a shield tunneling machine. However, there is no engineering case that can deal with integral translation and rotation of a large-diameter shield machine received by a steel sleeve where the rotating space is limited due to the absence of a deep section in the working shaft.

Based on the project of the underwater tunnel of the Karnaphuli River in Bangladesh, the construction technology and method of the integral translation and rotation of a shield tunneling machine are optimized and successfully applied where there’s no deep section in the working shaft and the working space is confined, which represents the success of the key technology. The technology mainly includes the design and application of a new steel ball base, the preparation of the working shaft space and its base, the leveling and translation of the shield tunneling machine, the translation of the shield machine, and its rotation at 180° in situ. We hope the success of the case can provide more references to the projects of the same kind.

2. General Situation of the Project

The underwater tunnel project of the Karnaphuli River is located at the outfall of the Karnaphuli River, on the outskirts of Chittagong, Bangladesh. Two tunnels are dug and each is 2450 m long. An air-cushioned slurry balanced shield machine whose diameter is 12.16 m is used to excavate tunnels. The shield machine starts from the working shaft on the west bank, and it passes through the riverbank, the deep trough, the Karnaphuli River and the mudflat. And it’s received at the working shaft on the east bank. Then, it’s translated from the left working shaft to the right one. After the 180° rotation in situ, it will start again to excavate the tunnel on the right.

The airtight steel sleeves are used to start and receive the shield machine. And the shield machine as shaft as the steel sleeve will be translated and rotated as a whole. A steel sleeve is made up of an extension steel ring, blocks of the body of a steel sleeve, a flat head plate, an integrated bracket, an end-cover ring and an end-cover plate. When receiving, the axis of the sleeve is aligned with the axis of the tunnel by adjusting the slope of a buttress. The total weight of the shield tunneling machine is 1400 t and the filling in the sleeve weighs 240 t when the shield is received. The weight of the steel sleeve is 600 t and the oil cylinder weighs about 20 t, so the total weight is 2260t. The length of the steel sleeve is 14.40 m, the outer diameter of it 13.23 m and the diagonal length 19.55 m. The minimum distance between the shield machine together with the steel sleeve and the lining wall of the working shaft is only 536 mm, which means the space for the rotation is limited. The limited space for rotation and the accurate calculation of the rotation displacement are both the hard and crucial part of the construction.
3. Structure Design of the Working Shaft
The plane size of the working shaft on the east bank is 46.7 m × 23 m, the vertical depth 22.85 m. There is no mid-partition in the working shaft, but there are two convex embedded columns and the distance between them is 17.6 m. And they can’t be removed because of the load-bearing structure. The distance between the open excavation section with no deepened stretch and the bottom of the working shaft is 6.45 m, which further reduces the rotation space of the shield machine. Furthermore, the minimum distance between the shield machine together with the steel sleeve and the lining wall of the working shaft is only 536 mm. Therefore, before the integral translation and rotation of the shield machine and the steel sleeve, the portal of the working shaft and the lower ring beam of the open excavation section should be partially chiseled out and the debris removed to increase some space for the rotation.

![Fig. 1. Layout of the East Bank Working Shaft](image1)

4. Design and Installation of the Revolving Steel Ball Base

4.1. Design of the Steel Ball Base
A new type of steel ball base is designed to smooth the translation and rotation of the steel sleeve and realize the 180° rotation of the shield machine together with the steel sleeve in situ. Besides, it’s also welded on the base of the steel sleeve so that the sliding friction between the sleeve base and the baseplate of the working shaft is turned into rolling friction. Thus, it can reduce the resistance of the translation and rotation of the shield machine and improve the efficiency when the construction safety is also guaranteed.

