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Research Article

Adaptability of the Cutter-Head of the Earth Pressure Balance (EPB) Shield Machine in Water-Rich Sandy and Cobble Strata: A Case Study

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Earth Pressure Balance (EPB) shield machines are considered to be the most efficient tunneling method for Metro tunnels due to their adaptability to a great variety of ground conditions, higher construction efficiency, and providing a safer working environment. There are many guidelines available for EPB shield machine selection. However, these guidelines are very general and cannot be used directly for an upcoming project. This paper takes Chengdu Metro Line 6 in China as the engineering background; the studied area is typical of a water-rich sandy and cobble stratum with high content of cobble. Three types of EPBs in the two continuous intervals exhibit significant differences in performance and encounter many difficulties such as wear of the cutter disc and tools, clogging, and severe surface settlement during the operation. These difficulties prevent the construction efficiency, increase the cost of the project, and cause delays in construction period. The causes of these difficulties are summarized by recording and comparing the operational parameters of the three types of EPBs. These parameters that are summarized include the advance rate, total thrust, torque, and the rate of rotation of the cutter-head. In addition, the surface settlements are also compared. The results indicate that the opening rate, maximum opening size, and the opening position of the cutter-head are key factors that affected the geological adaptability of the shield machine in water-rich sandy and cobble strata. Among the three factors, the maximum opening size and opening position are the most important factors influencing the strata adaptability of the cutter-head. To avoid frequent jams of the cutter-head, the maximum torque should be not less than 6,500 kNm. The maximum opening size should not be less than 420 mm × 420 mm. The effect of increasing the central opening of the cutter-head is that large cobbles and boulders can be discharged through the central opening when they cannot be discharged through the opening near the original position of the cobbles and boulders. This paper provides specific guidance on the selection of cutter-head for shield machines in water-rich sandy and cobble strata.

1. Introduction

With the rapid progress of urbanization, the problem of urban traffic congestion is becoming more and more prominent. The Metro has an important role in urban rail transportation because of its advantages in environmental protection, efficiency, and safety. As a central city in the nation, Chengdu must deal with significant traffic pressure, so the local government is vigorously promoting the construction of urban road transportation infrastructure. As of May 2020, the Chengdu Metro had opened seven lines with a total length of about 302 km, with another 391 km under construction. The Chengdu Metro is expected to reach 515 km by the end of 2020.

The shield tunnels have been constructed in the water-rich sand and cobble stratum in Chengdu for more than 10 years, and significant construction experience has been acquired in the process. However, the cutter-heads of EPB shield machines are impaired by severe wear and the formation of a mud cake, which have significantly reduced the speed of construction and significantly increased the cost of construction in the water-rich sand and cobble stratum that contains large boulders.

Due to the difficulties associated with the construction of shield tunnels, Li et al. [1] studied the wear of the disc cutter and proposed a model to predict the wear r in typical sandy cobble strata, and the clogging effect was studied through an energy method in a practical project [2]. Cao et al. [3] analyzed the performance of a slurry TBM (tunnel boring machine) in sandy cobble ground through a case associated with Lanzhou metro, and they summarized the challenges of tunnelling and proposed corresponding countermeasures by recording and comparing the operational parameters. An assessment method of logging in mechanised tunnelling was proposed in clay strata [4]. Most of the problems that arise in the construction of shield tunnels basically are due to unreasonable design of the cutter-head [5–11]. Sun et al. analyzed the engineering problems related to the cutter-head during shield tunnelling based on several engineering applications and they concluded that the cause of these problems was the poor adaptability of the design of the cutter-head to geological conditions [12]. Wang et al. analyzed the causes of the frequent stops of the shield machine in the cobble stratum construction of Beijing Subway Line 10, and the cutter-head of the shield machine was modified accordingly to make the construction proceed smoothly [13].

In fact, the performance of the EPB shield machine is the result of the interaction between the machine and the strata, which also reflects the adaptability between the machine and the strata [14]. The performance of the shield machine is reflected mainly by its operational parameters such as its advance rate, thrust, torque, and the rotation speed of the cutter-head. Based on Xuzhou Metro Line 1, the adaptability of the EPB shield machine in clay strata was evaluated, and the reasonable excavation parameters were proposed [15]. Jin et al. used indoor model tests to analyze the opening rate of the cutter-head on the excavation parameters and they discussed the relationship between opening rate and torque of the cutter-head [16]. Zhu et al. conducted a series of model tests to study the effects depth of the tunnel, the opening rate of the cutter-head, and the forward speed on thrust and torque, and they found that the forward speed exhibited an approximate positive exponential relationship with thrust and torque [17].

The focuses of this paper are the adaptability of EPB shield machines in the water-rich sand and cobble strata and the selection of the EPB shield machine. After preliminary selection [18, 19], four EPB machines (three types) were used in two continuous intervals (twin-bored tunnels), and their performances varied greatly. By recording and comparing the operational parameters (advance rate, thrust, torque, and rotation speed of the cutter-head), the adaptabilities of the three EPB shield machines were evaluated. Then the key factors that influenced the adaptabilities of the three EPB shield machines, including consideration of the geological features of the area, were discussed. Then, the specific basis was presented for the selection of the cutter-head of the EPB shield machine in the water-enriched sand and cobble stratum.

2. Location of the Project and the Geological Conditions

2.1. Location of the Project. The designed lengths of the continuous Tian-Xi and Xing-Xi intervals were 1580.525 m (from K12 + 960.635 to K14 + 541.600) and 1354.321 m (from K14 + 834.437 to K16 + 188.758). The longitudinal section has a V shape, and the maximum slope is 24‰. Figure 1 shows the location of the two continuous intervals. Four EPB shield machines (three types) were used for the construction, and the left line of Tian-Xi interval was EPB1, the right line of Tian-Xi interval was EPB2, respectively, and the two lines of Xing-Xi interval were EPB3. Table 1 provides the main parameters of the three types of EPB shield machines. The screw conveyors were the same on the three EPB shield machines, and the external diameter was 960 mm.

