Formation process of paste HDN slurry in gravel stratum

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Abstract: At present, due to the complex geological conditions and long-distance drive, scheduled and unscheduled cutter head intervention maintenance during shield tunneling has become a major innovation in shield engineering in China. Therefore, paste HDN has been successfully applied to cutter head intervention under pressure, but corresponding research work on its film-forming mechanism and process is lacking. Film-forming experiments and theoretical analysis of the paste indicated that the film-forming process of the paste during gravel-stratum formation can be divided into two stages: Seepage blocking of the forming pore diameter and forming of a mud cake on the excavation surface. The seepage process was completed almost instantaneously, and the forming process of a 5–10 cm mud cake required 1–2 days. In addition, a mud diffusion model was established for investigating the mud infiltration process. The results of the aforementioned experiments were applied to the cutter head intervention of Guangzhou Metro and Lanzhou Metro, and this application ensured the efficient and safe completion of the intervention task.

Keywords: Shield; paste HDN; Mud film-forming; gravel stratum

1 Introduction

In recent years, with the construction of an increasing number of river-crossing tunnels, shield technology has been widely used, owing to the good support this technology provides to high-permeability strata [1]. However, this technology has drawbacks, particularly problem of downtime associated with cutter replacement during construction. Obstacles or worn cutters that are encountered during the process of shield tunneling in China must be overhauled and replaced under pressure. For encounters with high-permeability strata, the formation of a mud film stratum with good air retention on the excavation surface plays the key role in intervention under pressure. This film provides a relatively stable environment for operation under pressure, thereby ensuring safe implementation of the stratum [2]. The common method involves the formation of a dense mud film on the excavation surface to ensure air tightness, and hence the selection of mud materials is quite important.

Paste HDN is an improved clay material mixed with plasticizer in specified proportions. The viscosity of the mud can reach 10^4 mPa.s, i.e., hundreds of times that of the traditional mud film (the viscosity of traditional mud film: 100–200 mPa.s). The formed film has a compact structure and is suitable for high-permeability formation. The film serves to adjust the mud pressure, thereby balancing the earth and water pressure in the excavated stratum. As the mud pressure is greater than the pore water pressure of the stratum, the fine soil particles in the mud penetrate the stratum under the action of the pressure difference. This leads to the formation of an impermeable mud film on the excavated surface. Through the formed mud film, the mud pressure can effectively balance the earth and water pressure in the excavated stratum [3]. Xiaorui et al. [4-5] have classified the types of mud films formed and their influencing factors into three types: “mud skin type,” “mud skin + permeable zone type,” and...
“permeable zone type” based on the accumulation form of mud particles on the forming surface in laboratory tests. The formation of various mud film types depends mainly on mud particle gradation and pore size formation. Cheng et al. [6] expanded the one-dimensional model of mud film formation to a two-dimensional model and analyzed the growth law of the film via the incremental analysis method. The relationships between the mud film filtration amount and thickness as well as factors such as time and mud weight were also provided.

Paste HDN has been widely used in shield construction, for example, in Fuzhou Metro the Shield passes through the Minjiang River section and Guangzhou Metro Line 14 Branch Shield passes through the boulder section. Moreover, practice shows that the “paste HDN” filter cake simplifies the traditional mud film manufacturing process, exhibits strong air tightness and water resistance, can ensure the safety of cutter head operation, and improve the working efficiency [7]. Wan et al. [8] performed a systematic study, but the film-forming process remains unclear. Therefore, in this work, the film-forming process of paste HDN in gravel-stratum formation is investigated through a film-forming test performed on the paste. The factors that influence the process are analyzed, in order to improve the film performance and guide the actual project.

2 Mud film-forming test

2.1 Test device

Figure 1 shows a schematic of a customized mud film device for the test apparatus. The main body of the device is a Plexiglas column (inner diameter: 8.4 cm, height: 80.0 cm). The bulk head of the pressure chamber is equipped with a discharge valve, and the top is sealed with a flange plate. Furthermore, the middle part of the flange plate is connected to an air inlet, air compressor, and air driven supercharger that supply high-pressure gas to the mud infiltration chamber. To simulate the mud pressure during construction, the gas pressure flowing into the pressure chamber can be set through a pressure regulating valve connected to the pressure chamber. The reverse pressure gas inlet is connected above the water collecting pipe, and the reverse pressure of the infiltration chamber can be set through the reverse pressure regulating valve to simulate the forming pressure. The lower part is connected to a water collecting device, which can record the filtration amount of mud membrane in real time.

![Figure 1. In-house-developed filter cake formation test device](image)
2.2 Test material
(1) Paste HDN
Figure 2 shows the materials prepared from paste HDN. The materials, A and B, are a dry powder and a liquid, respectively. The grain size distribution curve of the HDN is shown in Figure 3.

