Slurry Infiltration Column Tests on Saturated Sand

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Abstract. Slurry infiltration process contributes to the stability of tunnel face significantly during slurry shield tunneling construction. The support pressure cannot be transmitted efficiently to the face unless a compact filter cake forms. This paper aims at investigating the formation of filter cake in saturated sand by slurry infiltration column tests. A series of tests were performed under different filtration pressures using three concentrations of slurry in four types of saturated sand strata. In order to obtain the characters of the infiltration process and filter cake, pore pressure evolution was measured. Three types of filter cakes were observed in the tests, including external filter cake, external filter cake plus internal filter cake and deep infiltration. External filter cake transmits support pressure efficiently, while the other two types of filter cakes cannot provide sufficiently support pressure for the tunnel face. Especially, deep infiltration behaves no capacity of retaining pressure and should be avoided in engineering practice.

1. Introduction
During slurry shield tunneling, pressurized bentonite slurry is universally applied to resist the water-earth pressure and thus maintain the stability of the excavation face. During the tunneling process, mixtures of mud, water, bentonite and some additives would be compressed into the slurry cell.\textsuperscript{[1]} Owing to pressure difference between slurry and ground, the slurry could either accumulate on the excavation surface or penetrate into stratum, leading to the formation of filter cake.

The formation of filter cake plays a vital role in stability of excavation face.\textsuperscript{[2]} As the permeability of different strata might be varied significantly, the concentration of bentonite slurry must be adjusted according to the ground condition. Especially, in highly permeable ground such as sandy soil and gravel.
the quality of filter cake is more critical to the safety of excavation face.

In general, there are three typical types of filter cake as illustrated in Figure 1: intact filter cake (type I), a filter cake with infiltration zone (type II), totally infiltration zone without filter cake (type III). An intact filter cake is most efficient in transmitting support pressure, while infiltration zone (type III) is not capable of retaining a stable support pressure ahead of the tunnel face. If type III filter cake occurs, there would be high risks of water leakage and collapse of excavation face.

Figure 1. Three types of filter cake (Min et al., 2013a, b). I: intact filter cake; II: filter cake with infiltration zone; III: totally infiltration zone without filter cake.

In order to explore the formation process of filter cake, three different methods are frequently carried out, including slurry infiltration column tests, numerical modeling and theoretical analysis. Theoretical analysis attempts to explain the infiltration by means of mechanics and kinematics. Numerical modeling, coupled computational fluid dynamics (CFD)-discrete element method (DEM) for example, can be used for understanding the slurry infiltration process from a micro-perspective. However, some assumptions must be made in both numerical modeling and theoretical analysis, and the results would be influenced strongly by the selection of constitutive models and mechanical parameters. Compared with the former two methods, slurry infiltration column test is a convenient but useful tool to investigate the slurry infiltration behavior directly, which could also provide practical guidance for the tunneling project. Hence, it is adopted in the present work.

Normally the slurry infiltration column is a cylinder made of Perspex as shown in Figure 2. In the infiltration test, after the preparation of the sand column, slurry is added into the cylinder and pressurized so that the slurry infiltration process can be observed.

Figure 2. A typical apparatus for slurry infiltration column tests. (adapted from Min et al., 2013)
2. Experimental devices and tests procedures

2.1. Experimental devices
Figure 3 shows a system for infiltration column test, which consists of several elements as followed.

- Filtration cell made up of Perspex with a diameter of 10cm and height of 60cm.
- 4 pore water pressure piezometers allocated at a spacing of 10cm along the column height, as Figure 4 shows.
- An electronic balance that can monitor the weight of the filtrate.
- A cylinder for collecting filtrate.
- An air pump.
- A digital camera.

![Figure 3. The experimental devices. (1: inlet valve; 2: infiltration cell; 3: pressure piezometers; 4: outlet valve; 5: sealed connecter; 6: collector; 7: electronic balance; 8: air pump.)](image1)

**Figure 4.** Arrangement of the piezometers.

2.2. Materials used in tests
This paper focuses on the behavior of slurry infiltration in different saturated sand stratum. Consequently, sand, and bentonite slurry are the major materials used in the tests. Furthermore, sodium carboxymethyl cellulose (CMC) was used for increasing the viscosity of slurry. In all the tests, the content of CMC was 0.08%. Four different kinds of sand and three kinds of slurry with different bentonite concentrations were used as shown in Table 1.