2.2. Geological Conditions. According to the geology survey data from 72 boreholes and the foundation pit of Xipu station, the two intervals mainly pass through medium and highly compacted sandy cobble strata. Figure 2 shows the rock core from the boreholes and the foundation pit of Xipu station. The buried depths of the medium compacted sandy cobble and the highly compacted sandy cobble were 9–18 m and 18–13.4 m, respectively. The content of gravel was about 65.5–69.8%, and large-sized boulders are in the passing through strata. The largest boulder that was observed had a diameter of 64 cm. The hard minerals in the gravel were quartz and feldspar, and the content varied from 62% to 100%. Figure 3 shows the grading curve and the characteristic diameter of the particles.

Sand is defined as particles between 0.075 mm and 2 mm and pebble is particles between 60 mm and 200 mm in size. Figure 2 presents the particle size of the soil group. The sandy cobble strata are mainly composed of sand grain and cobbles, with high content of cobbles [20]. The strata are miscellaneous fill, plain fill, sand and pebbles and mudstone from the surface downwards, with thicknesses of 1.7 m, 3.2 m, 19.6 m, and 6.6 m, respectively, as shown in Figure 3. The mechanical parameters of the strata are listed in Table 2. There are 3 substrata of sandy cobble stratum, which were slightly dense cobble, moderately dense cobble, and dense cobble, with thickness of 5.1 m, 9.0 m, and 5.4 m, respectively.

The buried depth of the two tunnels ranged from 16.5 m to 21.6 m, the crossing strata are moderately dense cobble and dense cobble. The buried depths of the medium compacted sandy cobble and the highly compacted sandy cobble were 9–18 m and 18–13.4 m, respectively. The content of gravel was about 65.5–69.8%, and large-sized boulders are in

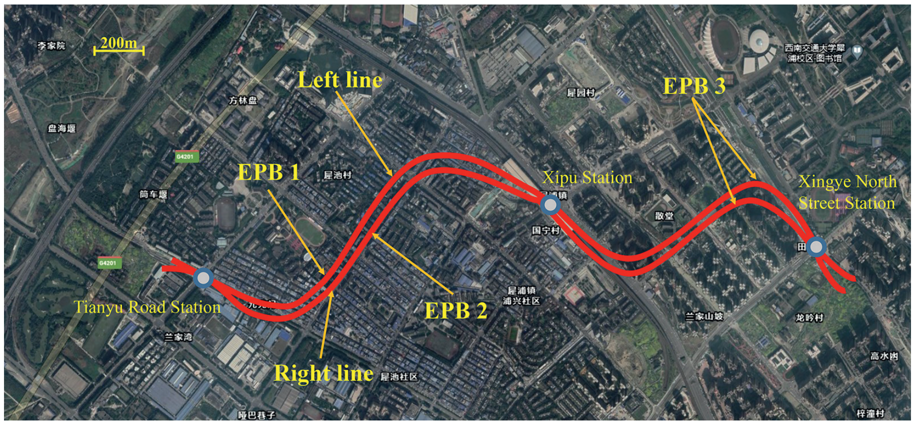


Figure 1: Layout and EPBs used in the two continuous intervals in Chengdu Metro Line 6.

Table 1: Main working parameters of the three types of EPB shield machines.

EPB type	Cutter-head	Opening ratio (%)	Diameter (m)	Nominal torque (kNm)	Maximum torque (kNm)	Maximum thrust (kN)	Driving power (kW)
EPB1	Face and plate	28	6.28	6850	9320	42 000	1200
EPB2	Face and plate	32	6.28	6048	8687	34 000	945
EPB3	Face and plate	30	6.28	5380	7430	31 651	945

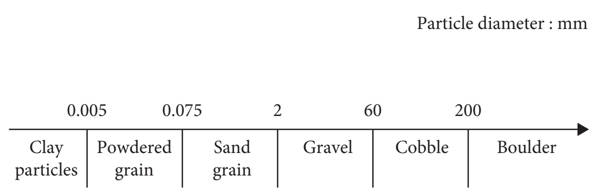
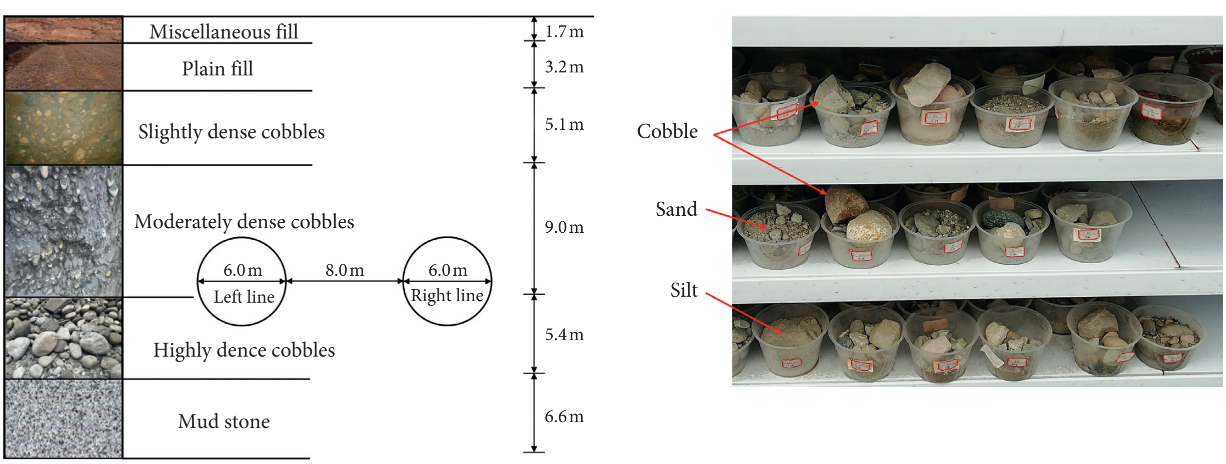


Figure 2: Particle size grouping of soil.



(a) (b)

Figure 3: Geology condition of the strata: (a) stratigraphic distribution with depth and (b) composition of the sandy and cobble layer.

Table 2: Mechanical parameters of strata.

Stratum	Density (kN/m^3)	Young's modulus (MPa)	Poisson's ratio	Internal friction angle (°)	Cohesion force (kPa)
Miscellaneous fill	17.5	1.5	0.37	10	8
Plain fill	18.5	6.2	0.32	20	15
Slightly dense cobbles	21.4	29.6	0.30	38	0
Moderately dense cobbles	21.8	34.0	0.27	44	0
Highly dense cobbles	22.0	38.5	0.22	48	0
Mud stone	22.4	60.0	0.21	41	60

the passing through strata. The largest boulder that was observed had a diameter of 640 mm. The hard minerals in the gravel were quartz and feldspar, and the content varied from 62% to 100%. Figure 4 shows the grading curve of the particles.

