Study on Penetration Damage Caused by Leakage of Earth Pressure Balance Shield Machine Tail Skin in Water-rich Silty Fine Sand Stratum

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Abstract In order to study the principle of stratum seepage damage caused by shield tail leakage during the EPB shield tunneling in water-rich silty fine sand stratum, a targeted-designed device is used. The results of this research are as follows: (1) The soil loss after leakage could be divided into three stages: initial, rapid growth, and destruction. Besides, the proportions of water leakage and sand leakage in these stages are significantly different; (2) The process of stratum seepage damage caused by tail skin leakage is divided into two stages: the first stage is the formation of subsurface cavities, and the second stage is the instability and destruction of subsurface cavities; (3) When the leakage point is under the tunnel, two flow areas were formed toward the leakage point. When the leakage point is above the tunnel, one flow area is formed at the crown area of the tunnel. Based on the test results, in the actual project, the seepage damage stage and the development of subsurface cavities can be judged based on the amount of water and soil leakage to provide a certain basis for construction risk control and emergency disposal.

1. Introduction
Leakage problems in segments, tail skin, and articulation joints are common during shield construction; however, they are often overlooked. Particularly in the water-rich silty fine sand stratum, the particles are relatively loose, resulting in fast loss of soil and water during leakage, which can cause ground collapse, segment structure damage, and the tunnel can submerge by sediment. Such types of accidents mostly happened in water-rich silty fine sand ground conditions. For example, Tianjin, Nanchang, Wuhan, Nanjing, Foshan, and other cities in China can result in numerous casualties and economic losses. Studies about the influence of shield tunneling under water-rich fine sand conditions primarily focus on ground deformation caused by excavation disturbance. For example, Lv Xilin¹¹ studied the ground subsidence deformation characteristics of water-rich fine sand stratum induced by stratum loss through elastic-plastic finite element numerical simulation and further analyzed the influence of soil parameters change and groundwater seepage. In terms of tail skin leakage, the research mainly focuses
on the treatment method of shield tail seal system failure and the performance of the shield tail seal system itself. For example, Chen Chi[2] studied the causes of tail leakage and measures to prevent leakage from the aspects of selection and injection of tail skin sealing grease and synchronous grouting, precast and installation of segments, shield mechanism sealing, and tunnelling. Wei Linchun[3] designed a tail skin brush loading simulation test device that can simulate different tail skin clearance and then carried out experimental research on the working state of tail skin brush under those different tail skin clearance. In the aspect of stratum seepage damage caused by shield tunnelling, the research mainly focuses on the seepage damage of the excavation face, lack of study on the influence of shield tail leakage on stratum. For example, Zhu Wei[4] showed that in EPB shield construction, even if the stratum stability is good enough to meet the requirements of unfilled chamber excavation, local seepage damage and even excavation face collapse will occur.

There are few reports regarding the influence of tail skin leakage on sand stratum; however, the research on the influence of structure leakage on stratum in other underground engineering fields can be used for reference. Cao Hong[5, 6] used a one-dimensional seepage test model to study the development process of vertical seepage deformation of uniform sand using foundation pit engineering. Tang Aiping and Li Liping[7, 8] studied the mechanism of water inrush and sand inrush by simulating few primary factors related to a specific mine with self-designed test equipment. Liang Yan[9] and others simulated the process of water inrush and sand inrush under different initial water pressures and summarized the relationship between water and sand inrush, including their main influencing factors.

Liu Chengyu[10] designed a set of visual test devices for water and sand gushing, which can change the diameter of round gushing port, and studied the influence of thickness span ratio, fine particle content, and other factors on water gushing, sand gushing, and induced settlement.

The working conditions studied above are different from that of tail skin leakage. Inspired by the previous experiments, a visual device for the penetration damage test of tail skin brush was designed to study the entire process of penetration damage after tail skin leakage in water-rich silty fine sand stratum for understanding the law of soil and groundwater losses around the tunnel and shield machine, aiming at the safety of construction personnel onsite.