The steel ball base mainly includes a self-aligning top seat, an anti-off plate, a middle seat, a steel ball anti-off circle, and a steel ball. The self-aligning top seat is made up of two parts, a cylindrical support and a semicircular ball. The cylindrical support whose dimension is Φ 400 mm × 120 mm is made of 40 cr steel. The top of the support is welded with the steel sleeve base. The Q345B steel is preferred for the semicircular ball whose dimension is Φ 200 mm × 120 mm. It will be directly rubbed with the middle seat. When the steel ball support touches the ground as a whole, the semicircular ball can rotate relative to the middle seat, which can ensure that the steel ball can also touch the bottom plate of the working shaft during the integral translation and rotation. The anti-off plate whose dimension is 80 mm × 16 mm × 130 mm is made of Q235B steel. A hole whose diameter is Φ 38 mm is set on the upper part of the anti-off plate for the installation of the spring that can limit the position of the self-aligning top seat. The triangular middle seat whose height is 160 mm has three outriggers, and 40 Cr steel is preferred for it. A groove whose depth is 80 mm is set on its top center and its diameter is the same as that of the self-aligning ball head. The outriggers are provided with grooves of 100 mm in diameter and 60 mm in depth, and they will be in direct contact with the lower part of the steel ball.
Moreover, the outriggers are provided with an 8 mm oil hole in lateral direction so that butter can be easily injected during the construction. Q235B steel is preferred for the steel ball anti-off circle whose inner diameter is 89 mm, outer diameter 160 mm. It’s connected to the middle seat by bolts to prevent the steel ball from falling off. The diameter of the steel ball is 100 mm and its rotation diameter is 500 mm. It’s put in the groove on the outrigger of the middle seat, and it will directly touch the ground.

![Fig. 2. Structure Diagram of the Cross Section of the Steel Ball Base(units:mm)](image)

4.2. Calculation of the Bearing Capacity of the Steel Ball

A three-dimensional model is established in numerical simulation software to analyze the stress and deformation of the steel ball base.

Force analysis and boundary conditions: during the process of receiving, translation and rotation of the shield machine, the steel ball group mainly bears the dead weight of the shield machine and steel sleeve. The vertical load is 2260 t (including 1400 t of the shield machine, 550 t of the sleeve structure, and the rest may be the packing which can’t be cleaned and other things). A contact surface is arranged between the steel ball and the base to restrict the displacement on the upper end face of the steel ball base. The calculation and force model are shown in Fig. 3.

The cloud pictures of the stress and deformation of the steel ball base are obtained by numerical calculation and analysis, as shown in Fig. 4. The maximum stress of the steel ball group is 55.36 MPa (located on the contact surface between the steel ball and the base and it’s less than 345 MPa), which meets the strength requirement. The maximum deformation of the single steel ball group is 0.07 mm under the load effect (located on the outermost side of the base), and the structural deformation is within the controllable range.

![Fig.3.Model Diagram of the Steel Ball Base](image)

![Fig.4.Cloud Pictures of the Analysis of the Steel Ball Base](image)
4.3. Mounting of the Steel Ball Base

The steel ball and the anti-off plate are assembled in advance in the processing plant. Before the steel ball base is mounted, the steel sleeve base is turned over 90° while the self-aligning top seat is welded. The middle seat should be connected by a piece of rebar after welding. When the steel sleeve is in position, the piece of rebar should be removed. The welding position of the steel ball group shall be decided according to the steel structure of the sleeve base and the requirements of translation and rotation. Before the steel sleeve goes down into the working shaft, the 38 groups of steel ball bases should be mounted in the middle area. After the gradient-adjusting buttresses are removed by a vertical jacking cylinder, the remaining 10 groups of ball bases are symmetrically installed on both sides, five groups each side, between the positions where the buttresses were installed. So there’re 48 groups in total.

The semicircular ball is lubricated with butter when the steel ball is being mounted. After installation, butter is injected into the gap between the steel ball and the middle seat through the grease injection hole. Meanwhile, the matching long pipe should be designed to realize the smooth translation and rotation of the shield tunneling machine and the steel sleeve.