3. Performance of EPBs in the Continuous Intervals

3.1. Comparison of the Single Operational Parameter of the EPBs. EPB shield machine construction parameters were generated in the tunnelling process. The parameters are one of the effective means of expressing the adaptability of the equipment stratum. During the excavation, the parameters of the advance rate and the rotation of the cutter-head represent the efficiency of the excavation. Torque and thrust were the main parameters that were used to estimate the performance of the EPB shield machines. Therefore, the four basic parameters shown in Figure 5 were recorded by the dashboard in the operation cabin.

In order to compare the adaptability of the three EPB shield machines to the water-rich sand and cobble stratum, the main construction parameters of the three types of EPB shield machines, i.e., their advance speed, thrust, torque, and the rotation speed of the cutter-head, were compared statistically by taking the 60 rings of stable tunnelling process in two continuous intervals with similar geological conditions.

Figure 6 provides a comparison of the advance rates of the three types of EPB. The figure shows that EPB3 had the lowest advance rate, i.e., 30–70 mm/min, and the advance rate was around 50 mm/min most of the time. EPB2 had the highest advance rate of 70–110 mm/min, and the advance rate was around 100 mm/min most of the time. The advance rate of EPB1varied from 55 to 100 mm/min for most of the recording rings, and the advance rate was around 80 mm/min. The advance rates of EPB2 and EPB1 had wider ranges than that of EPB3, but the advance rate of EPB2 became more stable.

Figure 7 compares the working thrust during the operating process of the three EPBs. The figure shows that, among the three EPBs, EPB1 had the largest working thrust, i.e., between 14,000 and 22,000 kN, and it was around 18,000 kN most of the time. EPB2 had the smallest working thrust, i.e., between 10,000 and 12,000 kN, and it was around 11,000 kN most of the time. The thrust of EPB3 varied between 13,000 and 18,000 kN, and it was around 11,000 kN most of the time. Considering the parameter of working thrust, that of EPB2 was at a low level for a long time, and it had the lowest range of fluctuations.

Figure 8 compares the cutter-head torque of the three EPBs during normal operation. The figure shows that, among the three EPBs, EPB3 had the highest working torque; i.e., it was between 3500 and 5300 kNm, and it was around 4,400 kNm most of the time. EPB2 had the lowest torque; i.e., it varied between 3,000 and 4,000 kNm, and it was around 3,500 kNm most of the time. The torque of EPB1 ranged between 3,500 and 5,000 kNm, and it was around 4,000 kNm most of the time. However, it varied significantly at some rings, i.e., rings 23, 26, and 32. From comparing the data, it was apparent that EPB2 had the lowest working torque and the minimum range of fluctuation.

Figure 9 shows the comparison of the rotational speed of the cutter-heads of the three EPBs during the construction period, and it is apparent that rotation speed of the cutter-head of EPB1 had the highest average rotational speed and the largest fluctuation range, i.e., 1.65–1.95 rpm. EPB2 had the most stable rotation speed; it stayed between 1.6 and 1.68 rpm for most of the construction rings. Of the three models, the EPB3 model had the lowest average rotation speed, and it varied from 1.50 to 1.73 rpm.

From the analysis of the four main parameters, it was found that EPB2 had the minimum thrust and torque, the most stable rotation speed of the cutter-head, and the maximum advance rate. The fact that it had the maximum advance rate is important because advance rate is the most basic indicator of excavation efficiency. The ranges of the fluctuations represent the stability of the parameters. The stability of the operating parameters is essential for safe, efficient, and fast tunnelling. Therefore, among the three EPBs, EPB2 demonstrated the best adaptability with the water-rich sandy and cobble strata.

3.2. General Performance of Each EPB Shield Machine. Figure 10 shows the comprehensive performance of each of the EPBs. The parameters of EPB2 were relatively stable, but the parameters of EPB1 and EPB3 fluctuated over large ranges. EPB3 had the minimum advance rate; it had the maximum torque and thrust. The advance rate of EPB1 was between the rates of EPB1 and EPB3; it had high values of torque and thrust, and the rotation speed of the cutter-head had the largest range of fluctuation. When EPB2 was working at the maximum advance rate, its torque and thrust were less than the torque and thrust of the other two shield machines. The rotation speed of the cutter-head of EPB2 was more stable than those of EPB1 and EPB3. All of the operating parameters of EPB2 fluctuated within the minimum range. Figure 11 shows that the average daily advance rates

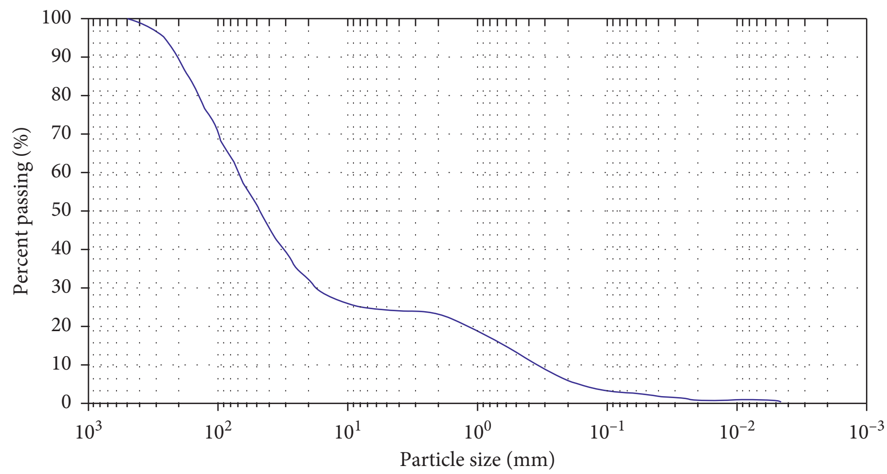


Figure 4: Characteristic grading curve of the strata.