2. Test materials, devices, and methods

2.1. Test materials

The sand sample used in the test is 60 – 120 mesh river sand, as shown in Figure 1. The main laboratory test and in-situ test indexes of sand are shown in Table 1. The grading curve is shown in Figure 2. According to the “soil classification standard” (GBJ145-90), the test material is fine sand, the effective grain size is \( D_{10} = 0.03 \) mm, the constrained grain size is \( D_{80} = 0.18 \) mm, the coefficient of uniformity is \( C_u = 6 \), and the coefficient of curvature is \( C_c = 3.13 \). It belongs to poorly graded sand, the sand particle size is relatively uniform, and the particle size is concentrated in the range of 0.1~0.25 mm. For poor grading of sand, when the tail skin brush leaks due to excessive wear or other reasons, the coarse particles that play the role of skeleton in the seepage channel either do not exist or have a very low content. Compared with well-graded sand, the fine particles are easier to remove by water flow, making it easier to form a penetrated seepage channel, inducing the disaster of water and sand leakage.
2.2. Test devices
The test device mainly consists of three parts: test model, water supply, and data acquisition device. The test model is made of 10 mm thick acrylic glass, which is transparent, and the internal soil losing process can be observed, as shown in Figure 3. The test model is divided into two parts: a soil tank in the middle to simulate the penetration damage and a water tank on both sides to simulate the groundwater recharge. There is a permeable plate between the soil tank and the water tank, which only allows water to pass through and has good permeability, ensuring that the water level in the water tank is consistent with that in the soil. The soil tank was used to hold the prepared sand samples in the test. A circular hole with a diameter of 100 mm is made at the center of the front of the soil tank to install the tube. There is a water inlet and several overflow holes with different heights on the outer wall of each water tank.

![Structure of test device](image)

Figure 3. Tail skin brush penetration damage test device.

The tunnel at the rear shield is simulated by a 100 mm diameter acrylic glass tube with a length of 300 mm, extending 50 mm to facilitate collecting water and sand during the test, as shown in Figure 3. In order to better observe the formation flow damage mode, a 16 mm circular drain hole is made above the front side of the tube, and the position of the drain hole can be adjusted by rotating the tube.

The water supply is composed of a water tank and a water hose with a diameter of 24 mm. During the test, the water is supplied through the water inlet holes at the bottom of water tanks and controls the constant water level condition by discharging water through the overflow hole. Because the water level on both sides remains unchanged throughout the test, the boundary on the left and right sides of
the soil tank can be regarded as the horizontal stable infiltration boundary, whereas the front and rear sides of the soil tank are glass plates, which are impermeable boundaries. The data acquisition device consists of two parts: water leakage and sand leakage measurement device and soil deformation shooting device. A group of measuring cups with the same volume is used in the water and sand leakage measurement device. The total mass of water and soil loss in each period can be obtained by moving the measuring cups at a certain time interval. After the sand water mixture in the measuring cup is sealed for 24 hours, the total mass and volume of the fine sand and water are measured after stratification. The density of sand and water can be used to calculate the respective mass and volume of sand and water. The soil deformation camera and tripod were used to record the soil loss, deformation, and ground settlement along the depth direction during the entire test.

2.3. Test program

Seven groups of water and sand leakage tests were performed to study the entire penetration damage of soil around the rear shield in case of tail skin brush leakage. Table 2 presents the details.

| No. | Dry density (g·cm$^{-3}$) | Buried depth (cm) | Water level (cm) | Leakage position |
|-----|----------------|-----------------|-----------------|-----------------|
| 1   | 1.5            | 20              | 45              | under           |
| 2   | 1.5            | 20              | 45              | above           |

2.4. Test procedure

Under constant water level, the soil particles flow into the tube with water along the leakage point under seepage. By observing the evolution law of stratum flow damage around the rear shield from the front side of the device, the main test procedure is as follows:

1. Install the tube, tighten the drain hole with a bolt to ensure good sealing and prevent the loss of sand before the test.
2. Calculate the required filling amount according to the specified dry density of the soil, weigh and configure the soil samples, load and compact the soil samples in layers, and lay a thin layer of red sand every 5 cm to facilitate the observation of soil deformation. After loading, add distilled water to the water tanks on both sides and place it for 24 hours to fully saturated the soil sample.
3. Connect the water inlet hole and the water tank, pull out the bolt rapidly in a vertical direction, and receive the water and sand with a measuring cup. During the test, the water head is kept unchanged, the process of water and soil loss is photographed, collected, and measured. Simultaneously, the deformation of soil is obtained according to the scale on the plexiglass panel.
4. At the end of each test, clean the device, dry the sand sample and repeat the above operation for the next test.

