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Parameters of Slurry Shield Tunneling in the Upper-soft Lower-hard Ground

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Abstract

The relationship and matching degree between construction parameters should be considered in large-diameter slurry shield tunneling to ensure the construction quality and reduce the surrounding environmental impact. Based on the test data of Heyan Road crossing river tunnel in Nanjing, the work analyzed the controlling difficulties of the construction section passing the upper-soft lower-hard ground with gray correlation analysis. The following aspects were included: the importance of parameters in the slurry shield construction, influence of cutting water pressure, cutter head speed, cutter head torque, advance speed, total thrust, grouting pressure, and grouting amount on the crown settlement, and the relationship of the parameters. Results showed that the influences of cutter head speed, cutting water pressure, grouting volume, total thrust, grouting pressure, advance speed, and cutter head torque on the crown settlement decreased in turn. During passing the upper-soft lower-hard ground, the increased proportion of hard rocks reduced the cutter head speed and cut water pressure to ensure that the grouting volume matched the pressure.

Keywords

Tunnel; Large-diameter; Slurry Shield; Upper-soft Lower-hard Ground; Tunneling Parameter; Gray Correlation Analysis.

1. Introduction

Slurry balance shield has safety, advanced technology, good construction quality, and adaptability to complex formations, widely used in cross-river tunnel shield construction. The slurry shield can stabilize the tunnel face with mud, compared with the earth pressure balance (EPB) shield. The muds are pushed to the tunnel face, where muddy water penetrates the soil to form a mud film with low permeability, namely mud cakes. Then the mud pressure acts on the tunnel face through mud cakes to protect its stability from deformation [1]. Therefore, a slurry balance shield is suitable for stratums with high water content especially for constructing cross-river and -sea tunnels with complex stratum [2] due to its safe and orderly tunnel shield construction.

Shield construction is complicated. Compared with EPB shields, slurry shields have more parameters, whose matching affects the next construction. Hehua Zhu [3] tested the shield model under different burial depths, cutter head aperture ratios, advanced speeds, and screw conveyor speeds by laboratory model experiments. The results proved the internal relationships between the dump silo bin′s pressure and dumping efficiency, the dumping quantity per unit time and advance speed, and thrust and torque. Besides, the tunnel depth, cutter head aperture ratio, and advanced speed affect thrust and torque. Guolin Yang [4] studied the relationship among penetration, field penetration index, and excavation driving specific energy, and the boreability of stratums based on the on-site test data. Penetration, field penetration index, and specific energy of excavation can be the indicators of boreability. Qingyang Qin [5] analyzed the correlation of cut water pressure, total thrust, shield advance speed, rotation angle, and pitch angle based on the actual test data of constructing the Xianxia West Road tunnel, proving the correlation among cut water pressure, advanced speed of shield, and dry sand concentration.

The research provided a basis for selecting shield parameters. Therefore, the work studied the influence of complex rock formations on shield construction parameters based on the test data of Heyan Road Crossing River Tunnel in Nanjing.

2. Engineering Geology'S General Situation

The southern section of Heyan Road the Crossing River Tunnel in Nanjing is located between the Yangtze River Bridge and the Second Yangtze River Bridge, about 7.4 kilometers from the upstream Yangtze River Bridge and 2.7 kilometers from the downstream Yangtze River Second Bridge. As the deepest tunnel in China at present, it is 4,215 m long, with a shield section length of 2,970 m, a water depth of 53 m, and a maximum water pressure of 0.79 MPa. Meanwhile, the stratigraphic structure that the project passes is complex, including sand layer, moderately weathered breccia, brecciform limestone, limestone, and pebbly sandstone [6], as well as regional fractures and 4 faults in the lowest trough section at the bottom of the Yangtze River. Since the complex geological structure, especially some sections with karst caves and faults, is not conducive to shield construction, the engineering construction needs to pass through the weak ground first (see Table 1).

