Study of Grease Escape of Tail Skin Sealing System with Earth Pressure Balance Shield Machine

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Abstract. In this paper, the grease escape test of shield tail sealing system is carried out, and the variation law of grease escape pressure and escape rate is studied with shield tail clearance, grease cone penetration and grease pressure as variables. The results show: (1) The smaller the shield tail gap, the greater the grease escape pressure, and the grease escape pressure has a non-linear relationship with the shield tail gap. The higher the grease cone penetration, the lower the grease escape pressure under the same shield tail gap. (2) When the grease pressure is greater than the escape pressure, the escape rate of sealing grease increases with the increase of grease pressure under the same shield tail clearance. (3) In the range where the grease pressure is greater than the grease escape pressure and less than the grease resistance pressure, the grease escape rate is linearly related to the grease pressure under different working conditions. (4) There are two escape modes of grease: non-uniform escape and uniform escape.

1. Introduction

On February 7, 2018, the shield tail seal leakage of the right line tunnel between huyong station and lvdaohu station of Foshan Rail Transit Line 2 project caused the tunnel buried and ground collapse, resulting in 12 deaths and 8 injuries, with a direct economic loss of more than 50 million yuan. Shield engineering accidents caused by shield tail leakage are not uncommon, such as Tianjin Metro Line 2, section TA15 of Nanjing Metro[1], Wuhan Metro Line 4. Therefore, it is very important to ensure the sealing effect of shield tail.

Shield tail sealing system is to set 3-4 wire brushes (called shield tail brush) at shield tail, and form 2-3 sealing grease cavities between shield tail brushes. By injecting grease with certain pressure into grease cavity, the sealing ability of external slurry, mud sand and groundwater is formed, as shown in Figure 1.
According to the working principle of shield tail sealing system, the parameters of sealing grease are one of the important factors affecting the sealing effect of shield tail. Wang[2] studied the effect of temperature on the grease of shield tail, and determined that the optimum temperature for using the grease was 5–35 °C. Gu[3] proved that the shield tail sealing system can meet the sealing requirement of water pressure resistance of 0.75 MPa under the condition of qualified welding quality between tail brush and inner side of shield shell. Yan[4] studied the test methods for water resistance, sealing property, volatility and pumping property of shield tail grease. Gao[5] put forward the important indexes for evaluating the water resistance of shield tail grease: the sealing method of grease, dangerous pore size and initial leakage time. When the pore size of sealing boundary reaches 1mm, the grease has the boundary condition of stable leakage, and it is easy to produce a large amount of grease leakage under pressure. Li[6] analyzed the effects of temperature and thickener on grease properties. At present, the research on grease mostly focuses on the characteristics of grease itself and water resistance, the shield machine parameter control in the construction process, such as tail clearance and grease injection pressure, also has an impact on the shield tail sealing effect. In this paper, through the shield tail sealing test device, with the shield tail clearance, grease cone penetration and grease pressure as variables, the influence of shield tail clearance on grease escape pressure and its escape rate is analysed.

2. Test equipment and scheme

2.1. Test equipment

Based on the application of shield tail brush sealing system in practical engineering, a grease escape test device for tail brush sealing system was designed, which can simulate the real state of tail brush sealing system. The schematic diagram of the test device is shown in Figure 2. The device consists of sealing grease injection system and tail brush sealing system, which can simulate the real environment of tail brush sealing system in practical engineering.

Figure 2. Grease escape test device

The sealing grease injection system is composed of water pump, water storage tank, grease storage device, water injection pipe and grease injection pipe. Through this system, grease can be injected into the grease cavity of tail brush sealing system, and the shield tail grease cavity can be filled with grease...
to control the grease pressure. The tail brush sealing system is composed of upper cover, bottom plate, side plate, two tail brushes, support, etc., which simulates the actual shield tail sealing system.

2.2. Test plan
Grease escape pressure refers to the grease pressure value when the sealing grease starts to escape out of the grease cavity.

In the test, the grease pressure was applied step by step, the initial pressure was 0.1 MPa, each step was 0.1 MPa, there were 12 stages, and the end pressure was 1.2 MPa. In the experiment, the escape pressure and escape rate of grease were measured under the conditions of 236.6, 286.4 and 342.3 cone penetration(0.1 mm) under the shield tail clearance of 55 mm, 75 mm and 95 mm respectively.

The grease escape test process is as follows.
(1) Fix the shield tail brush on the bottom plate, and manually coat the sealing grease on the wire brush.
(2) Stick sealing strip on side panel and install side panel.
(3) The sealing grease is loaded into the grease cavity, and the upper cover is installed to form a closed grease cavity.
(4) The sealing grease is injected into the grease cavity through the grease injection system to fill the remaining space.
(5) Adjust the different grease injection pressure, observe the grease escape at both ends of the sealing system, measure the escape pressure and rate, and analyze the escape mode.
(6) Replace different kinds of grease and repeat the test.

3. Result analysis

3.1. Grease escape pressure
When the penetration(0.1 mm) of grease is 236.6, 286.4 and 342.3, the grease escape pressure curves under different shield tail clearance are shown in Figure 3. It can be seen from the curve that when the grease cone penetration is small, the grease escape pressure decreases with the increase of shield tail clearance, but the relationship between them is nonlinear. When the penetration of grease reaches 342.4, the escape pressure of grease is basically the same under different shield tail clearance.

![Figure 3. Grease escape pressure under different cone penetration and tail clearance](image)

In addition, when the grease penetration is small and the shield tail gap changes between 55 mm and 95 mm, the grease escape pressure changes by more than 50%. In the process of shield tunneling, the sealing grease is injected into the grease cavity by quantitative, which may cause the local grease pressure to be too high or too low due to the uneven distribution of shield tail clearance, resulting in the decline of sealing performance of tail sealing system.

