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Analysis of Abnormal Use of Cement Paste in Perfusion during Tunnel Construction using TBM

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Abstract: During underground tunnel construction, rock burst causes substantial problems and impacts on the perfusion material use. This article explores the influences of rock burst on a construction project in a highly complex geological area in Tibet, including segment oscillation, injection port design, segments sealing, and slurry leakage, which contribute to the abnormal use of cement slurry during TBM tunneling. After comprehensively examined the reasons for the abnormal cement slurry filling during the TBM tunneling, we reach the conclusions that, in this tunnel, it is normal for the cement slurry volume to exceed its originally designed volume. The multiple factors affecting the cement slurry perfusion can be classified into three categories, including geological factors such as high ground stress, rock burst, and the complexity of the tectonic structure, human-made factors such as imperfect segment design and infusion hole design, and mechanical factors such as the reserved deformation and excavation adjustment due to rock burst. Abnormal perfusion does not result in any decreased quality in the backfill perfusion. Based on these conclusions, this paper also proposes recommendations to solve the abnormal use of the cement filling during the tunneling.

Keywords: rock burst, TBM double shield construction, perfusion, cement slurry, over-irrigation

1 Introduction

In recent decades, a large number of major construction projects have been or will soon be built in canyon areas in southwestern China (973 Project Office 2014). In these projects, many underground tunnels and constructions are conducted to a depth where meets high ground stress and complicated geological conditions. During large-scale excavation, deep-seated disasters such as rock bursts are almost inevitable, which often cause casualties, equipment loss, construction delay and other secondary risks. Tunnel Boring Machine (TBM) has been proven efficient in excavating rock in conventional way with the advantages of limiting disturbance to surrounding ground and producing a smooth tunnel wall (Fang et al 2013). However, during construction under high ground stress, TBM is facing new challenges. For example, due to the circle of the excavation channel and the outside diameter of the pipe are not always concentric, which potentially affects the TBM construction. In this case, filling materials such as pea gravel and cement slurry must be poured between the pipe segment and the rock wall during construction (Wang 2017). The filling materials combined with pipe segments forms a closed loop that together resists deformation and enhances barrier function (Wang et al 2015).

Using a double shield TBM heading reverse slope tunneling, a tunnel construction has been conducting from October 2015 to March 2018 in the Yarlung Zangbo River watershed in Tibet with an excavation diameter 9.13 m. Lining used "6+1" type quadrilateral precast concrete segments with a thickness of 35 cm. The lining diameter is 8.1 m. The double-shield TBM construction mainly utilizes the segment lining – after excavated, the tunnel is lined with ring-shaped segments immediately where the backfill between the segment and the surrounding rock is filled with grout to make the pea gravel grouting as a whole. However, during the implementation of the project, it was found that the perfusion volume of pea-gravel slurry was much greater than originally designed with a difference of about 60%. This has greatly aroused concerns of all parties involved in the project, which is not only about the pricing and the workload, more importantly, whether the abnormal perfusion volume would have potential impact on the project process design and its finish quality. Therefore, the research team went on site to investigate and analyze the reasons for the abnormal backfill volume during the TBM tunneling. Radar images and core sampling were taken to determine the quality of the injected water after rock bursts occurred.

2 Backfill Perfusion Process

Tunnel double shield TBM construction mainly uses pipe segments in lining, then fill the gap between the pipe and surrounding rock gravel to grout all materials together.

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Conventionally, backfill grouting process consists of following steps: firstly, injecting cement paste at the bottom of the arch within a range of 90° to support the newly installed segment, next filling pea gravel both sides and the top arch (within 270°). After that, pouring slurry on both sides and within 270° of the roof. Then, pouring grout and plugging holes. An initial quality inspection can be conducted at this stage before it is ready for filling irrigation. The last step is final quality inspection.

During this process, perfusion volume was automatically recorded by the TBM shield machine with a good level of accuracy. There is no possibility of artificial inflation or manipulation. The actual irrigation volumes are displayed in Table 1.

