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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.

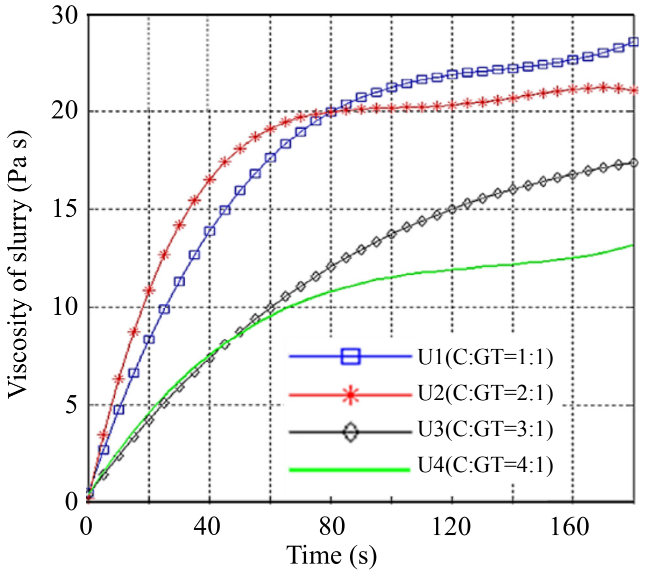


Fig. 1. Time-variant viscosity curves of typical grouts.

On the other hand, the viscosity curve of polymer-modified cement grouting consists of two sections. The viscosity shows a rapid increase in the first section and stays at a certain level for a considerable duration. In this stage, the grouting is regarded as a viscoplasticity flow with reasonable fluidity and good dynamic water resistance. The results after curve fitting are shown in Table 1.

2.2. Modeling of dynamic water grouting and studies of water-plugging by grouting

Previous studies reveal that fissures are the main causes of water inrush issues as they serve as water channels. Therefore, prevention of fissure-caused water inrush should be paid more attention to the construction period of underground engineering. Nevertheless, progress in this field (especially in dynamic water grouting) is relatively slow compared with grouts and grouting techniques. Due to the effects of groundwater flow, the diffusion of grout in a dynamic water grouting process is more complicated compared to that in still water. Hence, more efforts are required to fully understand the grouting diffusion in dynamic water grouting cases. As an attempt, a model for fissure-caused dynamic water grouting and an experimental set-up based on the model are proposed (Zhang et al., 2011a, 2011b, 2015a, 2015b; Liu, 2012). The fissure size is designed to be 4 m × 2 m × 5 mm. Fracture length is 4 m, fracture width is 2 m, and aperture is 5 mm. The experimental set-up consists of visualized table, control system, dynamic water simulation system, grouting system, and real-time monitoring system (see Fig. 2), which enables multi-parameter (e.g., flow rate, flow direction, pressure, and temperature) simulation and real-time monitoring of the grouting diffusion process under different environments and grouting conditions.

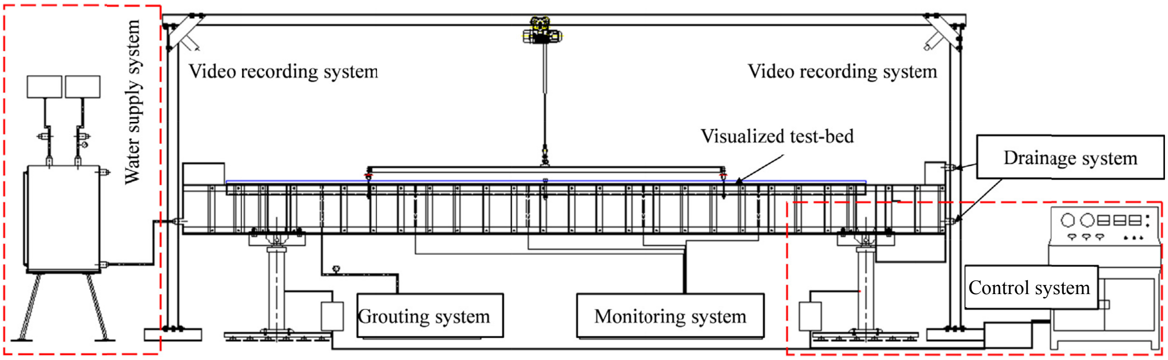
Stabilized diffusion pattern of cement grout is shown in Fig. 3. Based on a series of simulations and successive statistical analysis, U-shaped diffusion mechanism is proposed for the grouting, and layer-dependent diffusion mechanism is suggested for the cement grout. Also, it is demonstrated that this process is dominated by rapid and gravity-driven water depositions. Based on the diffusion pattern, the grouting diffusion area can be divided into filling diffusion zone, transition diffusion zone, and layer-dependent diffusion zone. In the layer-dependent diffusion zone, the grouting diffuses in a layer separated from the one of water flow in the fissure and no interactions are observed between the two layers.