Table 1. Soil′s physical and mechanical parameters

Item	Natural density	Natural moisture content	Void ratio	Compression modulus	Compression coefficient	Direct and quick shear	
	g/cm3	%	—	MPa	MPa-1	Internal friction angleφ/°	Cohesive force C/MPa
(1) 3-2 layers of silt-sand	1.97	21.75	0.699	11.29	0.15	31.10	3.89
(2) 4 silt-sand with silt	1.95	23.97	0.705	11.91	0.15	30.89	4.05
(2) 5 powder fine sand	1.97	22.76	0.674	13.22	0.13	31.10	3.65
(2) 6 powder fine sand	1.99	22.10	0.673	14.02	0.12	31.21	5.04
(3) 1 medium coarse sand	1.96	18.16	0.614	20	/	33.57	4.33

Table 2. Rock′s physical and mechanical parameters

Item	Density	Natural compressive strength	Saturated compressive strength	Dry compressive strength	Elasticity modulus	Poisson's ratio
	g/cm3	MPa	MPa	MPa	GPa	—
(8) 3j moderately weathered breccia	2.55	31.45	28.36	54.16	17.2	0.2

Shield construction of Heyan Road Crossing River Tunnel started from Baguazhou starting well, passing the Yangtze River, and ending at the Jiangnan working well. The construction passed through sand layers, upper-soft lower-hard ground, fracture zones, full-face weathered rock formations, and karst cave areas, where rings 712-853 stratums are typical upper-soft lower-hard bottom layers.

Shield advance differs from a single stratum in the upper-soft lower-hard ground, as the shield machine′s shield posture is difficult to be controlled. The construction process and the shield-tunneling parameters should adapt to the variable stratums, with difficulty in construction. For example, a scraper is used for tunneling in soft rock formations, while a hob for hard rock formations, so the upper-soft lower-hard tools configuration and wear are difficult to grasp. Meanwhile, the parameter settings of advance speed, cutter head speed, and cutting water pressure are different from those of a homogeneous ground. Therefore, studying the parameter changes of shield tunneling through the upper-soft lower-hard bottom is beneficial to smooth tunneling, which provides a reference for constructing similar large-diameter shields [7].

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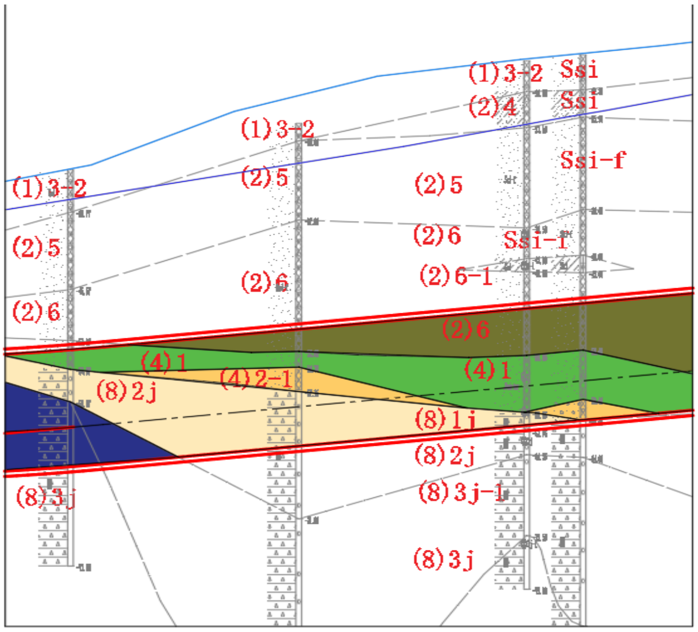

Figure 1. Geological distribution

3. Research On Shield Parameters

The work studied the main parameters of slurry shield tunneling construction in upper-soft lower-hard grounds from rings 710 to 855 since they are important for shield advance. The parameters were cut water pressure, advance rate, total thrust, arch axis settlement, cutter head speed, cutter head torque, grouting amount, and grouting pressure. Each parameter′s importance should be analyzed prior to their relationship.