![Figure 4. Arrangement of the piezometers.](image2)
Table 1. Materials used in tests

| Sand  | Classification | Diameter of aggregate (cm) | Slurry concentration of bentonite(%) | content of CMC(%) |
|-------|----------------|-----------------------------|-------------------------------------|-----------------|
| SI    | coarse sand    | 0.4-0.9                     | S1                                  | 8               | 0.08 |
| SII   | medium sand    | 0.1-0.3                     | S2                                  | 10              | 0.08 |
| SIII  | fine sand      | 0.01-0.08                   | S3                                  | 12              | 0.08 |
| SIV   | graded sand    | unmeasured                  |                                     |                 |      |

2.3. Testing procedure

General procedures of the tests are displayed in Figure 5. Details of each step would be described in following sections.

![Figure 5. General procedures of the slurry infiltration column test.](image)

2.3.1. Preparation of slurry. Bentonite, water and CMC were weighed according to the prescribed concentration (8%, 12% and 16%) using an electronic balance. After mixing and fully stirring, the slurry should be set still at least 24 hours for hydration of the bentonite.

2.3.2. Check of airtightness. Airtightness is essential to the slurry infiltration tests. In order to check the airtightness before testing, water was poured into the infiltration cell with the outlet valve closed. As the air is expelled out of the cylinder completely, the air pump was opened after closing the inlet valve. If the devices are sealed airtight, the pressures displayed in the piezometers will be stable and no water leakage will be observed.

2.3.3. Preparation of sand stratum. Firstly, coarse sand was poured into infiltration cell until a height of 5cm was reached to form a filter bed. Note that the filter bed must be compacted tightly; otherwise the fine sand of the simulated ground might pass through the filter bed, leading to failure of the test. Secondly, the ground was prepared layer by layer. Each single layer (normally 5 cm in height) must be compacted and then saturated with water coming from the outlet valve in order to reduce the disturbance to the ground. As is shown in Figure 6(a), a connector was connected to outlet valve, keeping the water level in connector higher than the surface of sand stratum. The outlet valve was opened slightly to allow the water to flow into the stratum. When the water level in infiltration column reached the surface of stratum, the outlet valve was turned off. It should be set still 10 minutes approximately to be saturated properly. Repeat the mentioned operations till the ground height reaches about 20cm as shown in Figure 6(b).
2.3.4. Adding slurry and loading. As is shown in Figure 7(a), slurry should be poured into infiltration cell carefully to avoid disturbance to the ground. Inlet valve is to be opened after sealing the cylinder up. Then, air pump would be opened to raise the slurry pressure to 50kPa. As soon as the outlet valve at the bottom is opened, the slurry starts to infiltrate. As Figure 7(b) shows, after the pressure readings on the piezometers become steady, the applied pressure continues to increase to 100kPa, which is used to assess the performance of filter cake under a larger pressure. The infiltration process is completed when the pressures reach a steady state again.

2.3.5. Observation and recording. The filter cakes were observed and the entire testing procedure was recorded by digital camera.

3. Results and discussion
In the slurry infiltration column tests, three types of infiltration phenomena were observed: (1) external filter cake; (2) external filter cake plus internal filter cake; (3) deep infiltration. Table 2 records the filter cake morphology of all the tests. Additionally, by recording the pore pressure evolution along the sand...
column during the infiltration tests, the pressure filtration characteristics of different filter cakes can be analyzed.

### Table 2. Results of the slurry infiltration column tests

| NO. | Sand | Concentration of bentonite | Type of filter cake                        |
|-----|------|---------------------------|------------------------------------------|
| 1   | SI   | 8%                        | Deep infiltration                        |
| 2   | SI   | 12%                       | Deep infiltration                        |
| 3   | SI   | 16%                       | External filter cake plus internal filter cake |
| 4   | SII  | 8%                        | External filter cake plus internal filter cake |
| 5   | SII  | 12%                       | External filter cake plus internal filter cake |
| 6   | SII  | 16%                       | External filter cake plus internal filter cake |
| 7   | SIII | 8%                        | External filter cake                    |
| 8   | SIII | 12%                       | External filter cake                    |
| 9   | SIII | 16%                       | External filter cake                    |
| 10  | SIV  | 8%                        | External filter cake                    |
| 11  | SIV  | 12%                       | External filter cake                    |
| 12  | SIV  | 16%                       | External filter cake                    |

### 3.1. External filter cake

Normally external filter cake forms when the slurry particles cannot pass through the voids in sand stratum under the applied external pressure. As shown in Table 2, the combination of sand with finer grain size and slurry with larger concentration tends to form external filter cake in the tests. The typical morphology of external filter cake is shown in Figure 8. The slurry particles accumulate on the surface of the sand column, forming a dense external filter cake with a thickness of 0.5 ~ 1 cm.

