The 2025 World Congress on
Advances in Structural Engineering and Mechanics (ASEM25)
BEXCO, Busan, Korea, August 11-14, 2025

Assessing clogging of sand deposit for slurry shield tunnelling

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ABSTRACT

The proper formation of slurry filter cake at the face in a slurry shield TBM is critical in face stability during the TBM operation. This study introduces the framework of assessing the clogging of sand medium through laboratory soil-column experiments. The advection-dispersion-based equation was used to quantitatively explain the transport and deposition of clay particles through the sand medium. The observed deposition profiles and breakthrough curves were quantified by three first-order rate coefficients to explain attachment, detachment, and straining. In addition, the impact of ionic concentration, inlet concentration, and angularity of sand was also investigated and discussed. It can be inferred that the framework shown in this study can be applied to assess the penetration depth of bentonite slurry, optimal swelling potential, and optimal bentonite concentration at a given injecting pressure.

Keywords: slurry TBM; face stability; clogging; soil-column experiment, deposition profile

1. INTRODUCTION

Slurry shield TBM has been extensively employed in tunnelling projects that require precise control of support pressure achieved by pressurized bentonite slurry. During the excavation, the slurry infiltrates the surrounding soils where the formation of filter cake on the excavation surface can be anticipated (Min et al., 2013). The appropriate formation of filter cake is critical to ensure the pressure transmission to the surrounding soils and to prevent excessive slurry penetration into the ground. Therefore, controlling the appropriate slurry concentration and injection pressure is necessary for successful excavation using slurry shield TBM, particularly for highly permeable soils.

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The failure of maintaining support pressure during the excavation may lead to the collapse of tunnel face.

Because of its importance in stability of tunnel face during the excavation, many previous studies investigated slurry infiltration and filter cake formation through laboratory-scale experiments. Many critical factors affecting the formation of filter cake were take into consideration such as slurry density and fraction of relatively large particles (Xu & Bezuijen, 2019). In addition, several modeling techniques such as multivariate model, computational fluid dynamics, and discrete element method were applied to obtain macroscopic and microscopic insights on the infiltration behavior of slurry and the formation of filter cake (Qin et al., 2023).

The mechanisms of clay particle infiltration and formation of filter cake can be also explained by colloid transport through porous media, which has been extensively investigated in the field of environmental engineering for the applications of filtering processes and contaminant transport through porous media (Bradford et al., 2002). Although mechanisms between infiltration of clay particles (usually bentonite particles for slurry TBM) and colloid transport through porous media are similar, the aggregation, platy shape and swelling characteristics of clay particles indicate the need for investigating clay particle transport through permeable soils (e.g., sand medium). Therefore, this study investigates the framework of assessing clay particle deposition on sand medium through laboratory soil-column experiments and one-dimensional advection dispersion equation with three first-order coefficients to account for three main mechanisms (attachment, detachment, and straining) explaining clay particle deposition.

2. METHODOLOGY AND RESULTS

2.1 Soil-column experiments

A flow cell with a height of 30.48 cm and a diameter of 7.62 cm was designed to measure the deposition profile of kaolinite particles with depth of saturated sand medium. 1, 2, and 5 g/L of kaolinite suspension were injected to the column for 10 pore volumes (PVs) at ionic concentration (IC) = 0 (deionized water), 0.001, 0.01, and 0.1 M controlled by $CaCl_2$ powder. Two sand types (ASTM 20/30 and GS 20/30) were selected to investigate the impact of angularity on the deposition behavior of kaolinite. In addition, the four pressure transducers were installed along the column to measure the reduction of saturated hydraulic conductivity at two 7.62-cm intervals from the top and a 15.24-cm interval between the middle and the bottom of the column.

