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Review

Protection against water or mud inrush in tunnels by grouting: A review

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ABSTRACT

Grouting is a major method used to prevent water and mud inrush in tunnels and underground engineering. In this paper, the current situation of control and prevention of water and mud inrush is summarized and recent advances in relevant theories, grout/equipment, and critical techniques are introduced. The time-variant equations of grout viscosity at different volumetric ratios were obtained based on the constitutive relation of typical fast curing grouts. A large-scale dynamic grouting model testing system (4000 mm × 2000 mm × 5 mm) was developed, and the diffusions of cement and fast curing grouts in dynamic water grouting were investigated. The results reveal that the diffusions of cement grouts and fast curing grouts are U-shaped and asymmetric elliptical, respectively. A multi-parameter real-time monitoring system ($\phi = 1.5$ m, $h = 1.2$ m) was developed for the grouting process to study the diffusion and reinforcement mechanism of grouting in water-rich faulted zone. A high early strength cream-type reinforcing/plugging grout, a high permeability nano-scale silica gel grout, and a high-expansion filling grout were proposed for the control of water hazards in weak water-rich faulted zone rocks, water inrush in karst passages, and micro-crack water inrush, respectively. Complement technologies and equipment for industrial applications were also proposed. Additionally, a novel full-life periodic dynamic water grouting with the critical grouting borehole as the core was proposed. The key techniques for the control of water inrush in water-rich faulted zone, jointed fissures and karst passages, and micro-crack water inrush were developed.

1. Introduction

Due to the rapidly increasing need for construction of underground engineering in China, various challenges have emerged as a result of complicated geological conditions of underground constructions. A typical challenge is the water inrush issue (Kuang et al., 2001; Yang et al., 2001; Ge, 2006). The percentage of long karst tunnels exceeds 40% in average and may be up to 65% in southwest and central south regions in China (Wang, 2004; Zhang and Fu, 2007; Qian, 2012; Hong, 2015). In most projects, water inrush issue was more or less observed. Surveys and previous reports reveal that 50% of domestic underground engineering are constructed in karst areas, and several major disasters caused by water inrush have been observed. Due to the complicated and challenging rescue process involved, sudden water inflow may cause severe casualty and huge economic loss. On the other hand, groundwater discharge is a waste of natural water resources and can lead to a significant reduction of the groundwater level, resulting in insufficient water supply and ecological deterioration in local area. In extreme cases, geological disasters such as large-scale karst collapses and ground fissures may be observed. Currently, grouting is the most commonly used method for prevention of water inflows. Considerable efforts have been made in the study of working principles, materials used, and techniques involved. In China, dynamic water grouting has been applied in mining activities since the 1950s, while researches regarding the fundamental principles did not attract attentions until the 2000s. Liu et al. (2011a) reported VCH, a novel grouting method, and analyzed its performance in dynamic water grouting. Also, the ratio of VCH in practical applications was optimized based on on-site

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measurements (Liu et al., 2011b). Li et al. (2013a,b) proposed the phase interface of grouts in dynamic water grouting by investigating the morphology of grout/water interface in the cases where different grouts were involved. Taking the time-variant nature of grout viscosity into account, the cement/water glass grout and polymer-modified cement grout are fast curing grouts widely used and are studied by laboratory tests. Nevertheless, the diffusion of grout in dynamic water grouting where water exhibits a considerable flow rate has not been fully understood (Axelsson and Gustafson, 2009; Gothäll and Stille, 2010; Li et al., 2011; Yang et al., 2011; Mohammed et al., 2015; Rafi and Stille, 2015; Sui et al., 2015). As a result, the principles of water-plugging by grouting remain to be clarified, as it is currently an empirical process. Meanwhile, determinations of grouting parameters (especially the grouting pressure) and process design are still empirical and the grouting techniques exhibit poor repeatability and wall rock instability, resulting in secondary disasters such as collapse and roof fall.