3.1 Gray Correlation Analysis of Tunneling Parameters

Gray correlation analysis [8-9] determines the optimal sequence by the parameters′ actual situation. The relevance degree is determined by the similarity between the sequence curve and geometric shape of the scheme as well as that of the ideal optimal sequence [10]. Compared with the analytic hierarchy process, correlation analysis, fuzzy comprehensive evaluation, and neuron algorithm, gray correlation analysis is suitable for dynamic mileage analysis due to its simple calculation. This method is more applicable because the shield tunneling parameters change with the ground.

Gray correlation analysis should determine the reference and the comparison series, where the reference series X_0 is the result comparison series, reflecting other series. Then, the series of related factors affecting the system′s characteristic behavior is obtained through system analysis, named comparison series X_i. Considering the correlation of parameters in slurry shield construction and existing monitoring, crown settlement is taken as a reference series, and the comparative series includes cut water pressure, cutter head speed, cutter head torque, advance speed, total thrust, grouting pressure, and grouting amount.

The referenced series is

$$X_0 = x_0(k)\ ,\ (k = 1,2,\cdots n) \tag{1}$$

The comparative series is

$$X_i = x_i(k)\ ,\ (i = 1,2,\cdots m\ ;\ k = 1,2,\cdots,\ n\ ) \tag{2}$$

The data needs to be processed in a unified dimensionless manner due to different meanings of factors and different unit dimensions of the data. The process is as follows:

$$x_0(k)^* = x_0(k)/\bar{x}_0,\ (k = 1,2,\cdots,n) \tag{3}$$

$$x_i(k)^* = x_i(k)/\bar{x}_i,\ (i = 1,2,\cdots,m\ ;\ k = 1,2,\cdots,n\ ) \tag{4}$$

where $\bar{x}_0$ and $\bar{x}_i$ are the average values of comparison and reference series, respectively.

Assuming that the referenced series has N comparative series, X_1, X_2, $\cdots$, and X_n, the correlation coefficients of each referenced and comparative series are calculated as

$$\xi_i(k) = \frac{\Delta\, min + \rho \Delta\, max}{\Delta_i(k) + \rho \Delta\, max} \quad , \quad i = 1,2,\cdots,n \ ; \ k = 1,2,\cdots,m \tag{5}$$

where

$$\Delta\, min = \min_i \left[\min_k(|x_0(k)^* - x_i(k)^*|)\right];\ \Delta\, max = \max_i \left[\max_k(|x_0(k)^* - x_i(k)^*|)\right];$$

$$\Delta_i(k) = |x_0(k)^* - x_i(k)^*|$$

ρ is the resolution ratio within [0, 1] and the coefficient or weight of $\Delta\, max$. Its value indicates the importance the researchers attach to $\Delta\, max$. Referring to the value of ρ based on Ref. [11], this work took $\rho = 0.69$ to get rid of subjectivity.

As the correlation coefficient cannot measure the overall correlation, the average value of each correlation coefficient, namely the correlation degree, is selected as the reference frame. The calculation method of the correlation degree is as follows:

$$r_i = \frac{1}{n}\sum_{k=1}^{n} \zeta_{0i} \tag{6}$$

Table 3. Ranking of gray correlation degree

Influencing factors	Advance speed	Cutter torque	Cutter speed	Incision water pressure	Total thrust	Grouting amount	Grouting pressure
Correlation	r_1	r_2	r_3	r_4	r_5	r_6	r_7
Correlation value	0.694	0.615	0.875	0.855	0.827	0.828	0.794
Rank	6	7	1	2	4	3	5

Table 3 shows that the gray correlation order of crown settlement is that $r_3 > r_4 > r_6 > r_5 > r_7 > r_1 > r_2$. Therefore, various construction parameters′ influence in slurry shield on crown settlement is in descending order as follows: cutter head speed, incision water pressure, grouting amount, total thrust, grouting pressure, advance speed, and cutter torque.

3.2 Cutter Head Speed

Gray correlation analysis shows cutter head speed′s greatest influence on crown settlement, implying that the speed cannot be too fast or slow in the upper-soft lower-hard bottom layer. Figure 2 shows the relationship between the cutter head speed and the crown settlement.

