Construction Risks and Countermeasures of Super-large Diameter Mix-shield Machine with Accessible Cutting Wheel

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Abstract. The accessible cutting wheel and cutter wear monitoring system for the super-large diameter mix-shield dramatically improves the safety and timeliness of cutter exchange in high pressure under water-crossing conditions, which potentially extends the adaptability of supersize Tunnel Boring Machine and accordingly enhances the performance as well as the economy of the project. However, through tracing and systematically analyzing dozens of mechanized tunneling using mix-shields with accessible cutting wheel in domestic and global projects, significant advantages, and time-related limitations were revealed, and corresponding risk are noticed, including: 1) The opening rate is zero at the center of the accessible cutting wheel and the isolation of slider pipe for disc cutter increase the probability of clogging on the cutting wheel panel and muck accumulation inside slide pipes; 2) Compared to the conventional cutting wheel, an incremental thickness of the accessible cutting wheel reduces the mobility of the slurry circulation and enlarges the distance between the slurry outlet and the tunnel face, favoring slurry stagnation since the discharge path of muck is increased; 3) The relatively large cutter spacing and low flexibility of cutter distribution result in weakening the rock-breaking ability, especially in very hard rock formation; 4) The timeliness and accuracy of cutter wear detection are insufficient, which easily gives rise to the formation of “rock ridges” on the tunnel face or secondary damage to other cutters as the “Domino Effect” if the firstly-broken cutter is not found in time. Given the limitations mentioned above, targeted countermeasures are proposed to address those problems, such as optimizing the flushing design, adopting auxiliary tunneling techniques, and strengthening the refined management based on relative geological conditions.

1. Introduction
In the 21st century, in countries and cities with developed economies and urbanization, land resources on the ground are becoming more and more scarce, and environmental protection requirements are getting higher and higher. Avoiding large-scale demolition, renovation, and reducing the impact of construction and operation on surrounding residents is the demand for investment and construction period control and the need for high-quality urban development. At the same time, the requirements of urban transportation and underground space development under complex construction environments
(especially across rivers, lakes, sea waters, etc.) as well as the increasing maturation of shield tunneling technology in mixed geology, obviously emerged the advantages of shield tunneling, which also gradually developed toward large diameter, deep overburden, and long distance \textsuperscript{1, 2}. Up to December 2020, there are 62 projects (including projects under construction) using super-large diameter shield tunneling (14 m and above) in the world, of which 17 are overseas, and 45 are domestic, with broad application prospects. The large size of the excavation cross-section and the associated overburden thickness requirements have significantly increased the probability of encountering mixed face ground conditions, which results in project execution challenges such as, higher technical requirements for shield machines, higher construction accuracy, and frequent inspection or replacement of cutters (wear). If the conventional cutting wheel is adopted, large-scale ground reinforcement or frequent intervention under high pressure with high-risk potential are required. To improve the safety, timeliness, and efficiency of cutter inspection and exchange, the design of the accessible cutting wheel came into being. It became a crucial part of the Tunnel Boring Machine (TBM) type selection, which significantly promoted the supersize TBM tunneling technology and supported the smooth completion of super-large diameter shield tunneling projects worldwide (see Table 1).

Indeed, the design and function of the accessible cutting wheel have limitations for, particularly complex mixed geology. In addition to the design features of the accessible cutting wheel, this article summarizes and analyzes the primary construction risks by using a supersize mix-shield machine and proposes countermeasures as reference for similar projects in the industry through systematic tracing of typical domestic engineering projects during participation in consulting, supervision, decision-making, or other work.

| Table 1. Typical domestic projects (Include completed and under construction) |
|---|---|---|
| Project | Front Shield Diameter (m) | Quantity of TBMs | Project Status |
| Wuhan Sanyang Road Tunnel | 15.73 | 2 | Completed |
| Dalian Metro Line 5 Sea-Crossing Tunnel | 12.26 | 1 | Completed |
| Shiziyang Tunnel (new) | 13.61 | 1 | Completed |
| Shantou Bay Tunnel | 15.03 | 2 | Completed |
| Shenzhen Chunfeng Road Tunnel | 15.8 | 1 | Under Construction |
| Nanjing Heyan Road Tunnel | 15.03 | 2 | Under Construction |