To obtain a saturated sand medium before injecting kaolinite suspension, a wet pluviation method was selected, which ensures the semi-homogeneous saturated state of sand medium. No. 200 plastic mesh was installed at the bottom of the column to prevent sand particles from flowing out of the column during the injection. In addition, the turbidity was selected to measure the deposited mass of kaolinite using the predetermined linear relationship between turbidity and the concentration of kaolinite suspension. The mass of deposited kaolinite was measured every 2.54-cm depth after the injection. Fig. 1 illustrates the experimental setup used in this study.

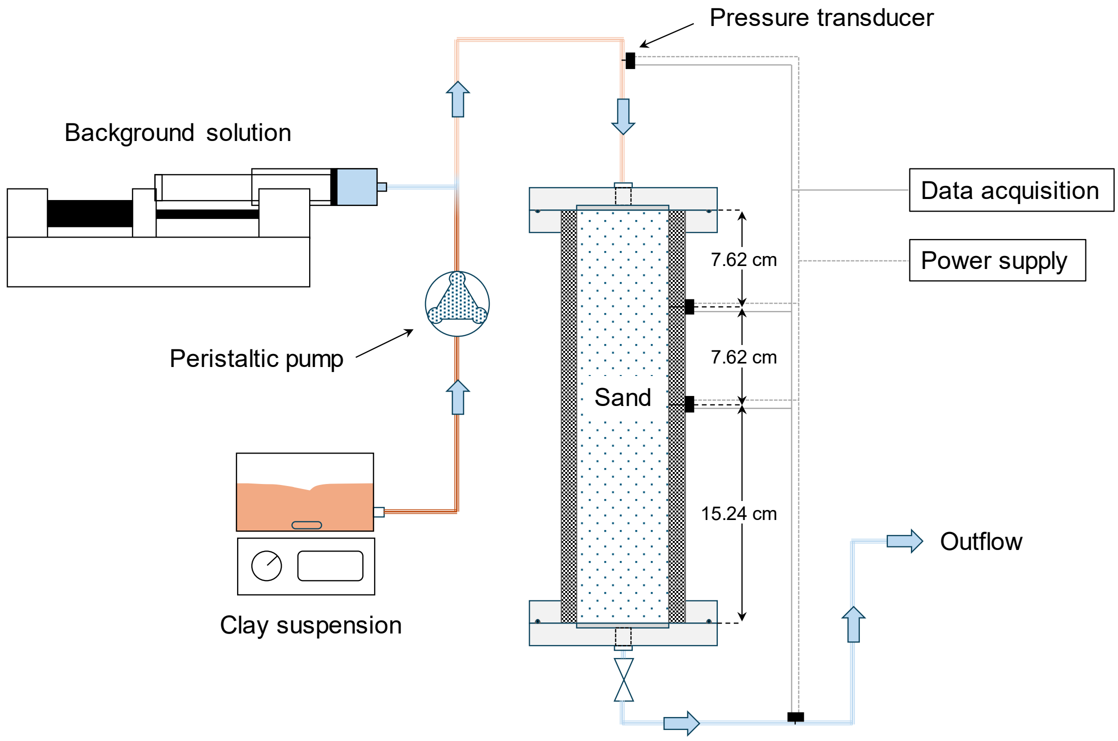

Fig. 1 Schematic Illustration of the experimental set-up

2.2 Advection-dispersion-reaction equation for clay particle deposition

The advection-dispersion transport with reaction to explain clay particle deposition in saturated sand medium can be expressed as:

$$\frac{\partial C}{\partial t} + \rho_b \frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial C}{\partial z}\right) - q \frac{\partial C}{\partial z} \quad (1)$$

$$\rho_b \frac{\partial S}{\partial t} = \theta k_{att}\psi_{att} C - \rho_b k_{det} S_{att} + \theta k_{str}\psi_{str} C \quad (2)$$

where θ (-) is the volumetric water content, C (M L^{-3}) is the clay concentration in aqueous phase, t (T) is time, z (L) is the traveled distance, D (L^2 T^{-1}) is the dispersion coefficient for clay particles, q (L T^{-1}) is the water flux, k_{att} (T^{-1}), k_{det} (T^{-1}), and k_{str} (T^{-1}) is the first order coefficients to account for attachment, detachment, and straining ψ_{att} (-) is the attachment function, ρ_b (M L^{-3}) is the bulk density of sand column, S_{att} (M M^{-1}) is the amount of attached clay particles.