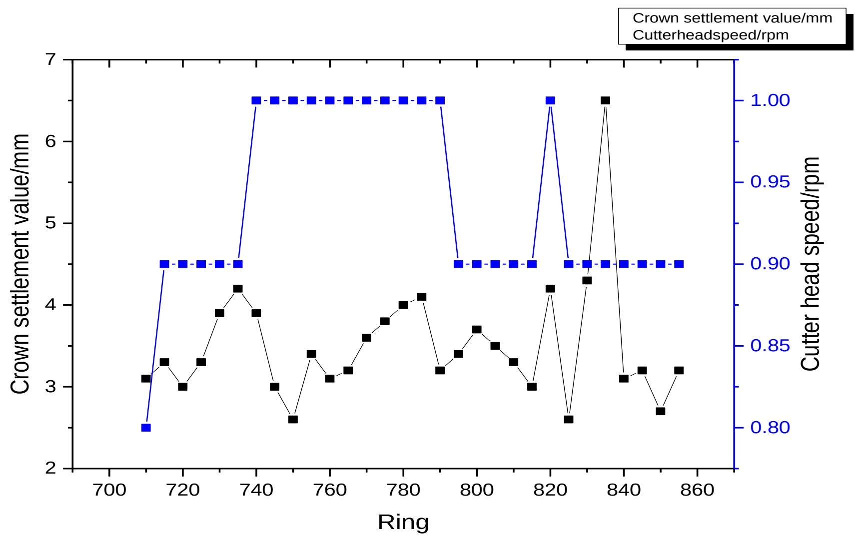

Figure 2. Crown settlement and cutter head speed

When the rotation speed of the cutter head is maintained at 0.9-1.0 rpm, the rotation speed of the cutter head remains constant. The sedimentation value of the vault is maintained at 2.5-4.5 mm within a controllable range. Therefore, keeping the cutter head speed constant without sudden change is an important prerequisite to ensure the orderly advancement of the shield.

Meanwhile, the complexity rather than the unity of the passing stratum makes it difficult to set the cutter head speed. A low speed reduces the advanced efficiency of the shield, while a high speed increases the cutter headwear. Weisen Zhang [12] combined the hard- and soft-rock stratums′ speed design and engineering practice to obtain a reasonable speed formula of the cutter head in the upper-soft lower-hard ground:

$$n_d = H(1-K)\,n_1 + Kn_2 \tag{7}$$

where $n_i = \sqrt{\frac{\alpha D}{1.2 q_{ui} v}}$ $(i = 1,2)$; α the cutter head torque coefficient; D the cutter diameter; q_{ui} the single formation′s unconfined compressive strength; v the advanced speed of the shield machine. $i = 1$ represents the hard rock stratum; $i = 2$ means the soft rock stratum. The formula shows that the speed of the cutter head speed is related to that of the shield advance. The ratio of advancing speed to cutter head speed is penetration, referring to the depth of the knife inserted into the soil. Currently, in the upper-soft lower-hard ground, the penetration is 14 mm/r. However, in rings 820-855, the penetration decreases to 7 mm/r, relating to the advance stratum. The proportion of the shield cuts through hard rock increases after ring 820.