![Fig. 5.Installation of the Steel Ball Base](image)

Fig. 5.Installation of the Steel Ball Base

![Fig. 6.Arrangement Diagram of the Steel Ball Base(units:mm)](image)

Fig. 6.Arrangement Diagram of the Steel Ball Base(units:mm)

5. Construction Methods of Translation and Rotation of the Shield

5.1. Construction Process

The translation and rotation of the shield tunneling machine include the removal of the segment of the shield machine, the arrangement of the shield machine pipelines, the removal of the restraint from the 1 # trolley and the temporary reinforcement of the cantilever equipment. The leveling of the shield tunneling machine is conducted after the vertical lifting cylinder system is installed. After the buttresses are removed, the shield machine is pushed along the top of the tunnel axis to the designated position and then the starting axis of the right line should be translated. When it's done, the oil cylinder should be adjusted continuously to lean back. In this way, the shield machine and the steel sleeve can be rotated 180° along the rotating axis, and the back jacking station is pushed to the starting hole. The detailed process is shown in Fig. 7.
Pipelines removal and arrangement

Erector reinforcement and 1 # trolley removal

Extended steel ring, steel cover plates and all constraints removal

Install and debug the vertical hydraulic system

Level the shield machine and remove the gradient-adjusting buttresses

Push apart the steel sleeve along the tunnel axis

Shield machine maintenance and the tunnel portal chiseling

Horizontal jacking shield machine and steel sleeve

Weld the counter-force base and hydraulic system for translation

Weld the counter-force base and hydraulic system for rotation and draw the path

Push the shield machine into position and install the slope-adjusting buttresses

Fig. 7. Flow Chart of the Translation and Rotation of the shield machine

5.2. Preparation for the Construction

5.2.1. Preparation for the Space of the Working Shaft and the Level. The space of the working shaft is measured again based on the rotation space for the shield machine. Meanwhile, both the elevation and the flatness of the bottom place should be measured. Moreover, the concrete structure on the surface of the bottom plate will be cut out if necessary.

The casting of the bottom plate should be conducted based on negative tolerance control, and the control standard is -3 cm. Mortar should be leveled on the 2000 mm × 6000 mm × 20 mm steel plate which will be used as the installation base to receive the steel sleeve, as well as the glide plane for the translation and rotation of the shield machine. The 60°V-type bevel between the steel plates should be welded and polished. The steel plate and the bottom plate are connected by embedded steel bars whose diameter is 22 mm, the depth of which is no less than 40 cm. Besides, the joint should be polished after welding.

The direction of translation and rotation of the shield machine and the sleeve shall not be higher in front than in rear. The position of plug welding can be adjusted according to that of an embedded steel bar when the bottom steel plate is installed. The number of the steel bars which are embedded at the outermost steel plates of the working shaft should be calculated by the 1200×1500 quincunx layout. As for the other steel plates, steel bars should be embedded at four corners. When the steel plates are laid, the cracks between them should be welded, and the steel plates and anchor bars should be polished by plug welding. The flatness of the steel plates is no more than 5 mm/m².

Fig. 8. Construction of the Bottom Plate of the Working Shaft

5.2.2. Arrangement of the Equipment in the Shield Tunneling Machine. After the shield machine is received, it is separated from the back-up by using the towing jack to push the trolley. And the slurry line, the electro-mechanical hydraulic pipeline and the cable of 1 # trolley are arranged as necessary. To reduce the rotation radius, a portal crane is used to remove the two joists in the rear half of the erector, and a stop should be applied to fix the erector at the front end of the joist.
5.2.3. Determination of Translation and Rotation Path of the Shield Tunneling Machine. Before the shield machine is jacked to the translation path, the in-situ rotation center of the shield machine is positioned. The body of the steel sleeve will also rotate, so the end cover ring and the extension steel ring should be removed before rotation. The rotation diameter is 19555 mm and the center of rotation is the intersection of the transverse center line of the working shaft and the center line of the right tunnel. Its distance from the left end wall is 2253 mm while the distance from the front end wall and the rear one is 523 mm. The distance from the end wall of the tunnel portal to the hidden column is 2197 mm while the distance from the hidden column of the side wall of the back tunnel portal is 3256 mm. Since the tunnel portal is concave, the space for the rotation of the head end is slightly increased and the distance between the ends is 685 mm. There is no deepened stretch in the open excavation section, so no concave space exists in the lower part. Because of that, the rotation center can move 343 mm forward and the distance from the front end wall and the rear one will be 866 mm.

