Model Test on the Synchronous Technology Combining with Shield Tunneling and Segment Assembling Based on the Linear Distribution Principle of the Thrust Force

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Abstract: Herein, we propose synchronous technology combining shield tunneling and segment assembly based on the active closed-loop control of shield propulsion systems to solve the problem of the too-long construction periods for long-distance shield tunnel projects associated with conventional shield methods. Analytical methods for the distribution of the total thrust force and the redistribution of the missing jacking force were established to stabilize the total thrust force vector in synchronous operations. Then, a super-large model test platform for the shield synchronous technology was developed. The obtained test results verified the feasibility of the analytical methods. The importance of the full-cylinder propulsion mode and the sufficient security of the segments were also confirmed.

1 Introduction

Shield machines have evolved as high-end underground-engineering equipment integrating multidisciplinary technology, and several relative technologies for excavation face stability[1,2], slurry treatment[3], synchronous grouting[4], ground settlement control[5], etc., have been developed. In the past two decades, with the gradual saturation of urban shallow underground space, shield method has been developed globally with increased buried depth, cross-section and distance. Several super-diameter submarine and urban road tunnels have been constructed[6]. The traditional process of “driving forward, stopping, and assembling segments” has been maintained in such a “series” form since the emergence of the first mechanized shield machine. In general, the time spent on shield tunneling is close to the assembling time of the whole segmental ring. However, the requirements of construction cost and period have been constantly improved. Improving the efficiency of shield construction and realizing continuous propulsion of shield machines are key problems facing shield construction technology and equipment manufacturing.

Synchronous technology combining shield tunneling and segment assembling (STSS) has been proposed. In such technology, segment assembling is performed in the process of shield tunneling, which improves the shield construction efficiency, greatly shortens the construction period, and reduces construction cost. To date, research and engineering applications of this technology have been recorded only in Japan. Several construction methods have been developed, including the “F-Navi” shielding[7], lattice cylinder shielding[8], double-cylinder synchronous tunneling[9], and “LoseZero” tunneling methods[10]. However, relevant scientific research and engineering application results have been limited.
not been reported, and research on STSS technology is evolving in China. Herein, using a shield machine, “Jiyue” of Shanghai railway airport connecting line projects, as the prototype, we developed STSS technology making full use of the additional stroke of the hydraulic jacks for the axial insertion of the key block. To verify the feasibility and reliability of this technology, a super-large model test platform with a similarity ratio of 1/2 was developed, and the linear redistribution analytical method for missing thrust force was employed to maintain the total thrust vector of the propulsion system. The technology was evaluated considering the oil pressure response of the propulsion system and maintenance capacity of the total thrust vector, the propulsion speed and attitude control of the shield, and the compression state of the segmental structure, etc.

2 Technical principles of STSS

2.1 Efficiency analysis
“Jiyue” slurry-air balance shield machine and the partition method of its propulsion system are shown in Figure 1. The machine was designed in a buried depth of 33 m with an excavation diameter of 14.07 m and a shield shell length of 13.33 m. The propulsion system (Figure 1a, b and c) consisted of 34 sets of dual hydraulic cylinders (360/280–3300 mm) evenly distributed along the circumference. The nine-block design of the segmental structure, including one key block, two adjacent blocks, and six standard blocks, is shown in Figure 1c. It has an outer diameter of 13.6 m, width of 2 m, and thickness of 0.55 m. Since the center angles of adjacent and standard blocks are similar, the entire ring is be regarded as type “1 + 8”. Two groups of hydro-cylinders are located in the area of the key block and four groups in other segments. The assembly sequence is B3, B4, B2, B5, B1, B6, L1, L2, and F.

![Figure 1. Shield machine and segment blocks](image)

Theoretically, assuming the average shield speed is 30 mm/min, and the segment assembling time of the single ring is 50 min, the total time consumed for one ring is 117 min when the conventional shield method is employed. However, the assembling space requirement of the first segment (B3) can be met if STSS technology is employed when the propulsion cylinder extends from its initial value of 1300 mm to 2100 mm. Then, the first seven segments can be assembled when the cylinder reaches the full stroke of 3300 mm, and only 10 min is needed to finish the rest two segments after the shield machine is shut down. Thus, the total operation time of the whole ring can be reduced by 40 min, and the shield construction period can be shortened by 34.2%.

2.2 Technology realization method
STSS technology is a closed-loop active control on the oil pressure of all rodless cavities of the propulsion cylinders. Different from the traditional valve control concept of shield propulsion systems, where hydro-cylinder units in each zone share the same proportional reducing valve, each hydro-cylinder unit in the shield machine adopting STSS technology is equipped with an independent proportional reducing valve, an oil pressure sensor, and a travel sensor, so each propulsion hydro-cylinder unit perform independent pressure regulation and telescopic function.