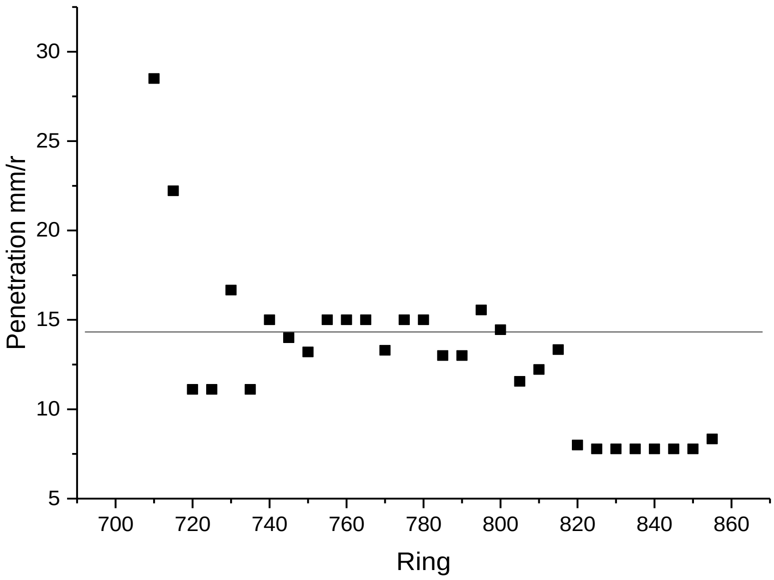

Figure 3. Tunneling rings and penetration

3.3 Cut Water Pressure

The water pressure of the cut is important for maintaining the stable tunnel face in shield tunneling, and varies with different geological conditions and tunnel depth. It includes groundwater pressure, rest soil pressure, and active soil pressure, which can be calculated into upper and lower limits. Upper limits should consider the rest of soil pressure, while lower limits should consider the active soil pressure. Besides, cut water pressure is divided into the upper, middle, and lower cut water pressures. The uppercut water pressure is the minimum pressure reached by the shield tunneling, which decides the tunnel face cut pressure. Generally, the tunnel face cut pressure is set by the uppercut water pressure.

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The upper limit of the water pressure of the cut is

$$P_{upper} = P_1 + P_2 + P_3 = \gamma_W h + K_0[(\gamma - \gamma_W)h + \gamma(H - h)] + 20 \quad (8)$$

where P_{upper} is the upper limit of the water pressure of the cut, kPa; P_1 the groundwater pressure, kPa; P_2 the rest soil-pressure, kPa; P_3 the active soil-pressure, also known as additional pressure, generally taken as 20 kPa; γ_W the unit weight of water, kN/m^3; K_0 the coeffcient of the rest soil-pressure; γ the unit weight of soil, kN/m3; H means the tunnel is buried deep to the centerline, m; The lower limit of cut water pressure is

$$P_{lower} = P_1 + P_2^* + P_3 = \gamma_W h + K_a[(\gamma - \gamma_W)h + \gamma(H - h)] - 2C_u K_a^{1/2} + 20 \quad (9)$$

where P_{lower} is the lower limit of cut water pressure, kPa; P_2^* the active soil-pressure, kPa; K_a the coefficient of the active soil-pressure; C_u the soil cohesion.

The water pressure value of the cut varies with different shield tunneling stratums and the Yangtze River water level. The shield's advanced speed affects the water pressure of the cut. Figure 4 shows their polynomial fitting, showing a positive correlation.

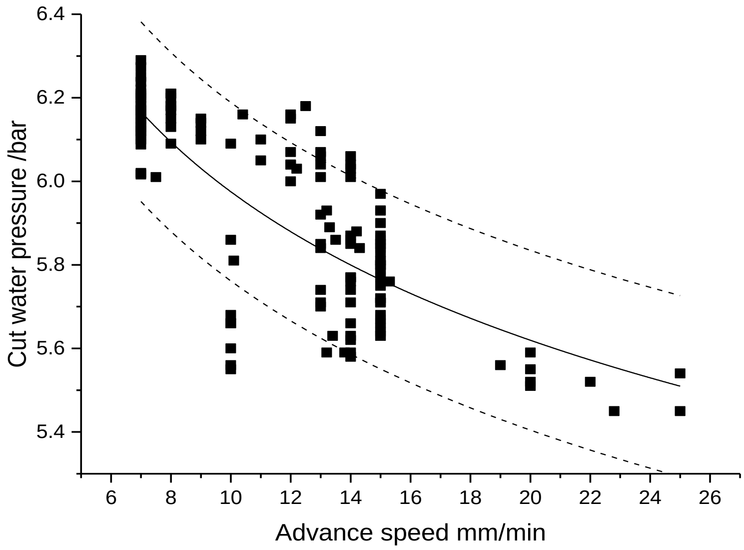

Figure 4. Advance speed and cut water pressure

For the low cutting water pressure, the front soil particles on the cutter head flow into the muddy water tank with the groundwater seepage or collapse. The increased volume of excavated earth causes the soil and dry sand amount to be higher than the theoretical value, resulting in over-excavation. Conversely, for the high cutting water pressure, the muddy water does not form mud cakes on the cutter head front to prevent the seepage of mud water and groundwater, making the front soil particles penetrate deep into the soil with high-pressure mud water. Excessive soil disturbance reduces the volume of excavated earth. It is lower than the theoretical value of the dry and soil sand, resulting in under-excavation. When the shield tunnels in the upper-soft lower-hard bottom layer with the advanced speed of 12-16 mm/min, the water pressure of the shield tunneling is stable, and the shield is in good running condition.