Previous studies (Wang et al., 2000; Xu and Fan, 2009; Xiao et al., 2010a,b) revealed that acid sodium silicate based grouts exhibited improved gel strength as the content of $CaCO_3$ increased (at constant H_2SO_4 content), and the critical point of gelation time was obtained. These grouting results have been demonstrated to be effective for cases where the flow rates were low. Modifications of conventional polyurethane grouts have also been reported (Feng and Kang, 2010; Ding et al., 2013; Feng et al., 2013; Wang et al., 2015). Three-dimensional (3D) interpenetrating networks consisting of organic (polyurethane) and inorganic (hydrated silica) phases have been obtained by polyurethane modification. These structures showed superior mechanical performance and non-flammable nature, which were suitable for industrial applications. Various grouting methods for underground engineering have also been reported and these grouting materials showed excellent performances. However, few studies of grouts specifically for dynamic water grouting have been reported (Axelsson and Gustafson, 2009; Akiyama and Kawasaki, 2012; Duan et al., 2012; Baltazar et al., 2014; Lu et al., 2014; Yang et al., 2014; Güllü, 2015; Indacoechea-Vega et al., 2015). Due to the high cost, strength degradation, toxicity, and short service lifetime, currently polymer materials are rarely used in dynamic water grouting. Therefore, improvements on these materials are of great significance.

As a geological disaster commonly observed in tunnels and underground constructions, water inrush leads to significant changes in the effective stress of strata and flow conditions of groundwater, resulting in exploitation/contamination of groundwater and ground settlement. Accordingly, the contamination of groundwater may affect the local ecosystem and residents. Previous studies proposed the method of pressure reduction by drainage, in which the water was drained by immersible pumps via vertical boreholes (active protection). Immersible pumps with large lift, high drainage discharge, and high power were introduced to this method. Also, groundwater control in soft layers by air pressure was combined with the new Austrian tunneling method (NATM) for construction of the tunnels in the English Channel. Since its first application in mines by Poetsch in 1883, artificial strata freezing techniques have been intensively studied and widely used for underground engineering. Due to the great advancements in grouting, the water-plugging method has attracted increasing attention in underground engineering. In this method, water channels were plugged by grouted curtains. Nevertheless, several limitations have been observed for this method. First, the thickness of the grouting reinforcement ring was designed based on the wall rock thickness at that time prior to construction, instead of the wall rock thickness after 10 or 20 years of operation. Second, the grouting design is an empirical process and most designs exhibit poor systematic compatibility. Arrangements of key boreholes are not well optimized. Third, the long-term functioning of grouting systems designed has not been fully investigated.

Despite the great achievements at this stage, increasingly complicated geological environments have been encountered in underground engineering and no systematic solutions have been proposed for addressing water inrush issues. Based on different water inrush cases, a full-life multi-purpose water inrush control approach is proposed in this study. Additionally, methods for the control of water inrush in water-rich faulted zone, jointed fissures and karst passages, and micro-crack water inrush are developed.

While great achievements have been made in the working principles and materials of grouting in tunnels and underground engineering, few studies of grouting mechanism and materials specifically for dynamic water grouting have been reported. Therefore, investigating the diffusion of materials in the grouting process is of great importance in order to develop improved grouts for dynamic water grouting. Practical factors such as safety and lifecycle issues of constructions should be considered in the design process to achieve precise control of water inflow prevention.

2. Advances in theory study

Grouting has attracted increasing attention globally and significant advances in the theories related to grouting have been reported. Based on fluid and solid mechanics, grouting studies are mainly focused on the flow of grouting in the stratum in terms of parameters such as grouting pressure, grouting flow rate, diffusion radius and grouting time to provide references for the design and execution of grouting process. Grouting theories proposed include the permeation grouting theory (Han, 2014; Liu et al., 2015; Yang et al., 2015), fissure grouting theory (Gothäll and Stille, 2009; Li et al., 2015; Zhang et al., 2015a,b), compaction grouting theory (Zou et al., 2006; Zou, 2007), and fracture grouting theory (Zhang et al., 2011a, 2011b, 2013; Zou et al., 2013; Li et al., 2014). However, the grouting time-dependent nature and grout/water interactions have not been included in the theories as mentioned above.

2.1. Constitutive model of typical grouts

Previous studies of grouting diffusion in the grouting process concentrated on the flow field of groundwater, grouting properties and grouting method used, while the time-variant nature of various parameters in the phase transition of grouts was not intensively investigated. As a result, the practical grouting processes may not be accurately predicted. The time-variant viscosity curves of polymer-modified cement grouting (Fig. 1) were obtained based on laboratory tests and on-site measurements (Li et al., 2013a,b).

As is shown, the viscosity curve of cement/water glass grouting can be divided into the low viscosity stage, the increasing stage, and the solidification stage. In the first stage, the viscosity is low, as well as its increasing rate. Then, the viscosity increases rapidly and a primary solidification is achieved, followed by a quick thickening phenomenon. At the end of this stage, the grout is a mushy solid–liquid mixture with considerable fluidity. In the final stage, the mixture is fully solidified and exhibits negligible fluidity.