![Figure 8. External filter cake. (a) side view (b) top view.](image-url)
Figure 9 depicts the pore pressure evolution during the test of 8% bentonite slurry in SIII sand. As the applied pressure (value of Piezometer 1) increases to 50 kPa, the pressure values of other three piezometers gradually rise to approximately 50 kPa and remains stable before opening the outlet valve as shown in Figure 9(a). Once the outlet valve is opened, the pressure values of Piezometer 2, 3, 4 rapidly decrease to 0 kPa while the pressure of Piezometer 1 still remains constant at the applied pressure, which indicates that the external filter cake can efficiently retain the support pressure. In order to further assess the performance of external filter under higher pressure, the applied pressure is increased to 100 kPa. It turns out that this type of filter cake still has satisfactory pressure stability and water tightness under 100 kPa. Figure 9 (b) shows the pressure distribution of different stages during the test. The pressure difference between Piezometer 1 (Z=10 cm) and Piezometer 2 (Z= 0 cm) could be seen as the pressure drop across the filter cake. As shown in Figure 9(b), an obvious pressure drop develops rapidly after opening the outlet valve. In only 1 second, the pressure drop between Piezometer 1 and 2 (40kPa) reaches around 80% of the total pressure drop, which indicates that if the external filter cake forms, it can transmit the support pressure in a fairly short time.

3.2. External filter cake plus internal filter cake
In general, internal filter cake forms due to some fraction of slurry particles pass through the voids in sand stratum under external pressure. As slurry infiltrates further in the sand, the voids are jammed by slurry particles gradually. Thereby, the remaining slurry particles can no more pass through and thus accumulate on the surface of sand column. As Table 2 shows, this type of filter cake is more likely to form in sand of medium size or in coarse sand but with large concentration slurry. The typical morphology of external filter cake is shown in Figure 10.
Figure 10. External filter cake plus internal filter cake. (a) side view (b) top view.

Figure 11 describes the pore pressure evolution in the test of 8% bentonite slurry in SII sand. The evolution of pressure is similar to the external filter cake until the outlet valve is opened. After opening the outlet valve, the pressure values of Piezometer 2, 3, 4 decrease to 0kPa, while the value of Piezometer 1 decreases to 20kPa within approximately 25 seconds as Figure 11(a) shows. After the applied pressure is raised to 100kPa and the outlet valve is opened, the level of slurry reduces sharply, which indicates that the water tightness of this type of filter cake is unsatisfying under 100kPa pressure. However, there is still a pressure difference of 15kPa between Piezometer 1 and 2 at the end as Figure 11(b) displays, i.e., this type of filter cake has certain capacity of transmitting support pressure.

(a) Time-history of pore water pressure (b) Vertical distribution of the pore water pressure (Z=0 means the interface between slurry and sand stratum)

Figure 11. Pressure filtration behaviors of external filter cake plus internal filter cake (8% bentonite slurry in SII sand stratum).

3.3. Deep infiltration
Deep infiltration occurs when almost all the slurry particles pass through the voids in sand stratum. It can be seen in Table 2 that combination of coarse sand and lower concentration bentonite slurry leads to deep infiltration. Figure 12 depicts a typical morphology of deep infiltration.
Figure 12. Deep infiltration. (a) side view (b) top view.

The pore pressure evolution in the test of 8% bentonite slurry in SI sand is displayed in Figure 13. Under the same operation as mentioned in former phases, the pressure values of four piezometers decrease to 0kPa under 100kPa applied pressure. It is apparent that this type of filter cake has poor air and water tightness.

Figure 13. Pressure filtration behaviors of deep infiltration (8% bentonite slurry in SI sand stratum).

4. Conclusion
A series of slurry infiltration column tests were conducted considering different combinations of three bentonite concentrations of slurry and four sizes of sand stratum. Three types of filter cakes were observed, whose characteristics are summarized below:

- External filter cake transmits support pressure efficiently with good water and air tightness.
- External filter cake plus internal filter cake is of poor water and air tightness at the beginning of infiltration but owns marginal airtightness and transmits a small fraction of support pressure due to the progressive jamming of voids inside sand column during slurry infiltration which eventually prevents the further infiltration of remaining slurry particles.
Deep infiltration is of the poorest water and air tightness and has the least capacity of transmitting support pressure. The slurry particles cannot effectively jam the voids within sand stratum, and thus slurry infiltration occurs continuously.

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