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Evaluation of grout diffusion range by grout injection methods

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ABSTRACT

Steel pipe reinforced grouting is widely employed in NATM tunnel excavation to stabilize the ground ahead of the face. With the accumulation of field experience, variations in the grouting procedure, such as sealing strategies, packer utilization, grout mixing and injection methods, and mix proportions, have emerged. In particular, the sealing process, which aims to prevent backflow of the grout, often results in significant time consumption, leading to the development of various seal-free injection methods. Representative methods include simultaneous injection and multi-stage injection using external packers. While previous studies have primarily focused on the post-injection ground stability, there remains a lack of quantitative investigation into the injection process itself and its performance. This study aims to assess the grout diffusion range under realistic field conditions using three-dimensional computational fluid dynamics (CFD) modeling. The model incorporates actual grout properties and injection sequences commonly used in steel pipe reinforced grouting. A series of parametric analyses was conducted to evaluate the influence of grout materials, injection methods, and ground properties on injection performance. The results reveal key factors governing the grout diffusion range and provide insight into the optimization of injection conditions. This study is expected to enhance the applicability of steel pipe reinforced grouting techniques.

1. INTRODUCTION

Grouting refers to the injection of a grout material into the ground with the intent of improving its engineering performance, typically by increasing stiffness, strength, and bearing capacity while reducing hydraulic conductivity (Bezuijen et al., 2011;). In tunneling, grouting is commonly performed ahead of the face and around the crown when the surrounding ground lacks sufficient shear stiffness, when faulted or crushed zones are anticipated, or when significant groundwater inflow is expected. In Korea, during NATM tunneling, steel pipe reinforcement grouting has been widely adopted (Park and Im, 2004). In this method, steel pipes are drilled and installed at prescribed spacing

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around the tunnel crown, and grout is injected so that the pipes and soil act compositely to provide both reinforcement and seepage control. After the steel pipes are placed and fixed by caulking the inlets, variants of the method are distinguished mainly by how grout is injected. The conventional approach, multi-stage grouting through steel pipes, prevents backflow by placing a sealant between the borehole wall and the pipe outer surface, and then uses a movable packer inside the pipe to sequentially pressurize multiple sections, promoting permeation into the ground. Because the sealant generally requires more than 24 hours to gel, however, this technique often delays construction and increases cost. To address these drawbacks, several seal-less procedures have recently been proposed. Although implementation details vary among contractors, they can be broadly grouped into simultaneous injection through multiple segments inside a pipe, which achieves the desired effect regardless of backflow but can demand multiple pumps or a complicated manifold, and multi-stage injection using external packers mounted between the pipe outer wall and the borehole wall, which blocks backflow externally and allows staged injection with a comparatively simple system.

This study numerically evaluates how grout spreads in the ground as a function of the injection strategy for steel pipe reinforcement grouting. Two representative no-sealing schemes are modeled: the steel-pipe simultaneous injection and the external-packer multi-stage injection. For each, the length of the injection segment assigned to a single borehole is varied. In addition, two levels of hydraulic conductivity and porosity are prescribed to represent loose and dense soils. The rheological and basic physical properties required to model the grout were obtained from simple laboratory tests, and the transient injection process was simulated using a commercial computational fluid dynamics (CFD) software. The diffusion ranges were evaluated based on injection method, and grout type, and the findings are expected to contribute to the evaluation of efficient injection processes under varying injection method.

2. GROUT VISCOSITY EVALUATION

Grouts can generally be categorized into cementitious grouts and chemical grouts (Chun et al., 2006). However, in the case of steel pipe reinforcement grouting, cement milk, prepared by mixing cement with water, is predominantly used as the primary material, except in special conditions such as cavities. To investigate the flow behavior of grout through numerical analysis, it is essential to evaluate the viscosity of the fluid. In order to initiate the flow of a stationary fluid, shear stress must be applied, and the resulting fluid velocity can be described in terms of the shear rate. Cement suspensions are classified as Bingham plastic fluids, which harden after stabilization following injection. A Bingham plastic fluid is characterized by a yield stress that must be exceeded for flow to occur, and once the flow starts, the shear stress is linearly proportional to the shear rate. Therefore, when the applied stress exceeds the yield stress, the viscosity remains constant regardless of the shear rate, allowing it to be measured using a conventional viscometer. In this study, a rotational viscometer was employed for viscosity measurements (Figure 1). Although viscosity is generally dependent on factors such as temperature and pressure, the measurements were conducted at room temperature, ignoring temperature effects. The spindle used in the experiment was selected based on the target viscosity range of the fluid; here, an LV-4 spindle with a measurement range of 1,000–2,000,000 mPa·s was utilized. The viscosity of the cement milk, prepared with a water-to-cement ratio of 135%, was measured over time under rotational speeds of 40, 50, and 60 RPM.

Fig. 1 Experimental setup for viscosity evaluation

3. NUMERICAL MODELING

A schematic of the three-dimensional numerical model developed in this study is presented in Fig. 2. The numerical analysis was conducted for a single borehole as a representative case. It was assumed that the steel pipe reinforcement grouting does not proceed forward along the borehole axis. Accordingly, the ground was modeled as a cylindrical domain with a radius of 1.5 m and a length of 12 m. The primary properties required to simulate the hydraulic behavior within the soil are porosity and intrinsic permeability. For comparison, two sets of soil properties were considered: a loose soil with a porosity of 0.4 and an intrinsic permeability of 10^{-9} m^2, and a dense soil with a porosity of 0.2 and an intrinsic permeability of 10^{-11} m^2. These values were chosen to represent ground conditions where the grouting effect is expected to be significant; the loose soil corresponds to a gravelly sand, while the dense soil corresponds to a dense sand (Bear, 1972). The steel pipe reinforcement grouting was modeled using two methods: a simultaneous injection method, where a single pump injects grout along the entire 12 m length, and a multi-stage injection method, where grout is injected in four stages of 3 m each. The initial condition for the ground was set to have a uniform pore water pressure of 200 kPa. In addition, the grout flow within the borehole was assumed to be laminar, with continuous fluid supply from the pump at a rate of 10 L/min, based on field injection conditions. Accordingly, the mass flow rate was set to 0.267 kg/s, calculated using the density of the cement milk, which is 1600 kg/m^3.

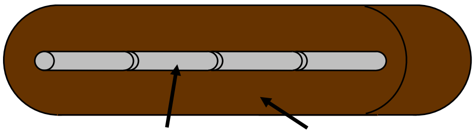

Fig. 2 Schematic for numerical modeling

4. CONCLUSIONS

In the case of loose soil, the grout exhibits a relatively wide injection range near the borehole while forming an overall uniform distribution. In contrast, for dense soil, the injection range is wide only in the vicinity of the borehole and decreases significantly beyond a certain distance. This behavior is attributed to the pressure from the pump not being fully transmitted as the distance from the borehole increases. Consequently, in dense soil with low permeability and porosity, the required pressure for grout injection and diffusion cannot be maintained beyond a certain range, leading to this observed phenomenon.

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