3.4 Grouting Amount

Shield grouting includes synchronous grouting, secondary grouting, and water blocking grouting [13]; grouting amount refers to synchronous grouting. As the shield advances to correct the deviation, there should be a gap between the shield shell′s inner face and the lining′s outer diameter on the designed axis, named the structure void. The void shall be grouted in time, and the grouting amount and pressure should be controlled for their influence on the surface subsidence and sedimentation rate.

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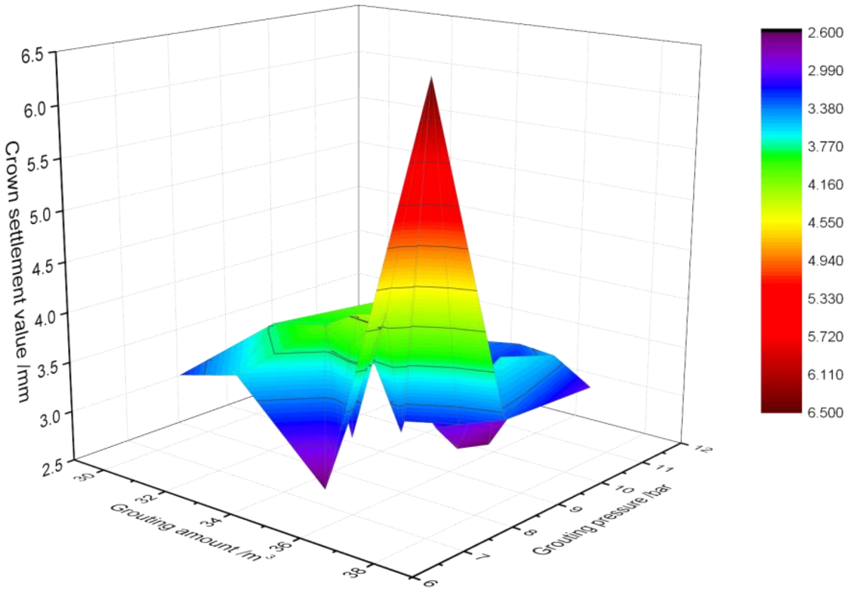

Figure 5. Grouting amount, grouting pressure, and crown settlement

Figure 5 shows that the grouting amount and pressure jointly affect the crown settlement. The graph has an abrupt change point for the large crown settlement value when the grouting amount is 37 m^3 and the grouting pressure is 8 bar. However, the overall change of the crown settlement value tends to be gentle when the grouting volume is 32-37 m^3. Therefore, the grouting amount and pressure should be strictly controlled when the shield tunneling passes the upper-soft lower-hard ground to avoid excessively large crown settlement.

3.5 Cutter Head Torque

Cutter head torque includes cutter head cutting torque, self-weight bearing torque, axial load torque, sealing device friction torque, cutter head′s front surface friction torque, frictional counter-torque on the cutter head′s circumferential surface, cutter head′s backside friction torque, and cutter head opening slot shearing moment. In the upper-soft lower-hard ground, cutter head torque varies with the change of soils in shield tunneling.

