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Research Paper

A filtration model for evaluating maximum penetration distance of bentonite grout through granular soils

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ABSTRACT

This paper presents a filtration model for evaluating the maximum penetration distance of chemically modified bentonite grouts. High-concentration bentonite grouts require chemical modifications to increase its penetration through soils; however, this modification complicates the evaluation of the maximum penetration distance due to the changes in the physicochemical and rheological properties of the bentonite grout. In this study, the yield stresses of 7.5%, 10%, and 12% bentonite grouts modified by 1–4% sodium pyrophosphate (SPP) (by dry weight of bentonite) were determined by matching a constitutive model (Herschel–Bulkley model) to the shear stress–shear rate curves obtained through rheological tests. The bentonite grouts were injected into sand columns with an injection pressure of 35 or 140 kPa. The maximum penetration distances of the bentonite grouts through the sand columns were calculated using analytical equations (based on the yield stress of the grouts), and then compared to the measured maximum penetration distances. The results showed that the analytical equations could capture the maximum penetration distance at high yield stress (greater than 28 Pa), but the equations significantly overestimated the maximum penetration distance at low yield stress due to filtration. A new filtration model is presented in this study to estimate the maximum penetration distance of the SPP modified bentonite grouts that can provide better prediction, particularly for grouts having low yield stresses. The model was calibrated based on the 1-D column tests and then independently validated with an additional set of column tests using a bentonite with different chemical composition.

1. Introduction

Permeation grouting is an effective method to improve the engineering properties of granular soil deposits without disturbing the original soil structure. Although cement-based and chemical grouts have been widely used in permeation grouting, clay grouts, such as bentonite, can be an alternative because of its low cost and environmental friendliness compared to conventional grouts [12]. Bentonite is a common material used in various civil engineering applications, such as landfill liners, cutoff walls, and nuclear waste repositories, due to its low hydraulic conductivity [23,27]. Recent studies also showed a possible application of bentonite grouts to improve the shearing strength of granular soils under static and cyclic loading conditions [18,40,49]. For these applications, bentonite grouts are injected into granular soil deposits in the form of concentrated suspensions that develop gel-like structures inside the pore spaces over time, leading to an increase in the resistance of the treated soils to static and cyclic loading. However, high-concentration bentonite grouts (without any chemical treatment to enhance their mobility) are not commonly used in grouting practice because of their limited penetration distance and thus, high application cost. Therefore, the maximum penetration distance of concentrated bentonite grouts needs to be increased to improve its applicability in permeation grouting.

The maximum penetration distance of a particulate grout is controlled by two different possible flow stoppage mechanisms: rheological blocking and filtration. For the rheological blocking, as the grout penetrates deeper into the soil under a constant pressure, the decrease of the pressure gradient and increase of flow resistance reduce the flow rate. As the flow rate decreases, the shear rate applied on the grout flow decreases and the shear stresses developed by the flow eventually reach the yield stress of the grout, resulting in stoppage of the flow. Since the flow stoppage of the grout is controlled by its yield stress, minimizing the initial yield stress of bentonite grouts would improve its penetration into soils [3]. Various ionic additives such as sodium hydroxide, sodium

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Nomenclature

List of symbols and abbreviations

a	migrating particle radius (L)
b	standard deviation of lognormal pore radius distribution
C	concentration of a solute (M/L^3)
C_o	initial concentration of a solute (M/L^3)
Cc	coefficient of curvature
Cu	coefficient of uniformity
COV	coefficient of variation
$\mathbf{D}$	hydrodynamic dispersion tensor (L^2/T)
D	diameter of filter material (mm)
D_{10}	effective grain size of soil (mm): diameter through which 10% of total soil mass is passing (mm)
D_{30}	diameter through which 30% of total soil mass is passing (mm)
D_{60}	diameter through which 60% of total soil mass is passing (mm)
d_{95}	diameter through which 95% of total grout mass is passing (mm)
D_r	relative density (%)
e	void ratio
$e_{\min}$	minimum void ratio of sand
$e_{\max}$	maximum void ratio of sand
G_s	specific gravity
i'	hydraulic gradient
K	intrinsic permeability (L^2)
K'	flow consistency index in Herschel–Bulkley model
m	mean of lognormal pore radius distribution
N_c	Burwell's second groutability ($D_{10,\text{sand}}/d_{95,\text{bentonite}}$)
n'	flow behavior index in Herschel–Bulkley model
n	porosity
P	injection pressure (kPa)
r	pore radius (mm)
R	particle radius (mm)
SP	poorly graded sand
SPP	sodium pyrophosphate
USCS	unified soil classification system
α^*	parameter representing the effective pore length (L)
τ	shear stress (Pa)
γ	shear strain (%)
σ	specific deposit (M/L^3)
λ	deposition coefficient ($1/T$)
μ_{eq}	equilibrium apparent viscosity (mPa · s)
μ_r	relative equilibrium apparent viscosity ($\mu_{eq,\text{ grout}}/\mu_{\text{water}}$)
ϕ_1, ϕ_2, ϕ_3, ϕ_4, and ϕ_5	empirical constants
θ	lumped parameter
V	pore velocity (L/T)