3. Test results analysis

3.1. The variation law of sand leakage and water leakage

Under each working condition, from the beginning of water leakage and sand leakage to the end of the test, the variation law of the accumulative mass of water leakage and sand leakage is similar. This paper selects the test results of working condition 1 for analysis, as shown in Figure 4. The volume sand content is defined as the percentage of sand volume in the total volume of sand and water mixture whereas the change of volume sand content with time is recorded.
The following rules can be found based on the above results:
(1) The changing curve for the mass of soil and water loss with time can be roughly divided into three stages: initial stage, rapid growth stage, and damage stage. In the initial stage (OA section), the amount of sand and water leakage increase slowly, almost linearly, with time. In the middle stage (AB section), with the development of water and sand leakage, the slope of the curve increases continuously. In the damage stage (BC section), a penetrated leakage channel is formed with the collapse of soil on both sides of the soil tank. A large amount of groundwater flows into the tube along the leakage channel, accelerating the speed of soil and water loss. The water leakage per unit time increases sharply. The changing trend of water leakage, sand leakage, the total mass of soil, and water loss with time is consistent.
(2) At the initial stage, as the penetration damage just occurred, only the fine particles in the coarse sand skeleton migrated under the action of water flow, so the total mass of soil and water loss increased slowly, with little difference observed between the amount of water leakage and sand leakage. With the gradual development of water and sand leakage, the speed of water and soil loss increases significantly after entering the rapid growth and damage stages. The main reason is that with the gradual loss of fine particles in fine sand, the pores between particles become larger, and the hydraulic channel gradually expands so that the seepage speed is accelerated and the development of water leakage is intensified, resulting in more particles moving to the leakage point under the seepage effect. Therefore, water leakage and sand leakage are coupling deterioration processes when the seepage starting condition is satisfied.
(3) The proportion of water leakage and sand leakage is different in each stage. In the initial stage (0–300 s), water leakage was the main factor, and with the increase of time, fine particles began to lose gradually, and the volume sand content increased rapidly. In the rapid growth stage (300–1320 s), the volume sand content remained stable, about 60%–80%, and the ratio of water leakage to sand leakage remained constant. After entering the damage stage (1320–1500 s), the volume sand content decreases rapidly from 80% to about 40%, and a large amount of water gushes into the tube. From the proportion of water leakage and sand leakage, the increase of water and soil loss rate in the rapid growth stage is primarily caused by the rapid increase of sand leakage. However, in the damage stage, massive loss of fine sand particles above the tube and the collapse of sand on both sides of the soil tank formed a penetrated leakage channel, resulting in a substantial increase in water leakage per unit time and a significant increase in the proportion of water leakage.

3.2. Soil collapse mode
The tail skin leakage will cause flow damage of the surrounding stratum, and the movement mode of soil is shown in Figure 5. The soil flows through the leakage channel in the flow area of the soil during the process of water leakage and soil leakage. The stagnation area is located outside the leakage channel, and the flow area boundary is just between them. The sand ellipse is the area where water and sand leakage occurred. The soil in a stagnant area does not participate in movement at the initial stage.
When the soil flows out from the top of the soil layer, the soil in the stagnant area gradually flows out, and the boundary of the flow area also expands to both sides.

Figure 5. Soil deformation mode.

(1) The leakage point remains under the tube.

Considering working condition 1, the evolution law of fine sand damage mode with time when leakage point is located under the tube. Figures 6 and 7 present the longitudinal damage mode of soil layer and surface damage mode under this working condition.

According to test results analysis, the following rules are obtained:
① Figure 6 shows that the fine sand closest to the leakage point will first flow to the tube when the leakage point is under the tube. At this time, the tube is directly above the leakage point, which is not in direct contact with the silty fine sand layer. Hence, the silty fine sand above cannot directly supplement and migrate downward; no leakage channel can form directly above the leakage point. Under the effect of seepage, the soil particles migrate along both sides of the tube to the leakage point.
(t = 150 s). With the continuous loss of soil in the flow area, the sand layer above the tube begins to appear voids and continues to extend to the surface. Macroscopically, two sand elliptical flow areas are formed at the symmetrical position on both sides of the leakage point (about 100 mm range).

(2) After the flow area extends to the surface, with the gradual outflow of the soil in the middle area of the surface, the fine sand in the stagnant area on both sides of the surface sand layer is gradually reduced by the horizontal soil interaction until the underground cavity is unstable. The horizontal seepage force causes the soil on both sides of the surface to gradually flow into the flow channel and flow out, leading to the collapse of the surface soil layer (t = 450 s). Following that, as more soil and water are lost, the soil on both sides above the flow area is no longer lost to the flow area; the cavity above the flow area is no longer filled with soil; the cavity area continued to expand downward; the angle between the boundary of the flow area on both sides and the horizontal plane increase continuously to extend toward the leakage points. The boundary shape of the upper flow region is in “W” state (t = 600 s). Finally, when the water is discharged after the test, the final damage mode of soil is V-shape.

(3) When the leakage point is under the tube, the surface does not change at the first period, shown in Figure 7. With the development of water leakage and sand leakage, the flow area on both sides of the tube extends to the surface, which shows that there are two symmetrical circular holes on the surface. Following that, the soil in the stagnant area on the top of the soil layer gradually began to flow into the flow channel, and radially the two holes expanded until they joined to form a nearly oval hole. Since then, the underground hole has been destroyed, and the surface sand layer has collapsed on a large scale.

(2) The leakage point is above the tube
The development of soil damage mode is described if the leakage point is above the tube by considering working condition 2. Figures 8 and 9 present the longitudinal damage mode of soil layer and surface damage mode under this working condition.

Figure 8. Soil longitudinal damage mode when leakage point is above the tube.
Figure 9. The surface damage mode when leakage points above the tube.