The rotation space of the shield machine and the sleeve is shown in Fig. 9 (not considering the use of the front portal space), the green circle is the contour circle of the rotation of the steel sleeve while the red circle is the control line of rotation. The location of the blue circle is decided by the concave space of the tunnel portal. During the actual rotation, the red circle should be taken as the control line of rotation while the rotation center should deflect in the direction of small mileage. When the distance is within 300 mm, the rotation center doesn’t need to deflect. But when it goes over 300mm, the rotation center should deflect in the direction of large mileage immediately.

Fig. 9. Rotation Path of the Steel Sleeve and the Shield Machine

5.3. Levelling of the Shield Tunneling Machine

5.3.1. Design of the Gradient-adjusting System of the Shield Tunneling Machine. The gradient-adjusting system of the shield machine includes gradient-adjusting buttresses, arc-shaped base and jacking system. A gradient-adjusting buttress is designed into two separate concave sections which are connected by bolts and will be easy to be moved away later. The height of a buttress is decided by the shape of the tunnel. They’ll be installed at the lower part of the base of the steel sleeve and are fixed by cards. They mainly bear the overall load of the shield machine and the steel sleeve. The arc-shaped base is designed as a box-shaped structure, and the bottom of it is provided with a spherical supporting steel plate. Its upper part is connected to the piston rod of a hydraulic jack and is arranged inside the gradient-adjusting buttress. The spherical supporting steel plate is designed as an arc to adapt to the different slope forms of the sleeve. In this way, it can bear the stress when the vertical cylinder jacks and retracts.

The jacking system includes jacking cylinder and PLC control system. The jacking cylinder is installed in the oil tank reserved at the holder base of the sleeve. From the front to the back of the cutter

![Diagram of Right Line Tunnel Portal and Open Excavation Section]
head, there are five 200T jacks and five 120T jacks each side, respectively. The working length of the piston rods of the jacks is 1100 mm. The steel bars welded outside the cylinder are taken as the protection device to fix the jacks, which can prevent the jacks from displacing.

The jacking cylinders are all double-acting ones. When the shield machine and the steel sleeve are jacked, the oil is supplied to the upper chamber of the cylinder and the piston rod is in a fixed state, that is, the cylinder is rising to jack the shield machine and the steel sleeve. When the leveling goes, the oil is supplied to the upper chamber of the cylinder. At this time, the body of the cylinder is fixed while the piston cylinder is rising. Each cylinder is equipped with a displacement sensor and a displacement switch that can sense the displacement when the cylinders are rising or declining at the same time or separately. And they’ll feed the signal back to PLC. The shield machine can move to the desired gradient according to the set displacement so that gradient-adjusting buttresses can be easily taken out or placed.

5.3.2. Leveling. The weight of the shield machine and the steel sleeve taken into account, ten 200t and ten 120t jacking cylinders are equipped each side, and they’re installed in the oil tank reserved at the holder base of the sleeve. From the front to the back of the cutter head, there are five 200t jacks and five 120t jacks each side, respectively. The shield machine and the steel sleeve are jacked when PLC automatic program of the hydraulic system works. When the gradient-adjusting buttress with the highest gradient is off the ground, gradient-adjusting buttresses can be removed one by one. The rest ten groups of steel ball bases will be installed on both sides of the sleeve base, five groups each side. Lubricating butter should be coated on the steel ball groups and the bottom plate of the working shaft to reduce the resistance of translation and rotation. The shield machine and the steel sleeve will go down by adjusting the jacking cylinders. The jacking cylinders can be adjusted simultaneously or separately by the PLC control system based on the set displacement to let the base of the steel ball contact that of the bottom plate of the working shaft asynchronously and complete the leveling of the shield machine.