chloride, and sodium polyphosphate can be used to reduce the initial yield stress of bentonite grouts [1,34,44]. These ionic additives break the network structures in the bentonite grout into smaller divisions, reducing their resistance to flow [1]. In this study, sodium pyrophosphate (SPP) is utilized because SPP significantly changes the initial rheological properties of the bentonite grouts while allowing a thixotropic increase of these properties over time (as compared to other additives for which the changes in rheological properties are relatively permanent) [19,44,51]. The phosphate anions attach to the edges of bentonite particles disrupting the formation of inter-aggregate bonds that contribute to the buildup of yield stress in bentonite grouts. This disruption leads to a reduced initial yield stress and apparent viscosity compared to unmodified grouts of similar concentrations [1,19,51]. Over time, the bentonite particles form inter-aggregate bonds under the influence of Brownian motion, leading to an increase in yield stress and apparent viscosity [51]. This time-dependent increase in yield stress and apparent viscosity is necessary for the improved strength and sustainability of the grouts [18,40,49]. Grouts in the field are often subjected to hydraulic gradients and if the yield stress of a grout is not higher than the flow induced stress, the grout will be mobilized by the ground water flow [17].

For filtration, the stoppage of particulate grout penetration depends on the relative physical configuration of the grout and soil. As flow progresses, filtration of particles occurs and the filtered particles block the flow paths, resulting in the stoppage of the flow [4,20,22]. Low particle content grouts generally have a lower risk of stoppage due to filtration, therefore, increasing the penetration of such grouts [4]. The change in flow conditions (i.e., velocity) and chemical properties of the grouts can affect the filtration process. Specifically, the increase in ionic strength due to a chemical modification of a grout can provide a favorable condition to particle deposition by changing the microstructures in the grout, resulting in a reduced grout flow [39]. Although the possibility of filtration clogging increases in the SPP modified bentonite grouts due to the increase in ionic strength (i.e., an increase in the amount of individual particles) [1,39], the SPP modification allows concentrated grouts to penetrate into sand pores where they could not have penetrated due to rheological blocking.

The hypothesis behind the new model is that the yield stress and/or filtration govern the maximum penetration distance of bentonite grouts through porous media. Particularly, filtration can be the more dominant stoppage mechanism for high-concentration grouts with low yield stresses such as the SPP modified bentonite grouts. Previous studies proposed various macroscopic flow models to simulate the filtration through soils [9,13,29,30]. In these flow models, the pore space of the matrix is represented as a network of cylindrical canals with random sizes. The flow rate in each pore throat is then calculated by solving the mass balance equation at each node of the network. The probability of a particle to be transported in a canal is proportional to the flow rate and its probability of being captured is a function of the canal and particle radii. Although these models consider the filtration phenomenon, the existing models do not capture the change in filtration due to the chemical modification of a grout and are based on constant flow rate conditions where the prediction of the pressure drop is more important than the penetration distance. The modified grouts have yield stresses that are much lower than what their concentration would indicate, and therefore, have a higher filtration compared to low concentration grouts having similar yield stresses.

This study presents the rheological properties of 7.5% (0% and 1% SPP), 10% (0%, 1%, 2%, and 3% SPP), and 12% (0%, 1%, 2%, 3%, and 4% SPP) bentonite grouts. The yield stress values were determined by fitting the Herschel–Bulkley model through the flow curves (shear stress–shear rate curves) obtained from the rheological tests. The bentonite grouts were injected into sand columns with different sand properties under a constant pressure of 35 or 140 kPa. The maximum theoretical penetration distances of the bentonite grouts through the sand columns were calculated using the analytical equations (using the yield stress of the grouts and properties of the sand column), and then compared to the measured maximum penetration distances. Finally, a new filtration model is presented in this study to better estimate the maximum