2. Design characteristics of the accessible cutting wheel
The accessible cutting wheel is implemented by designing the arms as airtight caves to create independent atmospheric pressure areas, which remain accessible to the working area toward the excavated tunnel. The pressurized excavation chamber is thus isolated with the independent arms, which provides atmospheric conditions for personnel to inspect and exchange the cutting tools (see Figure 1, 2, 3).

The disc cutter is usually back-mounted in the slide pipe, and the rear of the slide pipe is equipped with a gate (see Figure 4). Thus, cutters can be inspected or exchanged under atmospheric conditions by pulling out the slide pipe, closing up the gate, replacing the cutter, pushing the slide pipe back, and closing the gate—the program of closing the gate and changing the cutter.

The diameter largely limits the configuration of the accessible cutting wheel; generally, only when a shield diameter reaches 12 m or above has space to equip accessible disc cutters. The diameter of shield machine equipped with accessible disc cutters in China exceeds 14 m except for the Dalian Metro Line 5 Sea-crossing Tunnel with a TBM diameter of 12.26 m and Shiziyang Tunnel (new) with a TBM diameter of 13.61 m.
3. Risks analysis of mix-shield machine with accessible cutting wheel
The design of the accessible cutting wheel with a disc cutter is different from the design of the conventional cutting wheel, as shown in Table 2, and these differences will increase the construction risks accordingly.

Table 2. The design difference between the conventional cutting wheel and accessible cutting

|                  | Conventional cutting wheel | Accessible cutting wheel |
|------------------|-----------------------------|--------------------------|
| Cutter layout    | Flexible cutter layout      | 1. Due to the large size of the slide pipe, the number of cutters is limited, and the cutter spacing is relative large; |
| Disc cutter      | front and back connected    | 2. In order to increase the number of cutters, usually adopts twin disc cutter. The disc cutter is installed in the slide pipe, and the rear of the pipe is closed No opening in the center area of about 5m diameter |
| Opening rate     | Can be designed according to requirements | Greater than 1.5 m |
| Cutting wheel    | Within 1m                    |                          |

3.1. Discharge stagnation risk
Discharge stagnation refers to the excavated mucks, which cannot be smoothly discharged due to particle characteristics (specific gravity, size, and shape), TBM discharge capability, and construction
control [3]. According to the design features of the accessible cutting wheel, three locations are most likely to cause discharge stagnation: 1) Muck accumulation in slide pipe (see Figure 5). The sliding pipe is unidirectionally open to the tunnel face; therefore, free space in the pipe is given to keep the rotation of the disc cutter, thus leaving the opportunity for muck accumulation in the pipe; and thus, leads to discharge stagnation. 2) Muck accumulation in excavation chamber (discharge stagnation). The thickness increment of the accessible cutting wheel increases the discharge path from the tunnel face to the slurry outlet. In addition, the bottom of the excavation chamber favors discharge stagnation for a large-diameter double-chamber mix-shield. Therefore, the accessible cutting wheel structure increases the severity of discharge stagnation. 3) Blockage of slurry pipelines (discharge stagnation), the cutters spacing of accessible cutting wheel is relatively large, and the rock chips are larger, which is more likely to cause discharge stagnation.

Discharge stagnation will increase the load of the shield tunneling, causing secondary wear of the cutter head, and aggravate the damage of the cutting wheel, particularly sided-wear of disc cutter due to muck accumulation in slide pipe's limited rotation. Regarding the discharge stagnation in the excavation chamber and pipeline, forward and inverse slurry circulation are usually taken by turn to deal with it, which easily leads to pressure fluctuation impacting the tunnel face and results in slurry burst on the ground, over-excavation, and collapse.