![Figure 2. Paste HDN materials-A material and B material](image)

![Figure 3. Paste HDN particle laser particle curve](image)

(2) Strata

![Figure 4. Test gravel stratum](image)

Table 1. Range of grain size and permeability coefficient in single grain size stratum

| Grain size range/mm | 1–2  | 2–5  |
|---------------------|------|------|
| Forming permeability coefficient/cm/s | $1.2 \times 10^0$ | $5.2 \times 10^0$ |

2.3 Test program

The test program is shown in Table 2. The figure shows a one-to-one correspondence, i.e., each mass ratio of A and water (mA: m water) corresponds to four B liquid mass ratios, totaling 12 groups of mud.

![Table 2. Experimental research program](image)
2.4 Test process
(1) Weigh material A according to the test program in the laboratory, add the corresponding water quantity according to the mass ratio, and stir until agglomerated particles of the dry powder have disappeared. Subsequently, mix liquid B according to the test program, and stir thoroughly for homogenization of the mud.
(2) A filter stratum and gravel stratum are sequentially loaded into the test device and reversely saturated. The test mud is injected and the device is sealed. The pressure of the mud is set by the pressure regulating device, and the mud infiltration film-forming test is performed for a certain period. The changes in the filtration water quantity and mud film thickness are recorded during the mud film test.
(3) Perform mud film tests under different pressurization modes in order to measure the change in the filtration water volume during the mud film closing process. The thickness and moisture content of the film are determined after the test.
(4) After a given mixture test is completed, place another mixture in the testing apparatus and continue the test.

3 Analysis of paste HDN film-forming process

3.1 Analysis of film-forming test
Disassemble the device after the test to observe the mud film type. See Figure 5.
Based on the results shown in Figs. 6 and 7, and the results of the tests performed on paste HDN, the following conclusions can be drawn: The infiltration process of the paste under the action of pressure can be divided into two stages. In the first stage, the paste rapidly infiltrates and plugs the pores, within 100 s. The length of the infiltration zone changes only slightly with increasing time, and this process is referred to as the forming process of the infiltration zone. In the second stage, after infiltration by the paste is basically complete, the leachate discharge time is very long, i.e., the consolidation process of the paste HDN membrane occurs very slowly. Completion of the consolidation process generates a compact surface that leads to the formation of a mud cake, with good air tightness.

![Figure 5. Paste HDN formed filter cake in stratum](image)

![Figure 6. Leachate monitoring during permeate formation](image)

![Figure 7. Leachate monitoring during consolidation](image)
The test results shown in Table 3 indicate that the mud viscosity and forming grain size will affect the permeability distance, and hence a mud diffusion model is established to investigate the permeability distance of the mud.

Table 3. Filter cake formation analysis of a stratum

| Liquid A | Liquid B | Viscosity (Pa·s) | Permeation zone length of paste HDN in each forming grain (cm) |
|----------|----------|-----------------|---------------------------------------------------------------|
| 1:1.5    | 1/15     | 35              | — Impermeable                                                 |
| 1/20     | 41       | 2.5             | Impermeable                                                  |
| 1/25     | 40       | 3.5             | Impermeable                                                  |
| 1/30     | 39.5     | 5               | Impermeable                                                  |
| 1:2      | 1/15     | 15              | 19 5                                                        |
| 1/20     | 16.5     | 22.4            | —                                                           |
| 1/25     | 12.5     | 21              | —                                                           |
| 1/30     | 14       | 20              | 5.3                                                         |
| 1:3      | 1/15     | 3               | Full penetration 40.6                                        |
| 1/20     | 4.5      | Full penetration 28.5                                   |
| 1/25     | 5        | Full penetration 14.5                                    |
| 1/30     | 4.5      | Full penetration 17                                        |

3.2 Mud diffusion model

The particle pores generated during the forming process can be considered a series of pipelines, where mud infiltration will encounter the viscous resistance of forming particles around these pipes. This hinders the infinite diffusion of mud during forming, and usually stabilizes after diffusion to a certain range. The physical model of paste HDN diffusion during the forming process is shown in Figure 8.

Figure 8. Paste HDN diffusion model for a coarse-grained stratum

Knowing the forming pore diameter \( d \), mud pressure \( P \), mud viscous resistance \( \tau \), and long pipe length \( h \), the following equilibrium equation can be obtained based on the forming pore diffusion model shown in the figure:

\[
\frac{\pi}{4} d^2 P = \tau \cdot \pi d \cdot L
\]

The permeation distance \( L \) is determined from:
In the equation, the mud viscous resistance $\tau$ can be obtained by rotating the torque $M$ determined by the viscometer drum. Considering the drum radius and reducer used in this test, the calculation equation of the resistance is given as follows:

$$
\tau = \frac{M}{2\pi hr^2} \quad (M = 4 \times 10^{-5} \times A, \ A \text{ for dial reading})
$$

The above equation simply assumes that the forming pore is a long pipe with a uniform pipe diameter; this assumption is roughly consistent with the actual forming process. However, the process is quite complex, e.g., the process may be somewhat non-uniform or loose. This will lead to large errors, and even the smoothness of the forming particles will cause changes in the permeability distance. Therefore, the calculation equation derived from this model can only serve as a reference for engineering practice.

The penetration distances obtained in the experiment lie mainly between 10 cm and 40 cm. The results are compared with theoretical calculations, as shown in Figs. 9 and 10.

