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Filter cake formation for slurry shield tunneling in highly permeable sand

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ABSTRACT

For slurry shield tunneling projects excavated in the highly permeable soils, the slurry usually passes through the ground without forming a filter cake. As a result it may be impossible (depending on the yield strength of slurry) to built up the required support pressure which would lead to a face instability. This kind of face instability is influenced by the factors, such as the permeability of ground, the slurry pressure and the properties of slurry. How to form a thin and lowly permeable filter cake efficiently and quickly on the tunnel face becomes a crucial engineering problem for the slurry shield tunneling in the coarse-grained and highly permeable grounds. In this paper, a new apparatus was developed to study the filter cake formation on the surface of coarse-grained sands under elevated pressure. A series of pressure filtration tests were carried out on nine different slurries and five different soils. By measuring the quantities of discharged water during the test and observing the state of filter cakes formed on the soil surface, the criteria of filter cake formation was identified. The test results indicated three different types of slurry infiltration. Correspondingly, the following three different types of filter cakes were observed: a filter cake, a filter cake with an infiltrated zone, and infiltrated zone without filter cake. It was found that the ratio between the average pore size of soil ($\overline{D_0}$) and the particle size for which 85% by weight of particles in the slurry (d_{85}) may be used to classify the types of filter cake formation.
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1. Introduction

Slurry shield tunneling has been widely used, especially in undersea tunnels and excavation projects across rivers (Eisenstein, 1994; Harding, 1982; Min et al., 2010; Shen et al., 2004; Watanabe and Yamazaki, 1981). In this method, the tunnel face is supported by pressurized slurry and its stability has gained wide attention in past studies (Anagnostou and Kovari, 1994; Kim and Tonon, 2010). To maintain the stability of tunnel face, slurries should form a dense and lowly permeable filter cake on the face such that slurry suspensions are prevented from infiltrating into soils and the efficient transfer of support pressure onto soils is ensured. However, in the coarse-grained and highly permeable soils, slurry suspensions usually penetrate into the ground easily and filter cakes cannot be formed on the excavation surface. Then, the required support pressure is not able to (depending on the yield strength of slurry) built up to counteract the water and earth pressure, which may result in the face collapse during construction and lead to significant construction delays and remediation costs (Fritz et al., 2002; Fritz, 2007; Jebelli et al., 2010; Zhang et al., 2004). Thus, how to form a lowly permeable filter cake becomes a very important engineering problem for the slurry shield tunneling constructed in the coarse-grained and highly permeable grounds.

There are too many factors that control the formation of filter cake, such as the permeability of soil, the slurry pressure and properties of slurry (density, viscosity (rheological properties), grain size distribution, etc.) (Cheng et al., 2001; Han et al., 2008; Heinz, 2006; Kim and Tonon, 2010; Min et al., 2010; Watanabe and Yamazaki, 1981; Zhang et al., 2004). For the slurry pressure, many studies have been carried out which are based either on the limiting equilibrium analysis or limit analysis (Anagnostou and Kovari, 1994; Broere, 2001; Kim and Tonon, 2010; Li et al., 2009). Most of these studies have focused on the effect of slurry infiltration on the ground stability, but studies of formation of filter cake are rare.

Meanwhile, many laboratory model tests have been carried out to examine the effects of properties of slurry on the formation of filter-cakes. Watanabe and Yamazaki (1981) investigated the effects of density of slurry on the loss of slurry during the

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formation of filter cake in the highly permeable soils, and they found that the proportion of sand in the slurry played an important role in the loss of slurry. Cheng et al. (2001) conducted laboratory model tests for pure bentonite suspensions in a medium coarse sand, and the results showed that the viscosity of suspensions had a great impact on the filter cake formation. Fritz et al. (2002), Fritz (2007) and Heinz (2006) developed an apparatus for measuring the support pressure of slurry and conducted the support pressure tests to evaluate the best combination of additives in slurries such as polymer, sand and vermiculite (0.7–4 mm). The results of the study have been applied successfully in the excavation of Zimmerberg Base Tunnel, where the permeability of ground is greater than 10^{-3} m/s. Han et al. (2008) evaluated the factors that controlled the filter cake formation based on some tests conducted on a modified apparatus for soil with a permeability around 3×10^{-4} m/s. Their results indicated that the higher the viscosity of slurry, the denser the resultant filter cake. Using the same apparatus and soil, Min et al. (2010) investigated the effects of clay content of slurry on the thickness and permeability of filter cake. The test results indicated that the clay content of the slurry played an important role in the filter cake formation, and it could be used as a controlling parameter for slurry shield tunneling.

The matching between the grain size of slurry and the pore size of ground is crucial to form a filter-cake on the tunnel face. Even in highly permeable gravelly sands, a filter cake may be formed by adjusting the sizes and contents of the grains of slurry. The key objective of the study is to investigate the relationship between slurry properties and pore sizes of sand for the filter cake formation on the surface of gravelly sand under elevated pressure. A series of pressure filtration tests were conducted on five soil samples and nine slurry samples. The types of slurry infiltration and filter cake formation were presented, and the criteria of filter cake formation in the highly permeable sands were discussed.

