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Experimental Observation and Numerical Simulation of Cement Grout Penetration in Joints

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Abstract. This paper presents a comparison between experimental measurements and numerical estimations of penetration length of a cement grout in discrete joints. In the experiment, the joint was generated by planar acryl plates with a certain separation distance (; aperture). The joint model was designed in such a way to change the separation distance to in-situ conditions. Since a cement grout was used, the grout viscosity can be varied by controlling water-cement (W/C) ratios. Throughout these experiments, the influence of joint aperture, cement grout viscosity, and injection rate on a penetration length in a discrete joint was investigated. During the experiments, we also measured the time-dependent variation of grout viscosity due to a hardening process and included it as a function of elapsed time, in our numerical simulations, to demonstrate its impact on the estimation of penetration length. In the numerical simulations, Bingham fluid model, that has been known to be applicable to a viscous cement material, was employed. We showed from the comparison that the estimations by the current numerical approach were well comparable to the experimental measurements only in limited conditions of lower injection rates and smaller joint apertures. The difference between two approaches resulted from the fact that material separation (; bleeding) of cement grout was noticeable in higher injection rate and there could be a significant surface friction between the grout and joint planes, which are not included in the numerical simulations. The numerical simulation, meanwhile, could well demonstrate that penetration length can be significantly over-estimated without considering the time-dependency of viscosity in a cement grout

Keywords: cement grout; penetration length; Bingham fluid; time-dependent viscosity

1. Introduction

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Injection of cement grout is very popular in variety fields of civil and geotechnical engineering, which are represented by a dam foundation (Jones et al., 2018) and an underground construction work (Jamsawang et al., 2017). Clay and chemical grouts are normally too expensive and cement give a more economical and durable in underground constructions (Houlsby, 1990).

The primary objective of grouting in underground construction of rock is typically either to control water inflow, to strengthen a surrounding ground or both. All rock grouting, thus, involves the filling of existing fractures and joints and this is usually accomplished with cementitious grouts (Warner, 2004).

Underground construction, particularly in deep depths, is usually involved with a jointed rock mass. Injected grout in a subsurface jointed rock mass flows mainly through connected individual joints. Hence, the grout flow behavior should be first clearly understood in a single rock joint to be able to study grouting behavior in the jointed rock masses which containing multiple individual joints to be connected with each other. Although, the theory of grouting in rock joints is well established and the grouting performance can be estimated on a basis of good characterization of jointed rock mass, it is still difficult to accomplish a grouting exactly as designed and obtain the grouting performance as estimated, compared to homogeneous soil grouting (Zheng et al., 2016).

Grout penetration in a discrete joint has been extensively investigated either experimentally or numerically and reported that penetration is subject to mainly grout material properties and geometry of joint (Azimian and Ajalloeian, 2015; Chegbeleh et al., 2009; Hassler et al., 1991; Ghafar et al., 2017; Mohammed et al., 2015; Rahman et al., 2017; Saedi et al., 2013; Sohrabi-Bidar et al., 2016; Sui et al., 2015; Tani, 2012; Xiao et al., 2017). The comparison, however, between both experiments and numerical simulations have been seldom published.

Viscosity of cement grout is one of the influential parameters governing the penetration length which can even vary during the period of injection due to its hardening process. Kobayashi and Stille (2007) has first reported that the viscosity increment along with its hardening may reduce the penetration length remarkably depending on the level of water to cement (W/C) ratio. A time-dependent model of the cement viscosity thus should be established in a proper manner through laboratory experiments to be used in estimating grout injection performance by numerical approach.

Applicability of Bingham fluid model and its theoretical development in simulating a cement grout flow was first contributed by Gustafson and Stille (2005) and followed by Tani (2012) and Gustafson et al. (2013). Using coupled hydraulic-mechanical simulation of 1D Bingham flow through a single joint, authors have demonstrated that joint aperture change, induced by injection pressure, may affect the grout penetration length significantly (Kim et al., 2018). In the simulations, the effect of roughness as well as injection-induced aperture change were studied on penetration length and they were in a good agreement with the available analytical solution (Gustafson and Stille, 1996). We extended our numerical simulation to 2D in this study but, only the hydraulic analysis was used, since the grout injection pressure was not sufficient enough to cause a mechanical deformation of joint aperture.

In this paper, cement grout penetration behavior in a circular planar joint is investigated both experimentally and numerically. The numerical results of the grout penetration is verified by means of experimental observation of penetration behavior in a smooth wall joint. The Bingham fluid model in UDEC, which should be adequate within the range of W/C ratio between 1.0 and 2.0 (Li et al., 2017), is adopted to simulate a viscous cement grout flow in the joint.