Two working states, conventional propulsion and STSS states, are employed in the actual shield construction process. They can be switched seamlessly, and the latter is divided into two modes: full hydro-cylinder propulsion and STSS modes. The shield machine first perceives the total thrust force and obtains its spatial distribution in the corresponding ground conditions in the conventional propulsion state through an open-loop control on the oil pressure of each zone. Once the deviations of...
the attitude of the shield machine are within the allowed range, and the propulsion speed is stable, it can switch to the STSS state, and the oil pressure of the rodless cavities of the entire propulsion system is stored as a database at the same time and converted into the target total thrust force vector (the total thrust force \( F_T \), horizontal resultant moment \( M_{Pb} \), and vertical resultant moment \( M_R \)). The oil pressure of all the hydro-cylinders in the STSS state is automatically calculated and executed by the program to keep the thrust force vector constant.

Notably, the shield machine enters the full hydro-cylinder propulsion mode as a transition stage to stabilize the driving speed and attitudes of the shield machine before the next segment is assembled, and the propulsion system can be divided freely to meet the requirements of different working conditions in this mode. Some hydro-cylinders are retracted in the STSS mode to provide the space for the segment assembly (Figure 2), and the missing jacking force needs to be redistributed to the remaining working hydro-cylinders, that is, the incremental oil pressures would be superimposed with the initial target oil pressures of the remaining working hydro-cylinders to generate new target oil pressure.

![Redistribution sketch map of the missing thrust force](image)

### 3 Establishment of large-scale model test platform

To verify the feasibility and reliability of the STSS technology and create a training environment for its engineering applications, we developed a super-large model test platform (Figure 3), mainly comprising a steel outer frame, load system, testing shield machine, sliding support, and model steel segments, which can simulate the shield propulsion operations in different states.

The steel outer frame of the test platform, an enclosed internal load-carrying structure with the total length, width, and height of 13, 8, and 8 m, respectively, mainly comprises four main pull rods, eight oblique pull rods at corners, and two backup walls for the load and propulsion ends. All the components are made of Q345 welded H-beams with height, width, web thickness, and flange thickness of 700, 400, 30, and 40 mm, respectively. The load system comprises six groups of dual hydro-cylinders evenly distributed with a radius of 1800 mm (the inner diameter of the hydraulic cylinder, diameter of the piston-rod, and maximum cylinder stroke are 360, 280, and 3000 mm, respectively). The bottom of each hydro-cylinder is connected with the backup wall of the load end, and the front end is fixed on the support plate. At the beginning of the test, the resistance of the shield machine in the heading direction is simulated by setting the target thrust force of the load system, and maximum resistance of 13800 kN could be provided.

A metro shield machine with an outer diameter of 6.8 m was transformed into a model testing shield machine. The outer diameter of the prototype shield machine is 14 m, thus the similarity ratio is 1/2. The middle shield, propulsion system, and assembling machine were retained, and the cutter head, front shield, and shield tail were removed. A circular bearing ring was installed in the front of the testing shield machine to face the thrust force of the load system. The propulsion system consists of 17 groups of dual hydro-cylinders (the inner diameter of the hydraulic cylinder, diameter of the piston-rod, and maximum of the cylinder stroke are 240, 200, and 2200 mm, respectively), each of which is controlled by an independent proportional reducing valve, and equipped with an oil pressure sensor and a travel sensor. The shield machine is constrained by the soil in the actual stratum, and the sensitivity of the shield attitudes is relatively weak. To simulate the most unfavorable working
environment and promote safety redundancy in engineering applications, a spherical convex point was installed at the bottom of the testing shield machine in the vertical direction of gravity, contacting the supporting beam to form a single-point support. Only the vertical displacement of the testing shield machine is constrained, and the other five freedoms are unlimited.

The sliding support consists of four rows of pulleys, a bearing platform, four lifting cylinders, two support cylinders, a support beam, and two location-limited plates. Among them, four lifting cylinders lift the testing shield machine to the preset height in the preparation stage. After the load hydro-cylinders stretch to press the shield machine against the backup wall of the propulsion end, two support cylinders stretch to make the support beam contact with the spherical convex point and switch to the passive pressure maintaining state. Then, four lifting cylinders retract 1 cm each as a safety device against the falling of the testing shield machine. The location-limited plates can contact the baffles installed at the bottom of the testing shield machine so that the testing machine drives the sliding support to move forward and backward.

Two model steel segmental rings made of Q235 steel plate, with outer diameter, inner diameter, and height of 6.5, 6, and 0.95 m, respectively, were designed to verify the compressive performance of the segmental structure and provide the training materials for the synchronous assembly of the segments. A compressive strain collection system was set on the surface of the lining ring facing the shield propulsion system, and the numbering method of the measuring points was consistent with the cylinders.