Table 1. Tunnel grouting irrigation in the in No. 1 Linzhi project

Driving stakes to 500 m meter	No. of tunnelling tubes	Originally designed cement slurry use / m³	Actual cement slurry use / m³	Difference / m³	Difference Rate / %
K8+820 - K9+320 m	1 - 278	747.82	1724.02	976.20	130.54%
K9+320 - K9+820 m	279 - 556	747.82	1606.37	858.55	114.81%
K9+820 - K10+320 m	557 - 833	747.82	1571.11	825.98	110.45%
K10+320 - K10+820 m	834 - 1111	747.82	1170.00	422.18	56.45%
K10+820 - K11+320 m	1112 - 1389	747.82	967.84	220.02	29.42%
K11+320 - K11+820 m	1390 - 1667	747.82	920.96	173.14	23.15%
K12+320 - K12+820 m	1945 - 2222	747.82	626.45	-118.68	-15.87%
Total		5977.18	9512.88	3535.7	59.15%

3 Causes of Abnormal Irrigation

3.1 Rock burst

This construction project is located within the collision area of Indian and Eurasian tectonic plates, where the intense tectonic movement resulting in a very high level of structural stress. The measured maximum principal stress is 27.2 MPa. During excavating, such a high stress frequently caused rock bursts, among which includes more than four serious jams in the TBM.

During excavation, the cracked and exfoliated rock constantly gave out crisp sounds and striking the TBM shield. Following strong rock bursts in surrounding rock, local collapse, tunnel rock, and passive hollowing occurs between the wall and the segment, resulting in increasing demands on the amount of perfusion. Figure 1 shows an example of such passive hollowing. Surrounding the cutter-head, a large amount of exfoliated rock was crushed and discharged, resulting in a huge cavity, whose diameter is up to a few meters. This cavity needs a high volume of pea gravel and grout to fill up.

3.2 Over excavation

Rock bursts may cause serious damages on the TBM. To prevent the TBM shield body from being deformed by surrounding rocks, the diameter of the excavation was purposely increased than its original design, resulting in an enlarged annular gap, and consequently an higher volume of perfusion. The actual amount of over-irrigation is corresponding with the extent of rock bursts. The over-irrigation is up to 20 times to its original design and is even higher under certain some circumstances. Overall, the over-excavation due to rock bursts accounts for more than 70% of increase in the total irrigation volume.

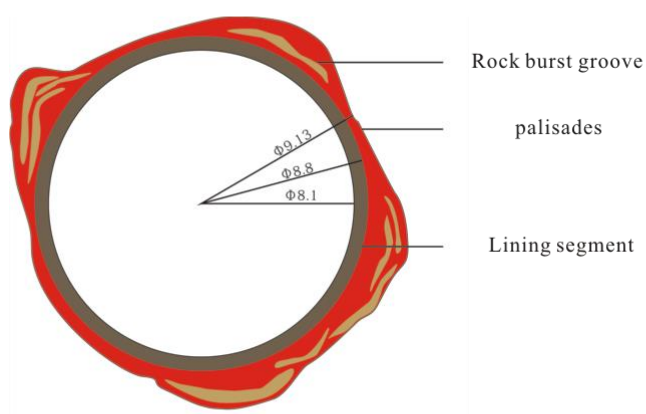

Figure 1. top: a cavity formed after rock burst; bottom: schematic diagram of cavity formed after rock burst

Aside from this, the scraping of the posterior segment of the cutter-head results in the blockage of the perfusion hole. By preventing the perfusion of pea gravel, the volume of cement slurry uses also increased.

3.2 Pipe axis swing

Because the excavation diameter is larger than the pipe diameter, the gravity and axial thrust of the TBM force the axial direction of the pipe irregularly oscillate along the tunnel, as shown in Figure 2. The skewing of the segments could result in a small angle toward the tunnel wall, which may partially block the perfusion orifice. A small angle may also lead to a narrow gap between the segment wall and the surrounding rock, which makes the perfusion of pea gravel difficulty, and then potentially form an empty area as shown in Figure 3 (red area). The empty area can only be filled with cement slurry, leading to a reduced gravel use and an increase of cement slurry use. Moreover, blockage of the perfusion hole will result in at least 1/12 of the rings failing to infuse the gravel (Figure 4), where leaves the option to fill it with cement slurry. This section can lead to over 20% cement slurry over-irrigation.