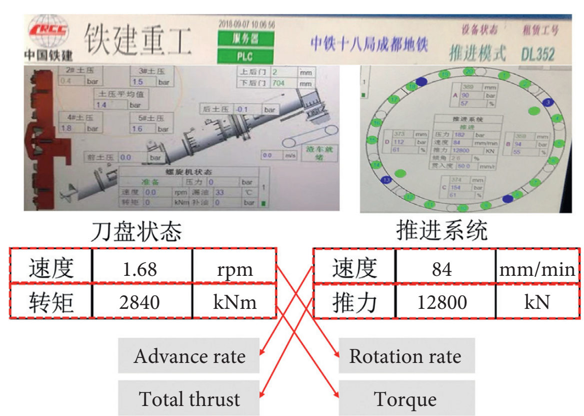


Figure 5: Main operational parameters displayed on the dashboard.

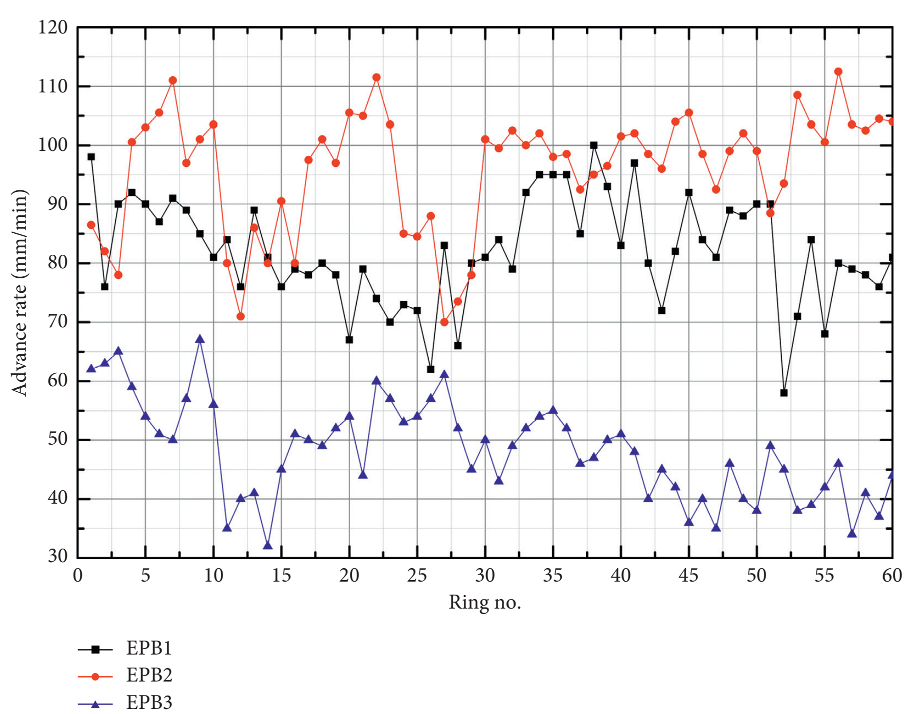


Figure 6: Advance rates of the three EPBs.

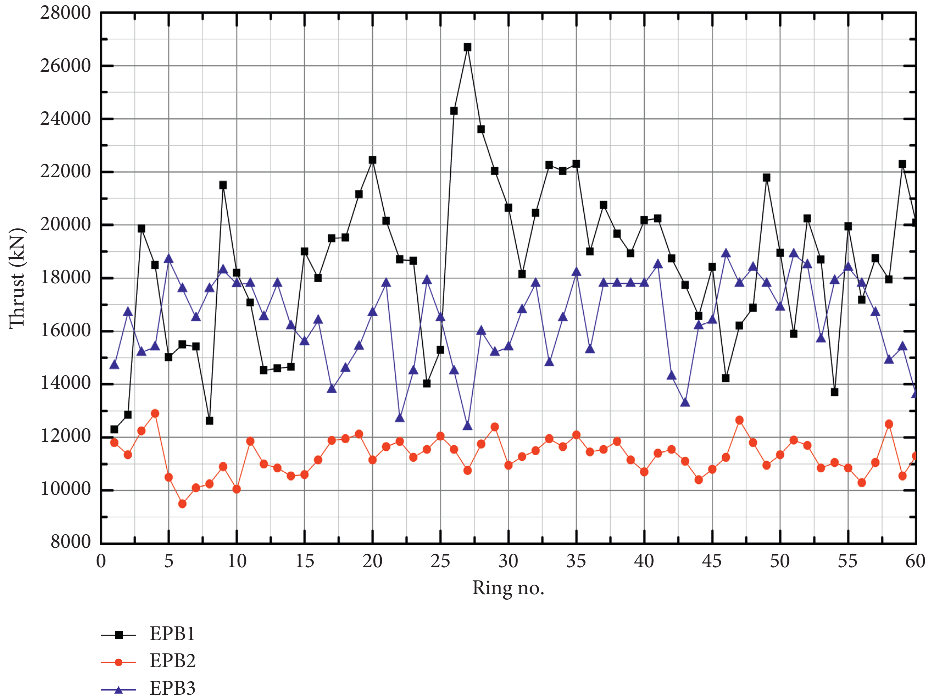


Figure 7: Thrust of the three EPBs.