Eqs. (1) and (2) enable incorporating attachment, detachment, and straining mechanisms for explaining clay particle deposition in continuum scale. Attachment is deposition of clay particles caused by the attraction energy between clay and sand (physicochemical aspect), detachment is dislodgement of attached clay particles caused by the hydrodynamic forces, and straining is deposition of clay particles by pore size restriction (physical aspect). Therefore, the formation of filter cake can be explained by the combination of attachment and straining mechanisms (Bradford & Bettahar, 2006).

2.3 Back-calculations and long-term prediction

The three first-order coefficients shown in Eq. (2) can be back-calculated from the observed deposition profiles. For simplicity and quantitative representation of dominancy between attachment and straining, the k_{det} in Eq. (2) can be fixed as constant (assuming that the detachment is proportional to the flow rate). Dirichlet and Neumann boundary conditions were applied at the inlet and outlet of the column to solve Eq. (1). The trust region reflective least-square algorithm was selected for back-calculation and Picard iteration was used until the difference of C reached 10^{-8} times initial clay concentration in each time step.

The long-term prediction of filter cake formation can be achieved by using optimized k_{att}, k_{det}, and k_{str} obtained from relatively short-term laboratory soil-column experiments. The calculated S from optimized k_{att}, k_{det}, and k_{str} in Eq. (2) can be converted to the reduction of porosity in the sand medium. The porosity closed to zero can be the elapsed time where the perfect formation of filter cake can be anticipated at given injecting conditions.

3. RESULTS AND DISCUSSION

3.1 Observed deposition profiles

Fig. 2 illustrates the observed deposition profiles as a function of inlet kaolinite concentration (Fig. 2(a)), median sand-particle size (Fig. 2(b)), and IC (Fig. 3(c)). As shown in Fig. 2(a), the penetration depth and mass of retained kaolinite are not proportional to the inlet concentration. For example, the retained mass of kaolinite at 5 g/L of inlet concentration was less than 5 times the retained mass of kaolinite at 1 g/L of inlet concentration. Furthermore, the penetration depth of kaolinite at 5 g/L of inlet concentration is even higher than that at 1 and 2 g/L of inlet concentrations.

The formation of filter cake for ASTM graded sand (median particle size (d_{50}) = 360 μm) was observed as shown in Fig. 2(b), whereas a low mass of kaolinite was deposited at the top of the column after injection for ASTM 20/30 sand (d_{50} = 720 μm) (Fig. 2(a)). It is more or less intuitive that the deposition near the injection becomes more significant at lower d_{50}, the results shown in Fig. 2(b) indicates the presence of a threshold d_{50} where the surface deposition (i.e., straining) becomes significant at given injecting conditions. Fig. 2(c) indicates that the impact of IC is also significant on the deposition of clay particles. This implies that the controlling IC may provide the effective formation of filter cake for slurry TBM.