Figure 5. Muck accumulation in slide pipe and bolt break

Engineering practices have validated the above hypothesis; to be more specific, several domestic projects have experienced discharge stagnation to different degrees. While tunneling in the conglomerate, pebbles, and the anchorage area of Wuhan Sanyang Road Tunnel, gravels, pebbles, and steel obstacles accumulated at the bottom of the excavation chamber (see Figure 6). The discharge stagnation further caused problems such as blockage of the pipeline, poor circulation, and secondary wear of the cutters. Figures 7 and 8 show typical instances of discharge stagnation in the slurry chamber while tunneling in the granite boulder section of Shantou Bay Tunnel, breccia section of the Nanjing Heyan Road Tunnel, and the fault fracture zone of the Shenzhen Chunfeng Road Tunnel.

Figure 6. Pebbles accumulated at the bottom of slurry chamber (Wuhan Sanyang Road Tunnel)

Figure 7. Rock block hindered at the bottom of the slurry (Shantou Bay Tunnel)

Figure 8. Rock block hindered at the bottom of the slurry (Nanjing Heyan Road Tunnel)
3.2. Clogging

Clogging is of two forms, primary and secondary. The primary clogging is a semi-consolidated or consolidated block formed by the small particles and debris in the excavation chamber or on the cutter wheel, resulting from the high content of clay minerals in the ground (clay minerals are the major clogging constituents. It quickly form clogs in various strata if its mineral content is more than 25%). The secondary clogging is produced by a mixture of fresh slurry or mortar with mucks during discharge stagnation or low advance speed. Technically, clogging is a kind of discharge stagnation since the conditions that facilitate clogging are the same for discharge stagnation.

Several domestic projects have encountered serious clogging problems in the aforementioned formations due to the openings at the center of cutting wheels. This makes penetrating the mucks difficult, thus limiting discharge rate (see Figure 9). The thickness of the clogging in the center area of the accessible cutting wheel is up to 80 cm. For example, during a digging project in the clay and mudstone layer of Wuhan Sanyang Road Tunnel, a severe clogging of the cutter head panel, openings, cutting tools, and slide pipe (see Figure 10) caused excavation difficulty. Further, it reduced the operation speed to less than 5 mm/min and daily performance to less than a ring, only 1/5 of the conventional advance speed. Shenzhen Chunfeng Road Tunnel also experienced severe clogging, particularly at the center area of the cutting wheel and in slide pipe when tunneling in mylonite. If the situation develops further, clogging will be formed on the entire cutter wheel, include openings, to block the excavation entirely (see Figure 11).

![Clogging in the center area of the accessible cutting wheel](image)

**Figure 9.** The thickness of the clogging in the center area of the accessible cutting wheel is up to 80 cm of a certain project

(a) Clogging in the cutting wheel  (b) Clogging cover the hob  (c) Clogging in the cutter barrel  (d) Clogging in the openings of cutting wheel

**Figure 10.** Shield clogging problem of Wuhan Sanyang Road Tunnel project
3.3. Cutter problems

(1) Limited layout of cutter

The design of a mix-shield machine with an accessible cutting wheel and disc cutters significantly impacts the layout of cutters due to space constraints. At present, the minimum cutter spacing of face cutters being used in engineering reaches 90 mm, and rock ridge forms when the damaged cutters are not replaced in time (see Figure 12). Per engineering experience, if the strength of rock is ≥ 90 Mpa, the cutter spacing should be controlled between 60–90 mm [5, 6]. The strength of the slightly weathered slate of Shenzhen Chunfeng Road Tunnel is generally over 120 Mpa with a maximum value of 173.7 Mpa; the maximum compressive strength of the slightly weathered granite at the Shantou Suai Bay Tunnel reaches 216 Mpa, with very high cutter consumption during tunneling.