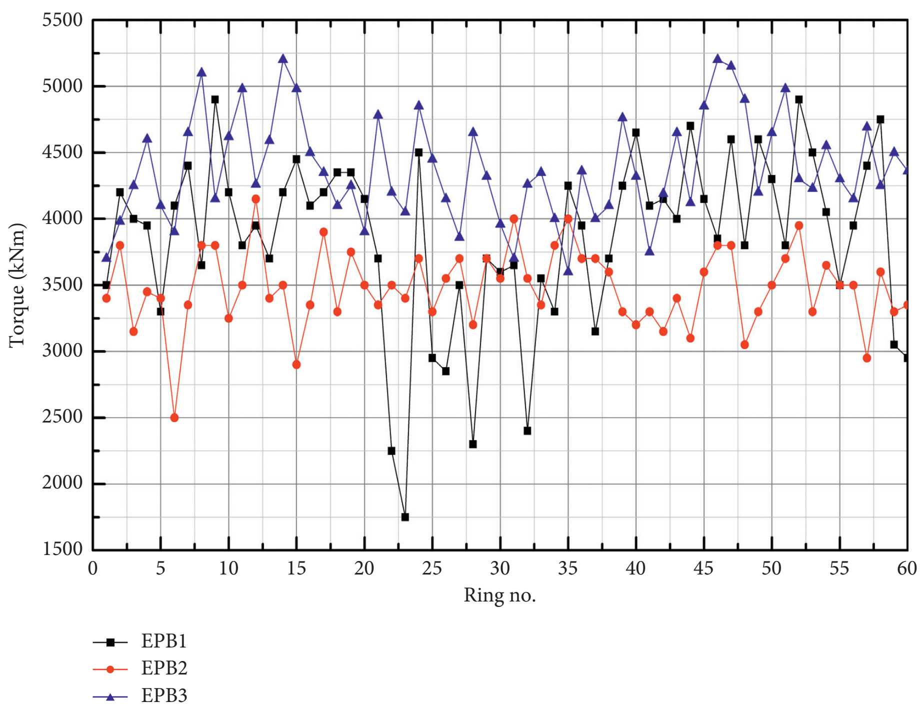


Figure 8: Torque of the three EPBs.

for EPB1, EPB2, and EPB3 were 12 rings, 16 rings, and 5 rings, respectively.

Surface settlement is another important indicator for evaluating the shield machine adaptability of the excavation strata, and severe ground settlement has a significant impact on the environment and the safety of surface buildings and underground pipelines. During the operation of the three EPBs in the four intervals, EPB3 experienced long periods of downtimes which induced severe ground collapse. The maximum surface settlement of the three EPBs during the excavation is shown in Figure 12. The maximum surface settlements that correspond to EPB1, EPB2, and EPB3 are 29 mm, 18 mm, and 37 mm, respectively.

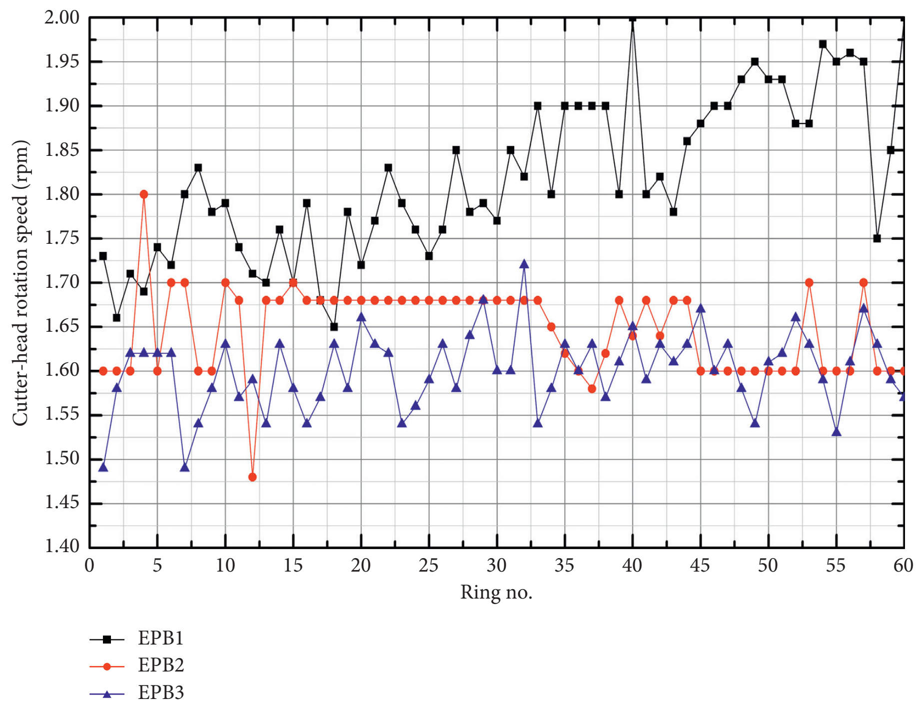


Figure 9: Rotation speeds of the cutter-heads of the three EPBs.

This indicated that EPB2 did the best job of adapting to the water-rich sandy and cobble strata.

During the construction period, EPB3 experienced frequent stops that were caused by the jam of cutter-head and excessive wear of the cutter tools. The average distance traveled between stops was about 30 rings, i.e., 45 meters. The frequent stops caused a significant decrease in the efficiency of excavation. Unlike EPB3, EPB1 only had stops that were caused mainly by the excessive wear of the cutter tools, and the average distance it traveled between stops was about 80 rings, i.e., 120 meters. The continuous excavation distance of EPB2 is about 160 rings, i.e., 240 meters, and the stops were caused mainly by the adhesion of the sand and clay to the cutter-head and the soil chamber. The mud cake was cleaned by manually opening the soil chamber, and, when this was done, the cutter tools were checked and replaced if necessary. Figure 13(a) illustrates eccentric and excessive wear of the cutter, for the high content of cobbles of the strata; the cutters often experience severe wear during the operation of EPB shield machine. Figure 13(b) shows the clogging of the cutter-head with clay, sand, and embedded gravel; the clogged cutter-head was cleaned manually by rod and hammer.

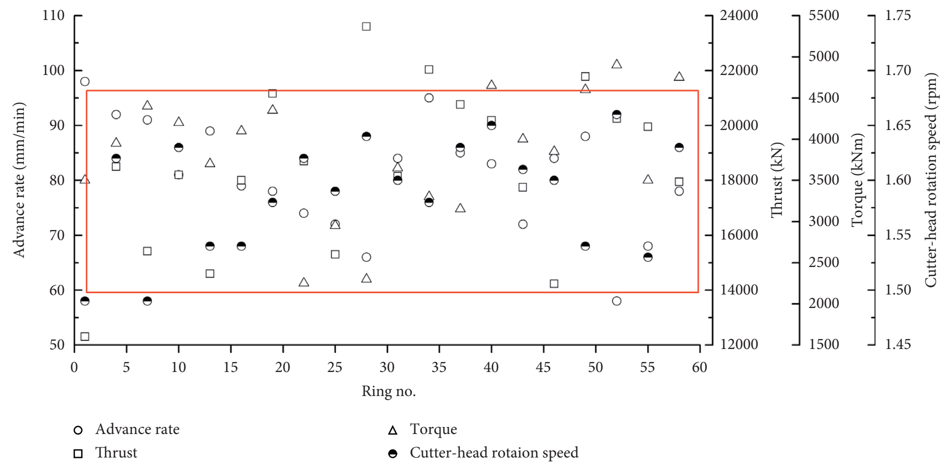
4. Analysis and Discussion

The three EPBs showed significant differences in performance during the constructions in two continuous intervals. However, all three of the cutter-heads, i.e., the ones for EPB1, EPB2, and EPB3, were panel type cutter-heads with opening rates of 28%, 32%, and 30%, respectively. Figure 14 shows that there were no obvious differences between the three EPBs. All three of them are within the suitable range of opening rates [21, 22], and also the arrangements of the tools were similar.