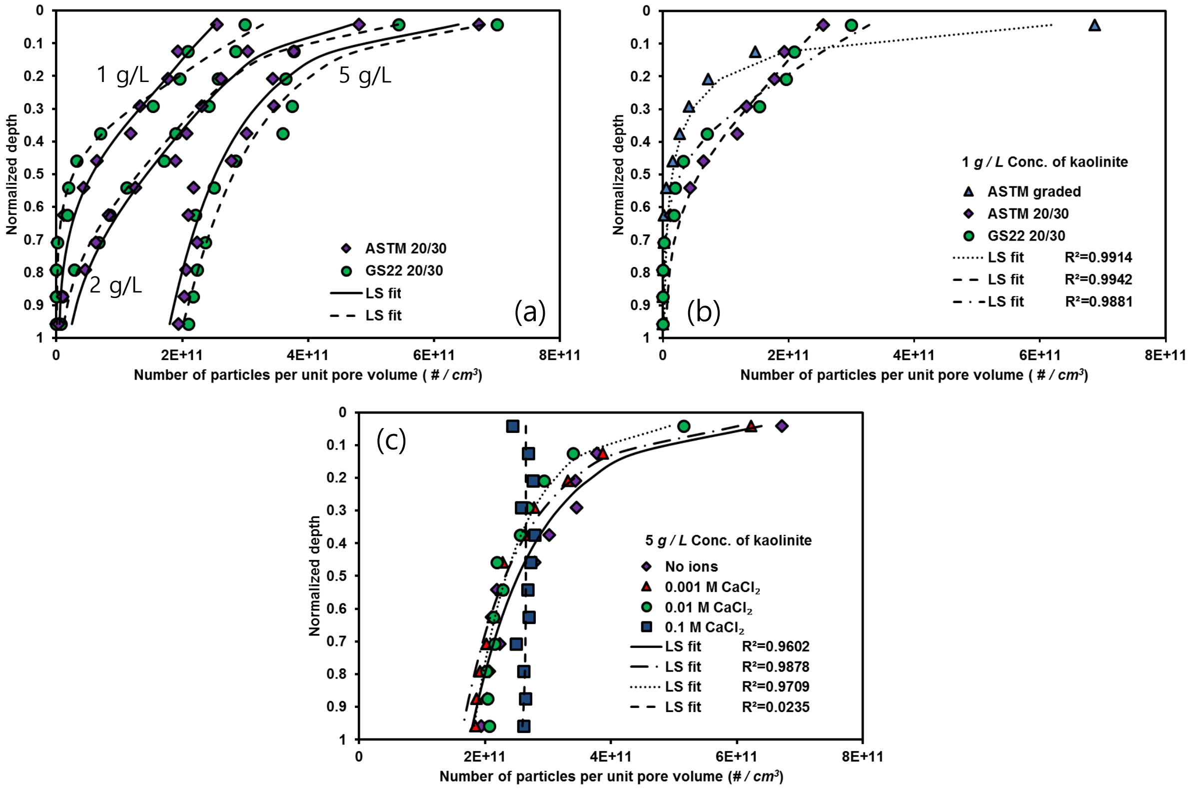

Fig. 2 Observed deposition profiles and modeled results as a function of inlet concentration (a), sand particle-size (b), and IC (c).

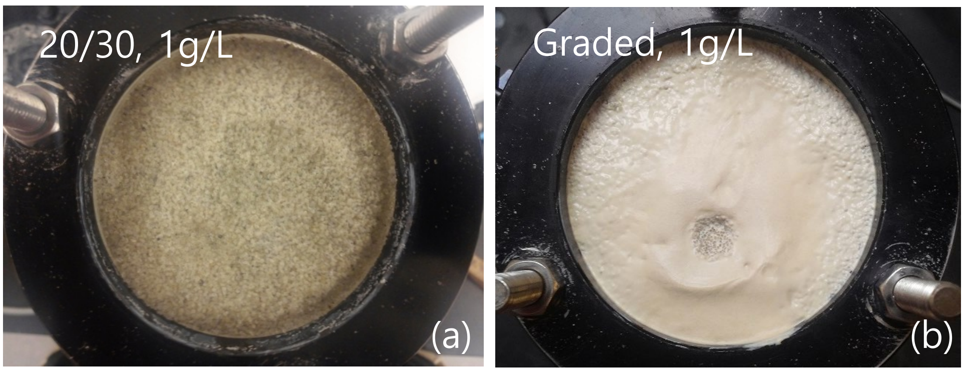

Fig. 3 Deposited kaolinite after injection at the top of the column for ASTM 20/30 sand (a) and graded sand (b) (corresponding to the deposition profiles in Fig. 2(b)).