![Figure 3. Model test platform](image)

4 Control algorithms of the total thrust force vector

The thrust force vectors (total load force $F_T$ and its horizontal and vertical resultant moments $M_{Fh}$ and $M_{Fv}$, respectively) of the load system can be calculated according to the set stratum conditions based on the similarity theory and executed before the movement of the testing shield machine. Then, the thrust force vectors (total thrust force $F_T$ and its horizontal and vertical resultant moments $M_{Fh}$ and $M_{Fv}$) can be derived from the conventional propulsion state based on the following calculation in the STSS state.

4.1 Full hydro-cylinder propulsion mode

The distribution model of the total thrust force and the segment assembly conditions are shown in Figure 4. A rectangular coordinate system XOY with the center of the propulsion system as its
coordinate origin was established, and whether the resultant moment was positive or negative could be
determined according to the quadrant where the total thrust force point is located. Since all the
hydro-cylinders are symmetrical about the y-axis, the propulsion system was divided into left and right
parts, except cylinder 9, which is on the y-axis. The jacking forces of the two top hydro-cylinders in
both two parts were set to $t_1$. Then, another rectangular coordinate system $X'O'Y'$ was built with
the coordinate origin located on the top of the propulsion system circle to measure the distance ($l_i$) from
the center of each cylinder to the $X'$-axis. Two growth rates $k_1$ and $k_2$ were assigned to the left and
right parts, respectively, to ensure that the jacking forces of the two parts increased linearly from top to
bottom as expressed below.

$$
t_i = \begin{cases} 
    t_i + k_1 l_i, & (i = 1 \sim 8) \\
    t_i + \frac{k_1 + k_2}{2} l_i, & (i = 9) \\
    t_i + k_2 l_i, & (i = 10 \sim 17)
\end{cases} \quad (1)
$$

Figure 4. Distribution model of the total thrust in the full hydro-cylinder propulsion mode

Then, $t_1$, $k_1$, and $k_2$ must satisfy the following three equations:

$$
F_t = \sum_{i=1}^{17} t_i \quad (2)
$$

$$
(k_1 - k_2) \sum_{i=1}^{8} l_i n_i = -M_{ty} \quad (3)
$$

$$
\left( t_1 + \frac{(k_1 + k_2)}{2} l_i \right) m_i + \sum_{i=1}^{8} \left[ 2 t_i + (k_1 + k_2) l_i \right] m_i = -M_{ty} \quad (4)
$$

where $n_i$ and $m_i$ are the distances from the center of each cylinder to the $Y$- and $X$-axis, respectively.

Finally, the target oil pressure of the rodless cavity of each cylinder unit ($P_i$) is expressed as

$$
P_i = \frac{2t_i}{\pi d^2}, (i = 1 \sim 17) \quad (5)
$$

where $d$ is the diameter of the rodless cavity.

4.2 STSS mode

The retribution calculation model of the miss jacking forces ($f_1$ and $f_2$) is shown in Figure 5.
Taking block B3 as an example, the propulsion system was rotated to a position where the middle of
block B3 was on the y-axis for the simplicity of calculation. A rectangular coordinate system oxy was set with the coordinate origin located on the top of the propulsion system circle to obtain the distance \( l_i \) from the center of each cylinder to the x-axis. Similar to the distribution method of the total thrust force, the propulsion system in the SRSS state was also divided into the left and right parts, and the incremental forces of two top hydro-cylinders in both two parts were set to \(-\Delta_i\). Two growth rates \( C_1 \) and \( C_2 \) were selected to distribute the incremental forces linearly from top to bottom in the left and right parts, respectively. Then, the incremental working force for each remaining working cylinder can be determined using the following equation.

\[
\Delta t = \begin{cases} 
-\Delta t, & (i = 17) \\
-\Delta t + C_1, & (i = 10 \sim 16) \\
-\Delta t + C_2, & (i = 1 \sim 7) 
\end{cases} \tag{6}
\]

Then \( \Delta t, C_1, \) and \( C_2 \) must satisfy the following three equations:

\[
\sum_{i=1}^{16} C_2 l_i + \sum_{i=10}^{16} C_1 l_i - 15\Delta_i = f_i + f_2 \tag{7}
\]

\[
\sum_{i=10}^{16} C_i l_i - \sum_{i=1}^{16} C_i l_i = (f_i - f_2)N_i \tag{8}
\]

\[
\sum_{i=10}^{16} (-\Delta_i + C_1 l_i) l_i + \sum_{i=1}^{16} (-\Delta_i + C_2 l_i) N_i = (f_i + f_2)L_i \tag{9}
\]

where \( L_i \) and \( N_i \) are the distances between the center of the retracted hydro-cylinder to the x- and y-axis, respectively.