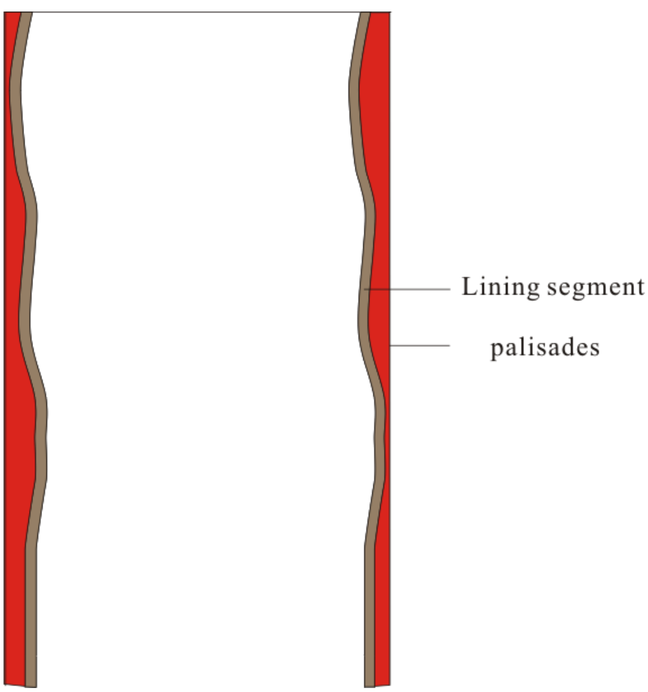

Figure 2. Pipe axis swings along the tunnel

3.3 Perfusion hole design

Pea gravel perfusion is mainly driven by gravity. The main area it reaches is below the perfusion hole. It is difficult to reach above the perfusion hole, as shown in Figure 5. The measured results show that there is often a blind spot above the perfusion hole, which requires cement slurry filling. This results in the pea gravel perfusion volume 5% less than the designed value, while the amount of cement slurry perfusion is 5% greater than its original design. This also indicates that in the project design, the location of the perfusion holes on

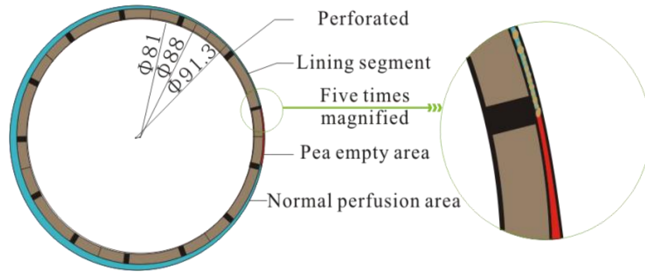

Figure 3. An empty area formed during pea gravel perfusion after the perfusion hole was blocked

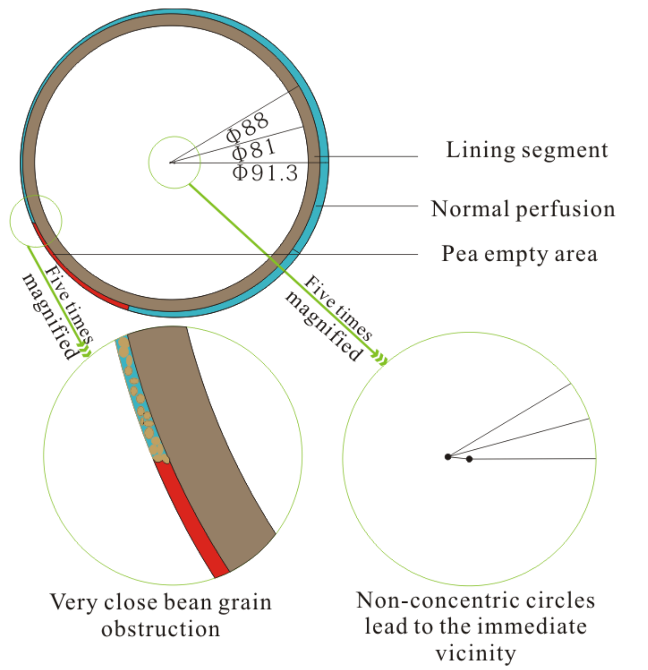

Figure 4. An empty area formed during pea gravel perfusion in the narrow gap between pipe and the surrounding wall due to pipe swing

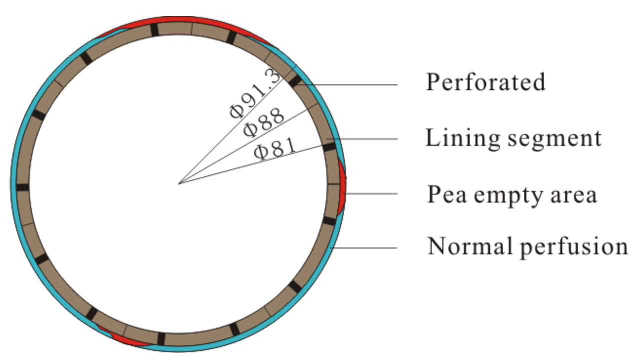

Figure 5. An empty area formed above the perfusion hole

the tube need to be optimized, or the cement slurry perfusion should be amended to be practical.