3.2 Optimized first-order coefficients and implications in shield tunnel TBM

Table 1 shows the optimized k_{att} and k_{str} for all experimental conditions. High R^2 values shown in Table 1 implies that the model (Eqs. (1) and (2)) well explained the column experiments. In addition, higher k_{str} / k_{att} values for more exponential deposition profiles were obtained, implying that the straining mechanism is dominant over attachment mechanism for high inlet concentration, low IC, and low d_{50} of sand.

The experimental results shown in this study may not be directly relevant to the formation of bentonite filter cake as kaolinite (non-swelling clay) was used in this study and the concentration of kaolinite suspension was less than 5 g/L, which cannot represent bentonite slurry. Nevertheless, the framework shown in this study can be applicable to the long-term prediction of bentonite particle transport through permeable soils and the formation of filter cake at the excavation front. For example, the injecting conditions with relatively high k_{str} values likely leads to the formation of filter cake with low penetration depth. In contrast, relatively high k_{att} may represent the high penetration depth with low chance of forming filter cake at relatively low injection time. Further study may be required to link between the framework shown in this study and the formation of filter cake for shield TBM using bentonite.

Table 1. Optimized k_{att} and k_{str} for all experimental conditions.

Sand	Ionic concentration (M)	Inlet concentration (g/L)	k_{att} (/ s)	k_{str} (/ s)	R^2
ASTM 20/30	0	1	0.4149	0.0284	0.9942
	0	2	0.2853	0.0408	0.9911
	0	5	0.0828	0.0268	0.9599
GS 20/30	0	1	0.3911	0.0480	0.9647
	0	2	0.2738	0.0456	0.9809
	0	5	0.1078	0.0221	0.9322
ASTM graded	0	1	1.31×10^{-8}	0.2220	0.9914
ASTM 20/30	0.001	1	0.2732	0.0492	0.9857
	0.01	1	0.2555	0.0473	0.9815
	0.1	1	0.3399	0.0262	0.9729
	0.001	1	0.0658	0.0262	0.9876
	0.01	1	0.0797	0.0183	0.9705
	0.1	1	0.1795	2.19×10^{-11}	9.64×10^{-4}

4. CONCLUSIONS

This study proposed the framework of predicting the formation of filter cake for slurry TBM using the laboratory soil-column experiments. The clay suspension was injected into the saturated sand column to investigate the impact of clay concentration, ionic concentration, and sand particle-size. The chance of forming filter cake at given injecting conditions was assessed using optimized first-order coefficients representing straining and attachment mechanisms. The exponential deposition profiles for relatively significant straining mechanism shown in this study indicate the chance of predicting formation of filter cake using long-term simulation of optimized first-order coefficients obtained from soil-column experiments.

REFERENCES

Bradford, S. A., & Bettahar, M. (2006). Concentration dependent transport of colloids in saturated porous media. Journal of Contaminant Hydrology, 82(1-2), 99-117.

Bradford, S. A., Yates, S. R., Bettahar, M., & Simunek, J. (2002). Physical factors affecting the transport and fate of colloids in saturated porous media. Water resources research, 38(12), 63-1.

Min, F., Zhu, W., & Han, X. (2013). Filter cake formation for slurry shield tunneling in highly permeable sand. Tunnelling and Underground Space Technology, 38, 423-430.

Qin, S., Cheng, Y., & Zhou, W. H. (2023). State-of-the-art review on pressure infiltration behavior of bentonite slurry into saturated sand for TBM tunneling. Smart Construction and Sustainable Cities, 1(1), 14.

Xu, T., & Bezuijen, A. (2019). Experimental study on the mechanisms of bentonite slurry penetration in front of a slurry TBM. Tunnelling and Underground Space Technology, 93, 103052.