In order to increase the number of disc cutters as much as possible, a twin-edge disc cutter is usually arranged in one slide pipe (including monoblock and double-shaft twin-edge). However, based on the rationality of cutter arrangement, a double-edge disc cutter should not be used when the rock strength is ≥60 Mpa, especially when the rock mass is incomplete, and the formation surface is uneven (see Figure 13). It is impossible for the cutter rings to contact the rock in a coordinated manner. Even if a double-shaft twin-edge disc cutter is used, the effect is still $1 + 1 < 2$, compared with two single-edge cutters. Moreover, when the forces on two cutter rings are uneven, the cutter structure is affected by side pressure (see Figure 14), and the cutter shaft is more likely to be damaged. The damage of these two blades is not identical, and if one of the rings needs to be substituted, the entire slide pipe has to be replaced. (See Figure 15).

Figure 12. Rock ridge formed on tunnel face
Figure 13. Uneven limestone at tunnel face
Figure 14. The twin-edge disc cutter in limestone stratum is subject to lateral force; one side of the blade is clamped and the other side is loosened.

Figure 15. Damage of twin-edge disc cutter of Dalian cross sea tunnel TBM with accessible cutting wheel.

(2) Fitting problem of cutter head and tunnel face
During inspection of 6.0 m diameter TBM in metro construction, personnel can enter the excavation chamber to check all disc cutter damage thoroughly and intuitively decide which cutter(s) must be replaced. Meanwhile, a comprehensive check of the rock conditions at the tunnel face and manual chiseling to the rock ridge can guarantee the fitting between cutters and tunnel face after replacing the cutters. However, the general idea of substituting cutters on the accessible cutting wheel is to replace the found one. In a situation when all the cutters reach their wear limit, it is difficult to replace. Moreover, if the fit between the cutter's trajectory and the tunnel face is poor, removing the raised ridge on the excavation surface is even more difficult. The uneven wear of cutters will inevitably lead to the unevenness of the tunnel face, with the largest wear of disc cutter corresponding to the most severe rock bulge (rock ridge). Therefore, the damage suffered by the newly replaced cutter is the greatest. More specifically, this cutter contacts on the protruded part in the first place (see Figure 16), with the instant impact on cutter provided by thousands of tons thrust force coming from the TBM, the probability of cutter damage greatly increases. The accessible cutting wheel of Shiziyang Tunnel (new) revealed that No. 17/18 cutters are frequently broken during tunneling, proving the above judgment (see Figure 17). In addition, the project feedback shows that 30% cutters are replaced too early, resulting from the difficulty in fully grasping the cutters status.

Figure 16. The fitting of the cutter with the rock before and after the cutter exchange.

Figure 17. The No. 17/18 disc cutters of TBM of Shiziyang Tunnel are frequently broken.

(3) Cutter damage problem
The problem of cutter damage was found to be quite prominent when tracing several domestic projects. For example, among the 574 inspected disc cutters in the granite section of the Shenzhen Chunfeng Road Tunnel, 436 cutters were scrapped; among the 140 cutters checked in the cataclastic section, 119 cutters were scrapped, and cutters were changed 104 times in the 44th ring tunneling in slightly...
weathered slate. In addition to the previous analysis, the reasons are summarized: ① The upper soft and lower hard ground condition or uneven hard rock formation along the tunnel alignment has a strong impact on cutters and easily causes damage to the cutters. ② The restricted cutting spacing results in weak rock-breaking ability and increased the cutter wear accordingly. ③ Clogging and discharge stagnation on the cutting wheel panel or in slide pipes or at the bottom of the slurry chamber enlarges the secondary wear and damage to cutters.

As experienced from several projects, in addition to normal wear, there are some other damages as sided-wear, cracking and ring falling-off, fracture of the cutter or slide pipe fixing bolt, and retraction/deformation/wear of slide pipe (see Figure 18). Among them, the fracture of the cutter/slide pipe fixing bolt and the retraction/deformation/wear are unique problems of the accessible cutting wheel, which are frequently seen in projects. This pertains to the structural design, quality of the slide pipe, and the unevenness of the tunnel face. For instance, when the TBM is advancing in the granite section of Shantou Bay Tunnel, it happened 52 times to the cutters and slide pipes. Another example is in Wuhan Sanyang Road Tunnel, slide pipe wear and deformation occurred, resulting in 177 replacements of the slide pipes sets within 264 m for left line and 95 sets within 170 m for right line.