5.4. Translation of the Shield Tunneling Machine

The translation of the shield machine is carried out in two stages. In the first stage, the steel sleeve is separated from the tunnel portal. The shield machine can move 2700 mm towards the direction of large mileage (towards the east bank) along the axis of the tunnel when the jacks set between the side wall of the tunnel portal and the base of the steel sleeve work. In the second stage, the shield machine and the steel sleeve are jacked 19981 mm along the horizontal direction of the working shaft (from the left tunnel portal to the right one). The jacking process will be conducted ten times. The translation path is defined based on the horizontal translation axis. The distance between the green lines and the red ones in the left and right should be 300 mm. The green lines are the contour lines of the rotation of the steel sleeve while the red ones are the control lines of rotation.

Fig. 10. Translation Diagram of the Steel Sleeve and the Shield Machine
5.5. **180° Rotation of the Shield Tunneling Machine**

According to the indoor test of the steel ball base, the rolling friction coefficient between the steel plate and the steel ball is 0.05, so the total thrust of the cylinders set for the rotation of the shield is 115 tons. Cylinders with 2-63t (20MPa) and 1100 mm stroke are chosen for the rotation. They’re arranged in the oil tank at the side of the mountain, and the two ends are connected by double U-shaped movable hinges. The angle between a cylinder and the shield machine is 45°. The stroke of a cylinder is 1100 mm and the length of the auxiliary jacking iron is 700 mm. If the length of each jacking is 1800 mm and the rotating angle is 9.5°, the length of a single jacking will be 1144.5 mm (with tools). The shield and the sleeve will rotate 19 times (not including fine-tuning positioning and process correction) to complete the 180° rotation in situ.

In the process of the 180° rotation, one group of the diagonal cylinders will be used as the rotation power when the oblique rotation thrust is too large or the proposed displacement of the rotation exceeds the limit. Meanwhile, the other group will be used to limit or balance the shield machine so that it can rotate according to the designed path.

![Schematic Diagram of the Rotation of the Steel Sleeve and the Shield Machine](image)

**Fig. 11. Schematic Diagram of the Rotation of the Steel Sleeve and the Shield Machine**

5.6. **The Shield Tunneling Machine in Position**

After the shield machine has rotated 180°, the cutter head can be trimmed and the cutting tools should be optimized and replaced. Meanwhile, the tail shield should also be cleaned and the tail brush reinstalled. After the hydraulic system, sealing system, lubrication system, propulsion system and grouting system of the shield machine are maintained, gradient-adjusting buttresses should be installed. However, its installation process is the opposite of that of the gradient-adjusting buttresses used to jack the shield.

In order to ensure the starting posture of the shield machine, the gradient-adjusting buttresses should be adjusted and polished according to the situation of the tunnel portal where the shield will start again, and how the shield is in the sleeve if necessary.

6. **Conclusion**

(1) In this paper, a new steel ball base was designed for translation and rotation of a shield tunneling machine and a steel sleeve, which can turn the traditional sliding friction into rolling friction and greatly reduce the resistance of the translation of a steel sleeve. Moreover, it can also reduce the number of cylinders needed. The bearing capacity of its base is high and its structure is simple. Besides, the operation is easy, so it should be popularized.

(2) It is not necessary to disassemble, lift and reassemble the shield machine when it is together with the steel sleeve translates and rotates as a whole. What is needed is to disconnect the main body of the
shield machine from the back-up equipment, which can improve the construction progress and shorten the construction period.

(3) The use of a steel ball base can help complete the translation and rotation of a shield tunneling machine and greatly improve the work efficiency. Moreover, heavy lifting equipment is no longer needed so that the construction will be extremely effective in remote areas or in the place outside our country where mechanical materials are deficient. Besides, this kind of translation and rotation of a shield tunneling machine needs less space, so it can realize the situation that a shield machine and a steel sleeve can rotate 180° in situ or even a larger angle in a confined space.

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