![Figure 5. Redistribution model of the missing jacking forces in the STSS mode](image)

Finally, the target oil pressure of the rodless cavity of each cylinder unit \( P'_i \) in the STSS mode is expressed as

\[
P'_i = \frac{2(t_i + \Delta t)}{\pi d^2} \cdot (i = 1\sim 7, 10 \sim 17). \tag{10}
\]

5 Analysis of test results

5.1 Oil pressure response and total thrust vector

We simulated the driving of the shield machine in a straight line, and the synchronous segment assembly was replaced by the retraction of the hydro-cylinders owing to the uncontrollable segment assembling time. The total load force and its horizontal and vertical resultant moments in a buried
depth of 10 m were calculated as $F_r = 10157\ kN$, $M_{r_h} = 0\ kN\cdot m$, and $M_{r_v} = 4328\ kN\cdot m$, respectively, in typical soft soil strata in Shanghai. After the conventional propulsion state, the total thrust force and its horizontal and vertical resultant moments were obtained as $F_r = 12620\ kN$, $M_{r_h} = 109\ kN\cdot m$, and $M_{r_v} = -6985\ kN\cdot m$, respectively.

One hydro-cylinder located in each segment (9 in total) was selected to show the oil pressure response of the entire propulsion cylinders in the STSS state. The actual oil pressure fluctuated near the target value owing to the PID closed-loop control on the rodless cavity (Figure 6). In addition, due to the occasional fluctuations of the load force, the oil pressure showed sudden jumps. Generally, the oil pressure response of each cylinder corresponding to the different target pressure was rapid, and the errors were controlled within 2%.

As shown in Figure 7, owing to the good responsiveness of the oil pressure, the total thrust force was considerably stable in the STSS state, and the error was controlled within ±3%, except for the occasional mutations. However, the vertical resultant moment fluctuated more than that the oil pressure, which is attributed to two reasons. First, because of the intervention of the force arms in the calculation of the vertical resultant moments, the fluctuation of the vertical resultant moment was amplified. Second, the continuous change in shield attitudes indirectly results in the instability of the resultant force point of the propulsion system.

![Figure 6. The oil pressure response of each cylinder in the whole process](image)

![Figure 7. Total thrust force vectors of the shield propulsion system](image)

5.2 Shield driving speed and attitudes

The horizontal and vertical deviations of the shield attitudes were controlled in the range of ±5 mm (Figure 8), and the results show that the shield machine returned to the original attitudes after each segment was assembled and the thrust system entered the full-cylinder propulsion mode. In this test, the changes in the stroke for the entire propulsion system (excluding the retracted cylinders) in the previous minute were collected to calculate the average shield driving speed, which increased slightly in the STSS mode and then returned to its initial value in the full-cylinder propulsion mode. The shield
speed was controlled with $-2$ and $+3$ mm/min. In sum, the responses of the shield driving speed and attitudes proved the importance of the full-cylinder propulsion mode as a transitional period in maintaining the steady driving of shield machines in the STSS state.

5.3 Compressive state of the segments

Figure 9 shows the changes in compressive strain in the entire section of the steel segmental ring model. The initial compressive strain was stabilized before the system entered the STSS state, and due to the direct influence of the jacking forces from each hydro-cylinder, the variation trend of compressive strain was similar to that of the oil pressures. The compressive strain at the measuring points located in the decompression zone decreased, some changed to tension, whereas the compressive strain in the pressurization zone increases continuously. Similar to the shield driving speed and attitudes, the compressive strains of each measuring point returned to the initial value after the testing shield machine changed to the full-cylinder propulsion mode.

Maximum compressive strain of 576 µε was recorded at measuring point 10 when the block B3 was assembled. According to the similarity theory, the maximum compressive strain will reach 1286 µε by equal proportion conversion of the load in engineering applications as the maximum working overburden thickness of the “Jiyue” shield machine reaches 33 m. Compared with the ultimate compressive strain of the concrete (3500 µε), the safety factor was 2.72, proving that the segmental ring has enough safety margins for engineering applications if the STSS technology is adopted.

6 Conclusions

(1) A synchronous technology combing STSS was developed based on the active closed-loop control on the oil pressure of the shield propulsion system, and the linear distribution analytical method of the total thrust force in the full-cylinder propulsion mode, as well as the redistribution analytical method of the missing jacking force, was established to maintain the stability of the total thrust force vector.

(2) A super-large model test platform of shield synchronous technology was developed with a
similarity ratio of 1/2, and PID closed-loop control on the oil pressures of the propulsion system was verified for high accuracy.

(3) The compressive strains of the segments were directly affected by the changes in the jacking forces, and the measured results show that the compression capacity of the segment is sufficient for the application of the synchronous technology in actual projects.

(4) In our future studies, numerical simulations and field measurements of the compressive performance of the segmental ring will be conducted, and synchronous technology will be investigated under unsteady loading.

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