(a) Sided-wear  (b) Ring falling-off  (c) Fracture of bolt  (d) Wear of slide pipe

Figure 18. Damage mode of disc cutter

4. Risk control of the mix-shield machine with the accessible cutting wheel

4.1. Risks control for discharge stagnation and clogging as well as countermeasures
(1) Machinery of TBM: increase opening rate of the cutting wheel and optimize the arrangement of cutting tools while digging in soft ~ hard plastic ground layers, prone to clogging (shrink the center enclosed area as much as possible); strengthen the cutting ability, reduce grinding capability, and try to discharge the muck in blocks; improve flushing system at the center area of cutting wheel and inside slider pipes, and innovate the internal circulation flushing (see Figure 19).

Figure 19. The most advanced anti-retraction and flushing device in the world designed and produced by Herrenknecht

(2) Construction: Enhance slurry circulation capability, take flushing of clogging into consideration while designing the slurry circulation system, and recommend using innovative slurry for pressurized flushing; during standstill or ring building, maintain slurry circulation to prevent the accumulation of mucks (See Figures 20 and 21).
(3) Auxiliary technology: innovation and application of clogging breaking technology, such as dispersant (hydrogen peroxide); in airtight ground condition, adopt auxiliary air pressure operation [7] to reduce loads of shield machine.

4.2. Risk control of abnormal cutter wear and countermeasures

(1) Cutter selection: For tough rock formation, study the reduction of the cutter spacing for accessible cutting wheel; for rock strength <60 Mpa and uneven tunnel face, consider the disc cutters with teeth.

(2) Cutter optimization: optimizing design and processing, such as adopting integral cutter hub, pre-tightening bolt; enhancing protection to cutters and cutting wheel, such as wear-resistance and anti-retraction devices to cutters; improving the strength of the cutters against lateral force, especially monoblocks are fitted in the center of the accessible cutting wheel.

(3) Cutter management: 1) Master the wear degree of cutting wheel and cutters as comprehensively, accurately, and promptly as possible, and discover the rock ridge area and the “Patient Number Zero” in time, including flushing and monitoring of cutter damage by using “snake-like robot,” all-around cutter detection technologies for temperature, rotation and wear; analysis of cutter damage according to changes in advance speed, torque, and muck samples. 2) Evaluate the fitting effect of the cutter and the tunnel face and replace the cutter in a reasonable and timely manner. 3) Consider the compatibility of cutter exchange and construction organization to improve engineering efficiency.

5. Conclusion and prospect

The design and function of the accessible cutting wheel on supersize mix-shield guarantees the safety and timeliness of the cutter exchange and the health of the working crew. However, compared to the conventional cutting wheel design under the same conditions, it is more prone to cause problems such as clogging and discharge stagnation. Meanwhile, the rock-breaking ability of TBM is reduced due to the limited space of setting slide pipes and large cutter spacing. Therefore, in the future, studies and innovations should be made in optimizing the design of the cutting wheel and strengthening the cutters, such as separated sites on the cutting wheel for pressurized areas (center area) and the atmospheric regions (face and gauge); or independent pressurized (>1 MPa) flushing device in the center area with significant flow rate; or additional screw conveyor combined with the accessible cutting wheel.

Future application of super-large diameter mix-shield is broad. Supersize TBMs are expected to tunneling under the three major straits of China in the foreseeable future: Bohai Strait, Qiongzhou Strait, and the Taiwan Strait. Moreover, the proposed Bering Strait tunnel project is studying the feasibility of using Φ19.2 m shield machine to construct the tunnel; super long-distance tunnel with supersize shield machine will become the new challenge in the world tunneling history once it is confirmed.
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