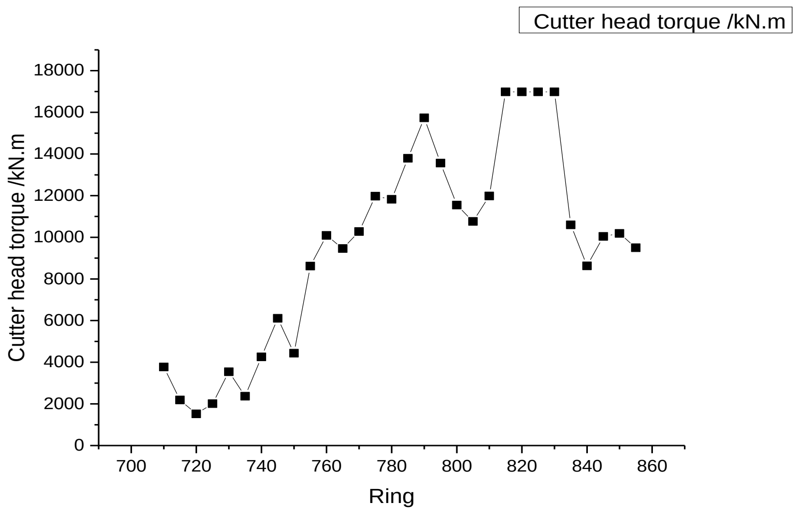

Figure 6. Measured cutter head torque

The change of cutting formation leads to cutter head torque′s fluctuation: In rings 710 to 750, the shield has tunneled to the upper-soft lower-hard ground, and the upper-soft soil layer accounts for a large proportion. Besides, the cutter-head torque changes less than the sand layer. With the shield advancing, hard rock′s ratio and cutter head torque increase, and the maximum torque reaches 1,700 KN.m in rings 810 to 830. However, the rock layer changes little and the cutter head torque is stable after ring 840. Therefore, the cutter head torque passing the upper-soft lower-hard ground depends on the stratum change, and the cutter head torque is positively correlated with the total thrust (see figure 7). They should be matched.

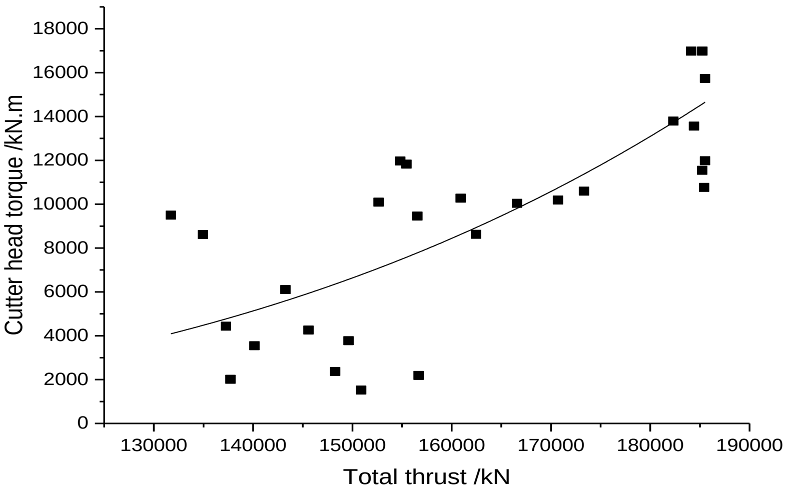

Figure 7. Total thrust and cutter head torque

4. Conclusions

Based on the section test data of Heyan Road Crossing River Tunnel in Nanjing passing upper-soft lower-hard ground, the work comparatively analyzed the influence of cutter head speed, cutting water pressure, grouting amount, total thrust, grouting pressure, advance speed, and cutter head torque on the crown settlement.

(1) The influence of cutter head speed, cutting water pressure, grouting amount, total thrust, grouting pressure, advance speed, and cutter-head torque on the crown settlement decreased sequentially. During passing the upper-soft lower-hard ground, the first three parameters should be noted.

(2) During passing the upper-soft lower-hard ground, the cutter-head speed should be stable and could be determined by the penetration value. As the proportion of passing the hard rocks in the stratum increased, the penetration value and the cutter head speed could be reduced.

(3) The results showed that the cutting water pressure was positively correlated with the advanced speed, which should be reduced simultaneously.

(4) The grouting amount and pressure affected the crown settlement together, which should be controlled when the shield passed the upper-soft lower-hard ground.

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