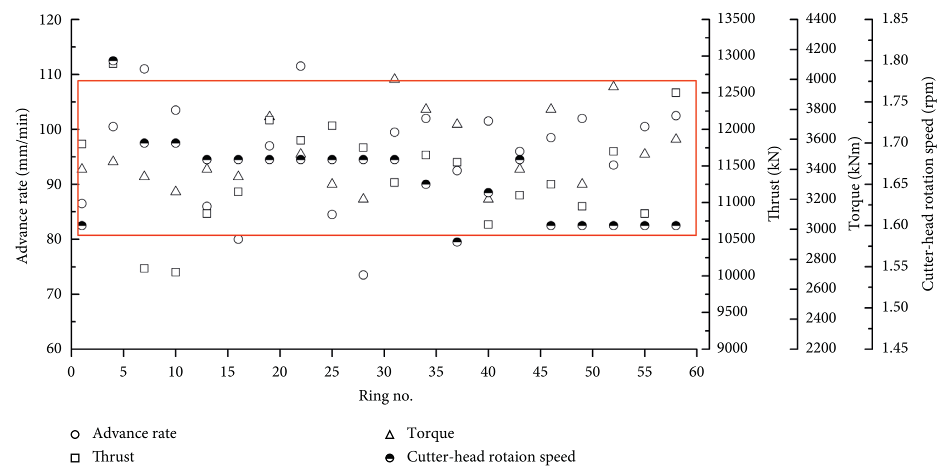
The main difference between the three EPBs is that the maximum size of opening EPB2 was larger than those of EPB1 and EPB3. Therefore, larger cobbles could be discharged by EPB2 more easily than they could be discharged by EPB1 and EPB3. More pebbles must be crushed by the cutter tools in EPB1 and EPB3 before they can be discharged from the face of the tunnel to the soil chamber. Figure 15 shows the cobbles discharged by EPB1and EPB3, most of which were crushed before they were discharged. That is also the reason for the excessive wear of the cutter tools of EPB1 and EPB3.

In order to understand the mechanisms of the cutter opening size and rate on the performance of EPBs, figures of the opening size and discharged cobble, wear of the cutters, and the relationship of driving power and the ability to avoid jams are plotted by field observation.

The comparison of the biggest opening size and the maximum discharged cobble diameter is illustrated in Figure 16. The maximum opening sizes are 390 mm, 300 mm, and 240 mm, and the maximum diameters of the discharged cobble are 318 mm, 272 mm, and 184 mm, respectively. The diameter of the discharged cobbles increased with the increase of the cutter-head opening size. The ratio of the two is nearly 1.3 which is in accordance with the results in literature [23]. Based on the geology condition, the largest boulder with a diameter is 640 mm. It is assumed that largest boulder can pass through the opening into the soil chamber after a single crushing and that the opening size must not be less than 1.3 times the diameter of the crushed boulder. Therefore, the maximum cutter-head opening should not be less than $420\,\text{mm} \times 420\,\text{mm}$.



(a)



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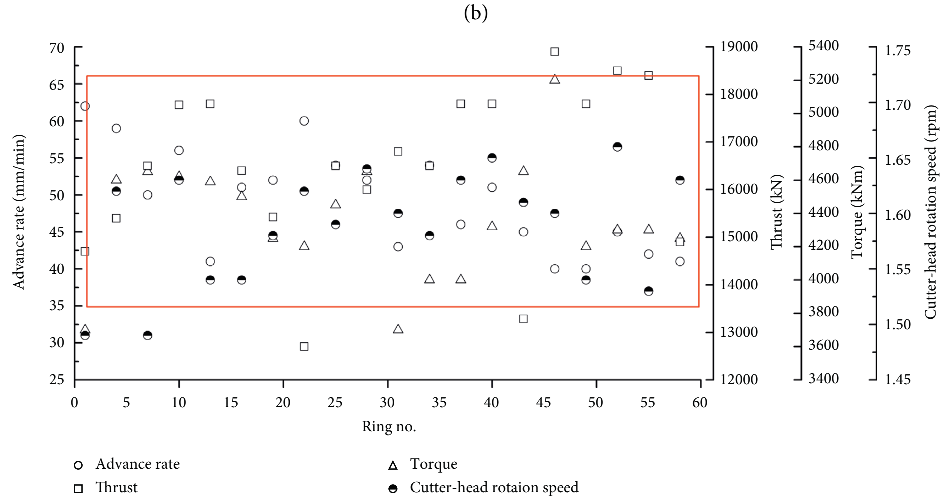


(c)

Figure 10: Comprehensive performance of (a) EPB1, (b) EPB2, and (c) EPB3.

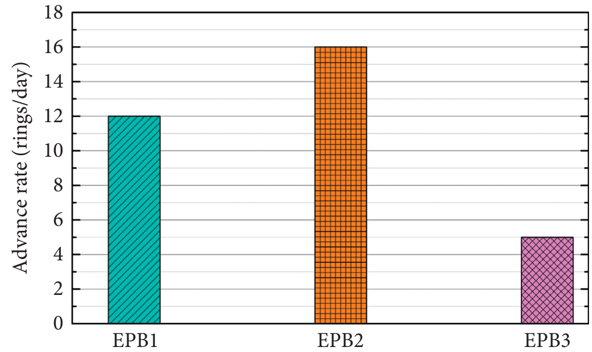


Figure 11: Daily advance rate of the EPBs.

