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Evaluation of pressurized slurry Infiltration into sand using blocking filtration laws

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ABSTRACT

The stabilization of the excavation face during slurry shield tunneling boring machine (TBM) operations is significantly influenced by pressurized slurry infiltration mechanisms, which consist of two sequential phases: slurry penetration and filter cake development. In this study, infiltration column tests were conducted under various slurry concentrations and pressure levels to investigate the transition between these two phases. The transition point was identified using the blocking filtration laws and compared with the results obtained from the Peclet number method. It was observed that increasing both the applied pressure and slurry concentration led to earlier transition points. Overall, the blocking filtration laws proved effective for characterizing changes in slurry infiltration mechanisms, showing good agreement with the previously established Peclet number approach.

1. Introduction

With the growing demand for underground space, the use of slurry shield tunnel boring machines (TBMs) has increased significantly. In this method, pressurized bentonite slurry infiltrates the ground and forms a low-permeability filter cake that allows the slurry pressure to act as effective face support (Anagnostou 1994; Zhang 2024). However, in highly permeable soils such as sand or gravel, bentonite slurry readily infiltrates the ground, delaying or preventing filter cake formation. In such cases, effective face support may not develop adequately, leading to tunnel face instability (Fritz 2007; Jin 2022). Therefore, identifying transitions in pressurized slurry infiltration mechanisms is crucial to maintaining face stability, particularly under high-permeability

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ground conditions.

In this study, infiltration column tests were performed under varying slurry concentrations and pneumatic pressure levels to explore these mechanisms. The blocking filtration laws and the Peclet number method (Talmon 2013) were applied to examine the phase transition in slurry infiltration. The transition point identified using the blocking filtration laws was compared with that obtained from the Peclet number method to evaluate the applicability of the blocking filtration framework.

2. Methods for determination of transition point

2.1 Blocking filtration laws

The blocking filtration laws describe four different fouling mechanisms caused by particle deposition either within the pores of the filter medium or on its surface during filtration. These include three pore-blocking mechanisms and one representing cake filtration. Under constant-pressure filtration, the four blocking mechanisms can be described using a general differential equation (Grace 1956):

$$\frac{d^2t}{dV^2} = k\left(\frac{dt}{dV}\right)^n \tag{1}$$

where t is the filtration time, V is the filtrate volume, k is a filtration-dependent constant, and n is the filtration exponent, which varies with the fouling mechanism.

The slurry infiltration process is conceptualized as an initial phase of pore blocking (slurry penetration) followed by cake filtration (filter cake development). Thus, the transition point between these two phases can be identified by analyzing the slope variation in a logarithmic plot of d^2t/dV^2 versus dt/dV, as described by Eq. (1).

2.2 Peclet number

Talmon (2013) proposed that the Peclet number (*Pe*) can be used to determine the transition point between slurry penetration and filter cake formation. It is calculated as:

$$Pe = \frac{ud}{c_v} \tag{2}$$

where u is the pore fluid velocity, d is the hydraulic pore diameter, and c_v is the consolidation coefficient of the clay suspension (e.g., bentonite slurry). A Peclet number of 10 is typically used as the threshold to distinguish between the two phases (Winterwerp 2004; Talmon 2013).

3. Experimental studies

The infiltration column test setup consists of an acrylic column, air supply system, digital scale, and porous stone, as shown in Fig. 1. The acrylic column has a diameter of 150 mm and a height of 600 mm. Pneumatic pressure is applied to the bentonite slurry and sand bed via the air supply system. The digital scale records the weight of filtered water, while the porous stone, positioned beneath the sand bed, prevents loss of solid particles during filtration.

The test procedure is as follows: First, silica sand is placed into the column and compacted underwater to form a sand bed. Excess water above the sand surface is then removed, and the bentonite slurry is gently poured over the sand bed to minimize disturbance. A constant pneumatic pressure is applied to the slurry, and the test begins with the opening of the bottom valve. The test continues for 30 minutes, during which the weight of the filtered water is recorded every second. A total of nine infiltration column tests were conducted using three slurry concentrations (30, 40, and 50 g/L) and three pressure levels (50, 100, and 150 kPa).

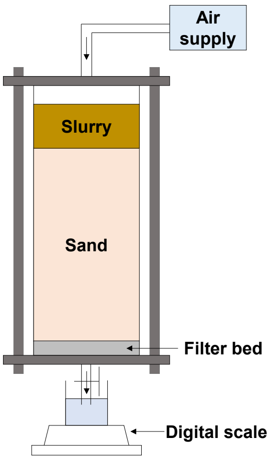

Fig. 1 Schematic of infiltration column test setup

4. Results and discussion

The transition points determined using the two different approaches are summarized in Table 1. The results show that higher pressure levels and slurry concentrations led to earlier transition points. Moreover, the transition points identified using the blocking filtration laws were found to be in good agreement with those determined by the Peclet number criterion (i.e., *Pe* = 10).

Table 1. Transition points determined from two different methods

Concentration (g/L)	Pressure (kPa)	Transition point (s)	
		Blocking filtration laws	Peclet number method
30	50	156	144
	100	98	83
	150	63	61
40	50	85	71
	100	51	45
	150	49	45
50	50	49	43

100	48	42
150	41	33

5. Conclusions

This study conducted infiltration column tests to investigate changes in pressurized slurry infiltration mechanisms under varying slurry concentrations and pneumatic pressure levels. The transition points between the slurry penetration and filter cake development phases were evaluated using both the blocking filtration laws and the Peclet number method (Talmon 2013). The results showed that the transition points obtained from the two approaches were in good agreement and decreased with increasing applied pressure and slurry concentration. These findings indicate that the blocking filtration laws are effective in identifying changes in pressurized slurry infiltration mechanisms.

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