![Figure 9 Penetration of paste HDN in a stratum](image)

![Figure 10 Penetration of paste HDN in a stratum](image)

The theoretical calculation equation describing the permeability distance of paste HDN during the forming process can reflect the main influencing factors. That is, the permeability distance is directly proportional to the forming pore diameter and inversely proportional to the mud viscosity (viscous resistance) within a certain range. This knowledge can be used as a guide for engineering practice. However, due to the influence of factors such as sample loading tightness, human interference, mud placement time, and particle shape formation, more accurate tests (than the conventional tests) are needed to obtain more practical calculation theories and equations.

Therefore, in actual engineering, the use of a permeable mud skin + a permeable zone type is generally recommended when paste HDN is applied to a high-permeability sand stratum for cutter head
intervention. Consider the low-permeability formation of silty fine sand. The use of low-viscosity paste HDN or ordinary bentonite mud is recommended for the infiltration step. This paste should then be replaced in order to increase the thickness of the mud film for closed air and intervention, thereby improving the maintenance efficiency, ensuring excavation surface stability, and personnel safety.

3.3 Forming process of paste HDN mud cake
During the consolidation process comprising the forming process of the mud cake, pore water in the paste HDN is continuously discharged and mud particles are continuously compacted. The thickness and density of the cake can change during the forming process, as discussed below.

For the test, we employ mass ratios of 1:2 and 1/20 w for paste HDN powder A and liquid B, respectively, and a pressure value of 0.2 MPa. The thickness and density changes of the formed mud cake are measured in units of days.

Change in mud cake thickness with time, Figure11; change in mud cake density with time, Figure12.

As shown in Figs. 11 and 12, with increasing time, the water in the mud is continuously discharged, and the mud cake becomes increasingly dense: the thickness accumulates continuously after the first two days of forming, and the subsequent deposition speed decreases. The rate of density increase gradually decreases from a high to a stable value. Regarding intervention in the actual shield construction, the compactness of the mud cake improves considerably after injecting the paste HDN and pressurizing for 2 or 3 days. Moreover, the chamber can be gradually opened with pressure.
4 Effect of Chamber Opening and Closure after Film-forming of Paste HDN

4.1 Air tighter effect
Figure 12 shows a mud cake formed by paste HDN mud employed in this work. The thickness of the cake can reach 5–10 cm, which is considerably larger than the thickness of the mud film formed by low-viscosity mud under normal circumstances. The air tighter value indicates the maximum atmospheric pressure that the mud film can bear [9]. In this test, when the air pressure is increased to 0.6 MPa, the film is quite stable for a prolonged period. This period is substantially larger than the gas-tight value reached by the film formed by ordinary low-viscosity mud, and the gas-tight time is relatively long.

4.2 Engineering Effect
A bid section of Guangzhou Metro used paste HDN material in a cutter head intervention project in gravel stratum. After the chamber opening is completed (see Figure 13), the permeability zone can reach 16.5 cm. According to Zhong et al. [10], coarse-sand formation and Lanzhou gravel-stratum formation occur in some other sections of Fuzhou Metro and Lanzhou Metro, as shown in Figure 14. After using the paste, mud film with a thickness of ~8–10 cm can be formed in a single step. The thickness of this film is considerably larger than that of low-viscosity mud used in actual engineering practice (see Figure 15 for the film-forming effect). In addition, after the paste HDN forms the film, the working time under pressure can exceed two weeks, leading to significant improvement in the efficiency of cutter change and maintenance for shield tunneling in China. The mud film formed by ordinary mud typically operates for 24–48 h under pressure. Furthermore, the film must be repaired repeatedly to avoid major safety accidents caused by air leakage, which leads to a significant decrease in the maintenance efficiency of intervention under pressure.
5 Conclusions
The findings of the present study can be summarized as follows:
(1) The film-forming process of paste HDN in a gravel stratum is mainly divided into two processes, the forming process of the permeable zone and the consolidation process of the mud cake.
(2) In general, the formation of a mud film is mainly based on the angle of the mud particles blocking the formation pore size. During the film-forming process of paste HDN, the penetration of mud is prevented by increasing the viscosity, thereby leading to the formation of a mud film with a certain thickness. This process differs from the formation process of an ordinary bentonite slurry film.
(3) The diffusion model of paste HDN in gravel stratum formation shows that the permeability distance of the permeable zone is directly proportional to the forming pore size. Furthermore, this distance is inversely proportional to the mud viscosity (viscous resistance) within a certain range. This knowledge can be used to guide engineering practice.
(4) The thickness and density of the mud cake decrease gradually with increasing time and eventually become stable. Moreover, the compactness and air tightness of the mud improve significantly after 2–3 days of mud pressurization when the shield mud material is used for the pressurized intervention in shield construction.
(5) The development of an infiltration zone + mud cake type mud film from paste HDN material is suggested for cutter head intervention under pressure in a gravel stratum encountered in shield engineering. Owing to this development, the air retention value and working time of intervention under pressure will improve, thus ensuring personnel safety.

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