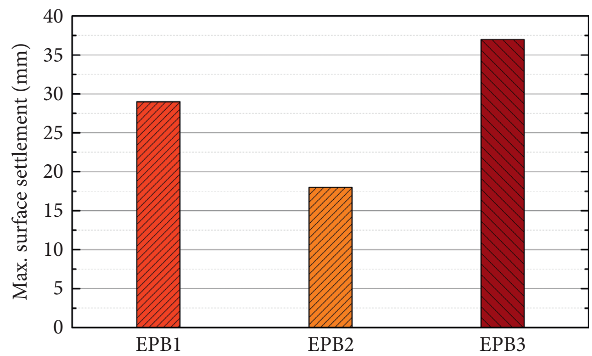
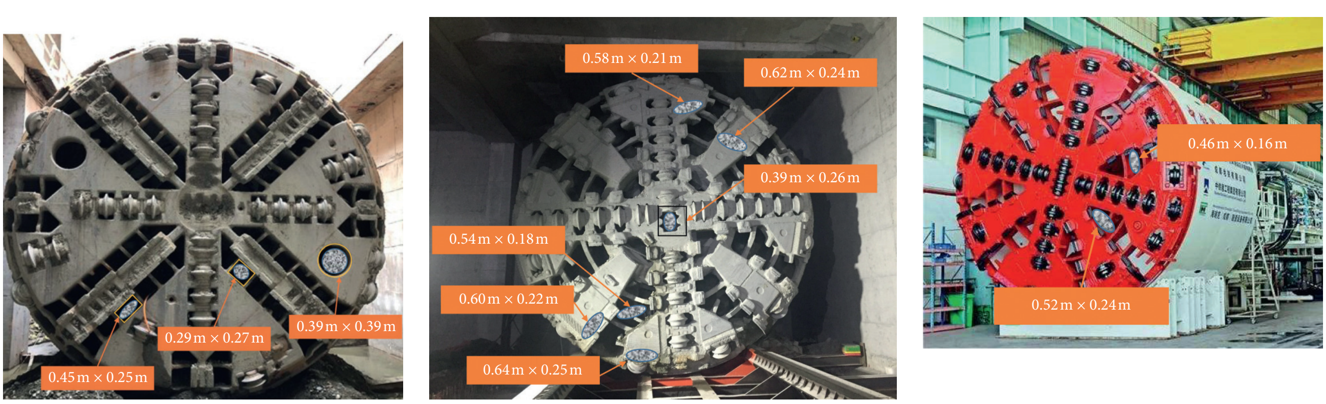


Figure 12: The maximum surface settlements of the EPBs.

(a) (b)

Figure 13: Excessive wear of the cutter tools and clogging of the cutter-head.



(a) (b) (c)

Figure 14: Cutter-heads of the three EPBs: (a) EPB1, (b) EPB2, and (c) EPB3.

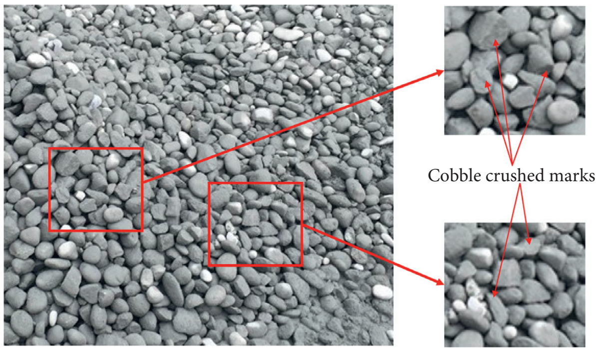


Figure 15: Cobbles discharged from EPB1 and EPB3.

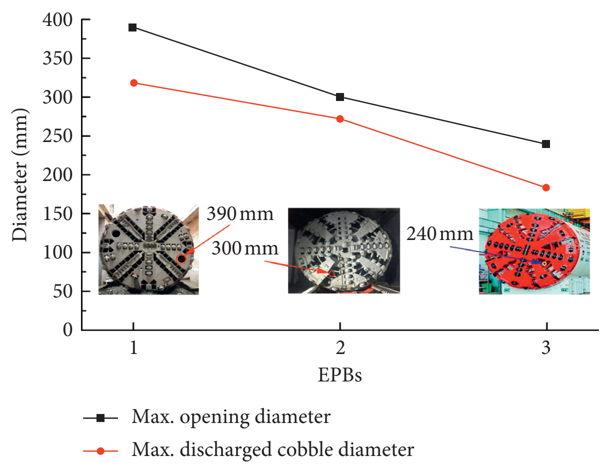


Figure 16: The comparison of the biggest opening size and discharged cobble diameter.

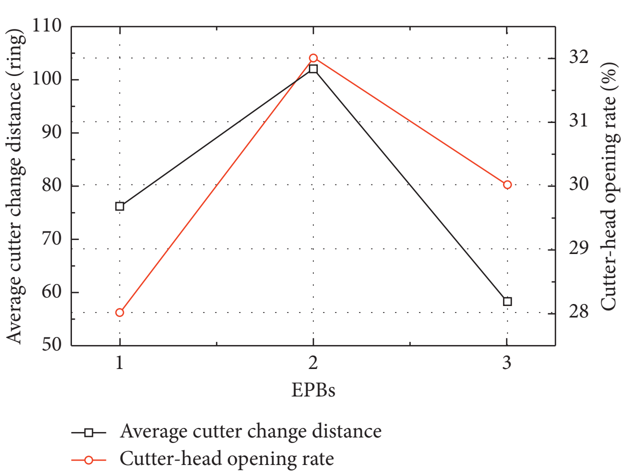


Figure 17: The comparison of the opening rate and average cutter change distance.

The severe wear and tear of EPB machines during tunnelling make it time-consuming, costly, and even dangerous to inspect and maintain the machines while inspection and maintenance of cutting tools in a timely manner are essential to ensure proper performance of EPBS machine [24]. The cutter wear is directly related to cobbles it crushed. The relationship between the opening rate and average cutter change distance is shown in Figure 17. We can infer from Figure 17 that the average cutter change distances increase with the increase of the cutter-head opening rate in the three EPBs. The average cutter change distances of the three EPBs are 58, 102, and 70 rings with respect to the cutter-head opening rate at 28%, 32%, and 30%, respectively. However, the cutter change distance of EPB2 is 44 rings longer than EPB1 and 32 rings longer than EPB3, the cutter-head opening rate of EPB2 is 2% higher than EPB3, and the cutter-head opening rate of EPB3 is 2% higher than EPB1. This may mainly be because of the difference of opening position of the three EPBs: in EPB2 one cutter in the centre of the cutter-head is not installed and the size of the central opening is bigger than EPB1 and EPB3. The maximum opening size is EPB1, but the two openings are located at nearly the edge of the cutter-head.