2. Experimental studies

2.1. Test apparatus

Based on the apparatus for measuring support pressure of slurry suspension (Fritz et al., 2002; Fritz, 2007; Heinz, 2006), an apparatus has been developed in this study. Fig. 1 shows the schematic layout of the test apparatus. The Perspex cylinder has an inner diameter of 8 cm and a wall thickness of 0.8 cm. The pressure is applied by a piston on which the dead weight is added. Using this apparatus, the slurry infiltration into the soil and the filter cake formation on the soil surface can be observed. Meanwhile the quantity of seepage discharge (Q) is also measured.

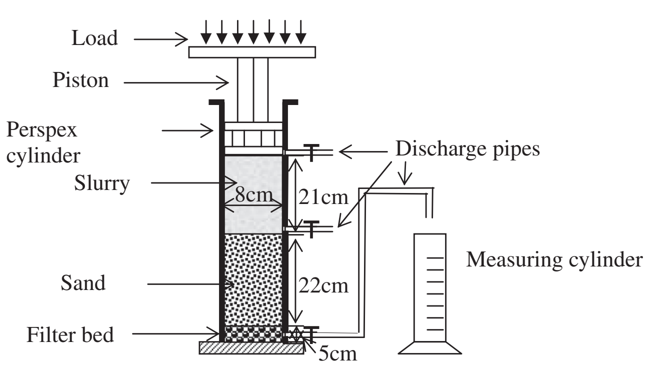

Fig. 1. Schematic layout of test apparatus.

2.2. Materials

In this study, nine different slurries were prepared by adding different proportions of fillers into the pure Na-bentonite suspension, such as silty sand, silt and clay. The Na-bentonite was taken from Tangshan of Nanjing city in China. The density (ρ) of pure Na-bentonite suspension was 1.06 g/cm^3, and its bentonite content was 9.1% in mass. Different proportions and grain size of fillers were added to adjust the density and grain size distribution of slurries. The density was performed with a densimeter typically used on site. The basic physical properties of slurries are summarized in Table 1. The grain size distribution curves of nine different slurries, measured by a laser particle sizer, are depicted in Fig. 2. The sand content is defined as the percentage by weight of particles of which the grain sizes are bigger than 75 μm. d_{85} Refers to the particle size for which 85% by weight of particles in the suspension are smaller. To adjust the viscosity (rheological properties) of slurries, different quantities of Carboxymethyl Cellulose (CMC) were added. The funnel viscosity performed with a Marsh funnel viscometer (the Marsh time of water at 20 °C was 25 ± 0.5 s) was maintained between 30 s and 40 s by adding 0.1–0.4% of dry CMC in mass. Fig. 3 is a sketch map of the rheogram of slurries used in slurry-shield TBM. Contrary to a Newtonian fluid, the slurry used in tunneling project requires a certain minimum shear stress to be able to flow. It behaves like a Bingham fluid. The minimum shear stress is named as static yield point or yield point (Longchamp et al., 2005). In slurry-tunneling practice, the convention is to use a value determined from the intersection on the rheogram of the straight line and vertical scale of co-ordinates. The extrapolation is called the dynamic or Bingham yield point. The plastic viscosity is the gradient of linear part in the rheogram. The rheological properties of tested slurries, summarized in Table 2, were measured by a revolving rheometer with 15 grades of rotation rate.

Five different coarse-grained sand samples with different grain size distribution were tested. The sand samples with uniform gradations, were obtained by screening between the nearest two sizes of standard sieves. The gradations were between 0.1–0.25 mm and 2–5 mm (see in Fig. 4). All the soil specimens were compacted to a dry density (ρ_d) of 1.5 g/cm^3 and the corresponding porosity (n) was 0.43. The hydraulic conductivity (k) of soils was measured by the constant head permeability tests. The basic physical indexes of soil samples are summarized in Table 3.

2.3. Test procedures

A 5 cm thick filter bed was placed at the bottom of Perspex cylinder (see Fig. 1), which consisted of uniform sand or gravel with grain sizes ranging from 2 to 5 mm. Then the test soil was placed which was saturated with water percolating from the bottom of apparatus. The thickness of soil specimen was 22 cm. Above the specimen, slurries in 21 cm thickness was added and a piston was put on the top of slurry.

Fig. 5 shows the loading sequence of the tests. Firstly, a vertical load was applied at the top of piston, on which the dead weight was added. The slurry flowed through the sand specimen and the discharge (Q_c) at the base of apparatus was measured by a measuring cylinder. When the quantity of Q_c reached a steady value, the corresponding time was considered as the formation time of filter cake. (Of course, if the yield strength was high enough, the slurry infiltration stopped even without a filter cake.) The same procedures were repeated for the next vertical load until reaching a pressure of 300 kPa (actually, this pressure is the difference between the slurry pressure and ground water pressure, the effective face support pressure). After each filtration test, the state of filter cake formed on the surface of soil specimen and the infiltrated distance of slurry suspensions in the soil specimen were recorded.

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