With the increase of cone penetration, the escape pressure of grease under different shield tail clearance decreases. Compared with the grease with cone penetration of 236.6, the grease escape pressure with cone penetration of 286.4 and 342.3 decreased from 0.4 MPa to 0.1 MPa and 0.2 MPa under 55 mm shield tail clearance. It can be seen that the grease cone penetration has a significant effect on the grease escape pressure.

3.2. Grease escape rate
When the sealing grease is injected into the sealing system, the sealing grease in the grease chamber will be compressed under the pressure, and the tail brush will also deform under the grease pressure, which leads to the similar phenomenon of grease escaping when the grease pressure is just applied. At the stage of sealing grease compression and tail brush deformation, the sealing grease injection rate is not constant and has a downward trend. Finally, the grease injection rate decreases to 0. When the sealing grease injection pressure is greater than the grease escape pressure, the sealing grease injection rate will gradually stabilize, and the sealing grease injection rate is the grease escape rate. Because the grease pressure is indirectly controlled by the water pressure of the grease storage device in the test, water may break through the grease layer and enter the grease cavity in the process of pressurization. The water pressure when the breakdown occurs is called the grease water resistance pressure. Taking the water resistance pressure or 1.2 MPa of grease pressure as the end point, the escape rate of grease with different cone penetration under different shield tail clearance is shown in Figure 4.

![Figure 4. Grease escape rate under different tail clearance and grease pressure](image)

It can be seen from the figure that when the grease pressure is greater than the grease escape pressure, the escape rate of sealing grease increases with the increase of grease pressure under the same cone penetration. Under the same shield tail clearance, the greater the penetration, the faster the escape rate. When the grease pressure is greater than 0.3 MPa, the escape speed of grease increases with the increase of grease pressure. When the grease pressure is greater than 0.3 MPa, the relationship between grease escape rate and grease pressure is fitted linearly. The fitting equation is $y=ax+b$. The results are shown in Table 1.

| Shield tail clearance(mm) | Cone penetration (0.1 mm) | a    | b    | R²   |
|--------------------------|--------------------------|------|------|------|
| 55                       | 236.6                    | 84.190 | -28.147 | 0.987 |
|                          | 286.4                    | 141.587 | -44.192 | 0.988 |
|                          | 342.4                    | 170.419 | 29.268  | 0.981 |
| 75                       | 236.6                    | 103.930 | -33.906 | 0.982 |
|                          | 286.4                    | 153.845 | -47.921 | 0.942 |
|                          | 342.4                    | 186.570 | -25.626 | 0.992 |
| 95                       | 236.6                    | 115.168 | -32.972 | 0.981 |
|                          | 286.4                    | 142.952 | -26.030 | 0.931 |
|                          | 342.4                    | —      | —      | —     |

It can be seen from the table that the variances ($R^2$) of the fitting equations are greater than 0.9, indicating that the fitting effect is good. When the grease pressure is greater than the grease escape pressure and less than the water resistance pressure, the grease escape rate is linearly related to the grease pressure under different working conditions. Under the same cone penetration, the larger the shield tail gap is, the larger the a value is, indicating that the oil escape rate increases faster with the increase of oil pressure. Under the same shield tail clearance, the greater the penetration of grease, the greater the a value, indicating that the grease escape rate increases faster with the increase of pressure.

4. Grease escape mode
By observing the phenomenon of grease escape during the test, it can be found that under different working conditions, the escape passage of sealing grease will form in the grease cavity (Figure 5).
According to the appearance of grease escape, it can be divided into two escape modes: non-uniform escape and uniform escape.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Diagram of escape channel in grease chamber}
\end{figure}

1. When the penetration of grease is 342.4, the sealing grease only escapes from a small part of the contact area between the overlap of tail brushes and the upper cover, and does not spread to both sides, which is called non-uniform escape mode (Figure 6).

2. When the penetration of grease cone is 236.6, the sealing grease first escapes from the area between the two tail brushes. During the escape process, the sealing grease expands to other contact areas between the shield tail brush and the upper cover. Finally, the sealing grease escapes from the whole contact surface between the shield tail brush and the upper cover, which is called uniform escape mode (Figure 7).

3. When the penetration of grease is 286.4, the escape mode of sealing grease is non-uniform under the condition of small shield tail clearance (55 mm) and high grease pressure (>0.6 MPa). And under other working conditions the escape mode is uniform.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Grease escape mode}
\end{figure}

\section{5. Conclusion}

1. The grease escape pressure is affected by shield tail clearance and grease cone penetration: the smaller the grease cone penetration is, the greater the grease escape pressure is. The smaller the shield tail gap is, the greater the grease escape pressure is. There is a nonlinear relationship between shield tail clearance and grease escape pressure.

2. There is a good linear relationship between grease escape rate and grease pressure. The higher the grease pressure is, the faster the grease escape rate is. When the cone penetration and shield tail clearance of sealing grease are determined, the grease escape rate can be inferred from the grease pressure.
(3) The grease escape mode can be divided into non-uniform mode and uniform mode. When the grease cone penetration is small, it is non-uniform mode, and when the grease cone penetration is large, it is uniform mode.
In this paper, by studying the influence of shield tail clearance, grease cone penetration and grease pressure on grease escape, some useful conclusions are obtained, such as setting appropriate grease injection pressure according to shield tail clearance. However, the sealing effect of the shield tail is also related to the performance of the tail brush. The relationship between the performance of the shield tail brush and the sealing effect can be further studied in the future.

6. References
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