Jamming problems are one of the most common causes of unexpected stoppages in shield tunnels during construction. There are two categories of jamming accidents called shield jamming and cutter-head jamming. The accidents of EPB cutter-head jamming have a large proportion in all jamming accidents [25]. The direct cause of the cutter-head jamming is that the torque required is greater than the torque available. Therefore, there are two ways to resolve jamming problems: one is to reduce the torque required by the cutter-head and the other is to increase the torque that the cutter-head can provide. The composition of the cutter-head is very complex, with torque generated by the shear forces on the front face, the circumference, and the opening accounting for 90% of all driving torque [26]. In some extreme cases, the shear of the cutter-head opening generates 70% of the total torque. The main reason for cutter-head jamming in sandy and cobble stratum is the large boulder that was stuck in the opening [27, 28].

The relationship between the average jamming distance and working (required) torque, nominal torque, and maximum torque is plotted in Figure 18. In Figure 18, we can infer that EPB3 had the highest working torque which was around 4,400 kNm, EPB2 had the lowest torque which was around 3,500 kNm, and the working torque of EPB1 was around 4,000 kNm. The required torque of EPB2 is the smallest one, EPB1 is the medium one, and EPB3 is the largest one during the excavation operation. In this engineering case, the average down distances caused by cutter-head jamming are 130 rings, 120 rings, and 65 rings, respectively. This is mainly caused by the ratio of the nominal torque, maximum torque, and the working (required) torque; for EPB2, the required torque is around 3,500 kNm and the corresponding nominal torque is 6,048 kNm and 8,687 kNm and the average required torque is 2,548 kNm smaller than the nominal one; for EPB3, the required torque is around 4,400 kNm, the corresponding nominal and maximum torque are 5,380 kNm and 7,430 kNm, and the average required torque is just 980 kNm smaller than the nominal one; for EPB1, the required torque is around 4,000 kNm, the corresponding nominal and maximum torque are 6,850 kNm and 7,430 kNm, and the average required torque is 2,850 kNm smaller than the nominal one.

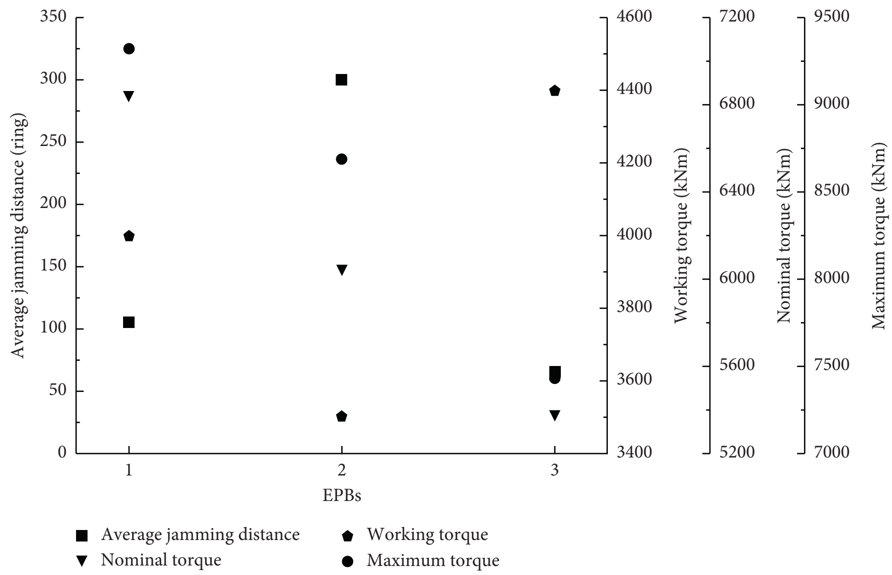


Figure 18: The comparison of the average jamming distance between the working torque, nominal torque, and maximum torque of the three EPBs.

Therefore, the nominal torque of EPB in this case should not be less than 6,500 kNm.

The surface settlement trend is consistence with the daily advance rate of the three EPBs. Many existing literatures [29–32] show that the source of surface settlement is the ground loss induced by tunnelling, the ground distortion develops gradually from the vault of the tunnel to the surface, and the ground loss can be compensated by simultaneous and secondary grouting. For EPB3, the repeated disturbance and low advance rate resulted in greater ground loss, for EPB1, the repeated disturbance is nearly the same as EPB1, but the faster advance rate affords sufficient space for the implementation of simultaneous and secondary grouting and limits the development of the ground distortion. The surface settlement corresponding to EPB2 is the minimum one among the three EPBs. This is mainly because less disturbance induced less ground loss during the excavation and the fast excavation speed provided enough time and space for simultaneous and secondary grouting. From the perspective of the surface settlement, EPB2 was the best one among the three EPBs.

5. Conclusions

Based on the different tunnelling efficiencies of the three EPB shield machines in two adjacent shield intervals of Chengdu Metro Line 6's water-rich sandy and cobble stratum, reasons were analysed by comparing the operational parameters (advance rate, thrust force, torque, and the rotation rate of the cutter-head). The parameter matching of each EPB shield machine also was analyzed in general, resulting in the following conclusions:

(1) The selection of an EPB shield machine must be based on detailed geological investigations. Poor tunnelling performance, such as jamming, clogging, and wear of the cutter-head, is due mainly to the poor adaptation of cutter-head on the EPB shield machine to the construction stratum.

(2) For the cobble strata, crushing the small particle size cobble that has high contents of quartz and feldspar will result in excessive wear of the cutter disc and other tools. Therefore, most of the cobbles should be discharged directly such that, after the crushing operations, a small number of large boulders will be discharged.

(3) The opening rate is a macroscopic indicator, and in addition to the reasonable opening rate, the maximum opening size of the cutter-head plays a more important control role. The large opening size allows larger cobbles to be discharged directly from the working surface into the soil chamber. Under the condition of ensuring the stability of the stratum, the size of the cutter opening is increased as much as possible to reduce both the amount of cobbles that are crushed and the frequency of the crushing.

(4) To avoid frequent jams of the cutter-head, the nominal torque of EPB should not be less than 6,500 kNm.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

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