3.4 Leakage between segments

After tunnel excavation, the ground stress is gradually releasing. This process takes time. Monitoring data show that this process could take up to several months or even years till the residual stress reaches to a relatively low value (3 - 5 MPa or so), during which the tectonic stress could possibly cause the tube pieces misplaced, deformed, and even damaged.

Due to rock burst and great deformation, the axial cracks or misplaced pipe sections occur in many places in this tunnel, which makes the sealing fail and cement slurry leak (Figure 6). If the leakage is not dealt with in time, the loss of cement slurry could result in a large amount. Even though the slurry leakage in this project was controlled in a timely manner, the residual slurry from the overflow resulted in about 3% of super-irrigation.

Figure 6. Slurry leakage between segments

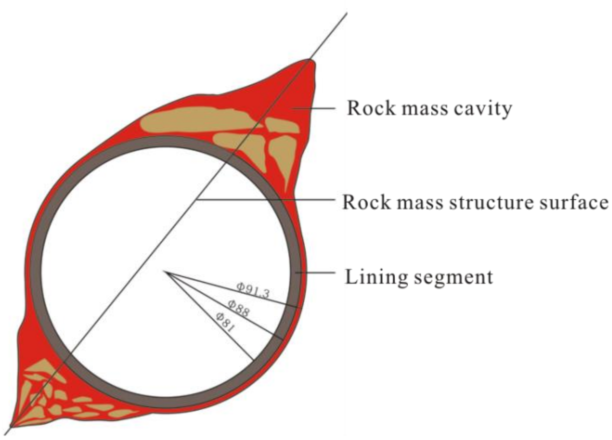

Figure 7. Cavities formed after rock cracks

3.5 Leakage followed structural cracks

The tunnel is constructed under complex geological conditions. In addition to the considerable underground depth, its tectonic stress is high, also there are several structural zones intersect within the tunnel. Such a tectonic structure produces too stress to the surrounding rock to be stable. At the same time, the fissure zone formed in this tectonic belt could bring about huge leakage of cement slurry, as shown in Figure 7. In the past, there was very limited data about the sudden and large amount of leakage, so in this project, the leakage of superficial cracks in the tunnel wall was overlooked. Generally, the over-irrigation volume followed structural crack leakage was relatively small, accounting for about 2%, which is within the controllable range. If this part of the over-irrigation volume is large, some measures, such as plugging, and/or controlling the super-irrigation in the lower range, can be taken.

4 Conclusions and Recommendations

For tunnel construction using TBM under rock burst conditions, there are multiple reasons for over-filling cement slurry in backfilling, including geological factors such as high ground stress, rock burst and complicated structural belt, technological factors such as reserved deformation and excavation in response to rock burst, as well as man-made factors such as optimization of the pipe slice design. Among of which, the reserved deformation due to the rock burst is the main factor to the over use of cement slurry. The post-test data showed that abnormal filling did not result in any decrease in backfill perfusion. Because the imputation is not related to any artificial error or manipulation, the perfusion volume statistics are concrete.

To avoid similar problems occurring in future projects, we recommend the following measures according to the above analysis:

(1) High-intensive rock burst caused by over-excavation is the main factor to the over-irrigation of cement slurry. The most effective prevention is to release ground pressure in advance to reduce the intensity of rock burst (Cai et al 2008, Chen et al 2011). Secondly, accurate calculation of the reserved deformation and reduced amount of residual deformation are also effective strategies to reduce the potential over-irrigation. Before perfusion, the tunnel should be reserved for a certain period of time, till the surrounding rock deformation stabilized, these unstable rocks spalled, and the stress released to a relatively stable status so that the influence of the residual stress becomes limited, to avoid the tube pieces being misplaced and rupturing, which would result in slurry leakage.

(2) A righting ring can be placed on the outer side of the pipe segment to not only reduce pipe swing, but also leave a space between the pipe wall and the rock wall to avoid the extremely closed corner and the blockage of the perfusion holes. Once a perforated hole is blocked, it should be cleaned before perfusion.

(3) Slurry leakage could damage slab sealing and cause structural cracks. Taking multiple steps of perfusion and adding quick-setting agent and fine aggregate at the time of the first perfusion without pressure perfusion could help dealing with such situations. After the initial filling of slurry has produced certain strength, perfusion can be completed gradually. Anyhow, a small amount of running slurry leakage is almost inevitable. To avoid disputes between project collaborators, a 3-5% perfusion loss should be allowed in the project design.

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