The test results analysis is as follows:
① Figure 8 presents the leakage point above the tube; the silty fine sand closest to the leakage point will flow to the tube first. However, due to direct contact between the upper part of the leakage point and the fine sand layer, the soil particles above the leakage point can directly migrate to the leakage point, forming a water leakage and sand leakage channel along the vertical direction of the leakage point \((t = 120 \text{ s})\). With the continuous loss of soil in the flow area, the sand layer above the tube begins to appear cavity and continues to extend to the surface. Only one flow area \((t = 150 \text{ s})\) is formed above the leakage point on the macro level.

② When the flow area reaches the surface, the pressure on the fine sand in the stagnation area is gradually reduced with the gradual outflow of soil. Due to the interaction force between the soil in the horizontal direction, they flow into the flow channel until the underground cavity is unstable, resulting in surface collapse near the flow area \((t = 300 \text{ s})\). After that, the boundary of flow area on both sides extends along the leakage point to both ends, and the angle between the two sides and the horizontal plane decreases. The upper flow area has a V-shaped boundary \((t = 450 \text{ s} \text{ and } t = 600 \text{ s})\).

The change law of the angle between the boundary and the horizontal plane of the flow area is opposite, mainly because when the leakage point is above, only one flow area is formed with a small flow range and fine sand. When the fine sand in the flow area is completely lost, the boundary of the flow area cannot extend below the leakage point and can only extend to both sides, resulting in a decrease in the angle between the boundary and horizontal plane of the flow area. When the leakage point is below, two flow areas are formed, and the flow area is large, with more fine sand particles are formed. The boundary of the flow area mainly extends downward, increasing the angle between the boundary and the horizontal plane of the flow region.

③ Figure 9 depicts the continuous loss of soil that extends the flow area to the surface with only one circular hole just above the leakage point. After that, the soil from the stagnant area began to drain to the flow area, which showed that the circular hole was radioactive expansion. Finally, the underground hole is destroyed, the surface sand collapses on a large scale.

To sum up, the whole process of ground penetration damage caused by tail skin leakage can be divided into two stages: the first stage refers to the formation of subsurface cavity, and the second stage shows the instability of that. The soil around the rear shield is eroded by groundwater, which is the main reason for the formation of cavity in the first stage.

4. Conclusion

(1) When the tail skin leaks, the leakage mass of soil and water can be roughly divided into initial, rapid, and damage stages. In the initial stage, sand and water leakages increase slowly, almost linearly, with time. The speed of water and sand leakage is obviously accelerated in the rapid growth stage. During the damage stage, a penetrated seepage channel was formed due to the collapse of the soil on both sides of the soil tank, a large amount of groundwater rushed into the tube along the seepage channel, and the water leakage increased sharply in unit time.

(2) Following tail skin leakage, the proportion of water leakage and sand leakage varies in each stage. In the initial stage, water leakage is the primary factor; as time passes, fine particles gradually lose, and the volume of sand content increases rapidly. In the rapid growth stage, the ratio of water leakage to sand leakage is constant, and the volume sand content is about 60%~80%. In the damage stage, the volume sand content decreases rapidly from 80% to about 40%, and a large amount of water gushes into the tube.

(3) After the leakage, the ground penetration damage can be divided into two stages. The first stage is the formation of cavities, and the second stage is the instability of cavities. The soil on both sides of the surface begins to flow into the flow channel gradually, causing the complete collapse of surface soil.

(4) When the leakage point is under the tube, cavities are first formed at the symmetrical positions (about 1D) on both sides of the stratum above the tube, and then extend to the surface gradually, where two symmetrical circular holes appear at the corresponding positions on the surface. With the
development of seepage, both cavities expand gradually till loss stability, and a W-tape flow area is formed. The water is discharged after the test, and the final damage mode of soil is V-type. 

(5) When the leakage point is above the tube, there is a cavity (i.e., sand ellipse) in the stratum directly above the tube, and the corresponding surface has only one hole. When the cavity becomes unstable, a V-shaped flow boundary is formed. Simultaneously, compared with the leakage under the tube, the influence range of the stratum collapse is smaller, as is the total mass of soil and water loss. 

This paper studies the law of ground penetration damage and the influence of leakage position on the damage mode after the tail skin leakage occurs in the water-rich silty fine sand stratum. Some useful conclusions can be considered as references for engineering risk control. For example, the present results can judge the stage of stratum failure and locate cavities based on the water and soil quality of the leakage in the project. Further, this result will help take corresponding measures like grouting or set up a reasonable enclosure treatment area after an accident based on the influence range of sand layer collapse and prevent the harm of secondary collapse to surrounding pedestrians and vehicles. However, the sand penetration damage is also related to the water level, tunnel buried depth, and sand layer characteristics; the above factors will be considered in future research.

5. References
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