Concerning the factors affecting the cement grouting diffusion in dynamic water, the grout flow ratio (ξ) is introduced. The grouting diffusion process is described using a ξ-based formula, and

Table 1
Time-variant viscosities of fast curing grouts.

Types of slurry	Water-cement ratio of cement grouting	Volume ratio	Equations of time-dependent viscosity	Scope of application
Cement-sodium silicate slurry	1:1	1:1	$\mu_1 = 0.003182t^{2.23}$	$t = 0–180$ s; $T = 20$ °C; No additives
		2:1	$\mu_2 = 0.008427t^{2.694}$	
		3:1	$\mu_3 = 0.01864t^{2.066}$	
	2:1	1:1	$\mu_4 = 1.422 \times 10^{-8}t^{4.215}$	
		2:1	$\mu_5 = 4.763 \times 10^{-6}t^{3.173}$	
Polymer modification materials	1:1	1:1	$\mu_6 = -7.89 \times 10^{-6}t^3 - 0.003195t^2 + 0.4467t + 0.6$	
		2:1	$\mu_7 = -1.005 \times 10^{-7}t^4 + 4.938 \times 10^{-5}t^3 - 0.008796t^2 + 0.6848t + 0.3$	
	2:1	1:1	$\mu_8 = 1.362 \times 10^{-6}t^3 - 8.608 \times 10^{-4}t^2 - 0.2046t + 0.5$	
		2:1	$\mu_9 = 4.303 \times 10^{-6}t^3 - 0.001705t^2 + 0.2378t + 0.5$	

Note: μ_i ($i = 1–9$) is the time-variant grout viscosity function of grout curing time t.



(a) Schematic illustration of the set-up.

(b) Experimental set-up.

Fig. 2. Model of dynamic water grouting and the experimental set-up used.

Fig. 3. Stabilized diffusion pattern of cement grout.

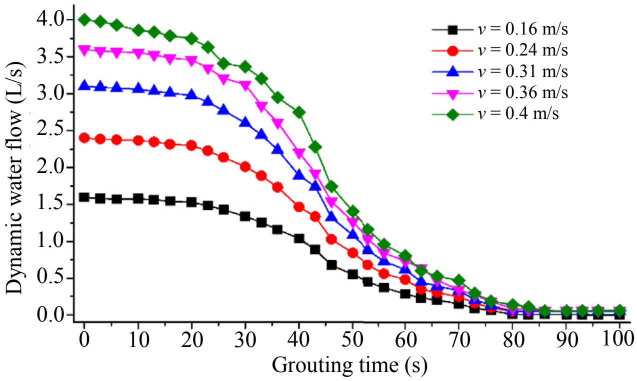
the relation between ξ and the diffusion opening (or reverse diffusion distance) is investigated. The water-plugging in dynamic water grouting could be attributed to the deposition flowing core area. The range of ξ for effective deposition by gravity is determined as $\xi \in [0.15, 1.5]$.

Due to their excellent dynamic water resistance and high retention rate, fast curing grouts have been widely applied in dynamic water grouting. The unique properties of these grouts result in different diffusion principles (compared with that of conventional grouts). Hence, single-plate fissure dynamic water grouting experiments are conducted on typical fast curing grouts to investigate the grouting diffusion pattern, grouting pressure distribution, grouting retention rate, and dynamic water flow rate. The grouting test results are shown in Fig. 4. The results reveal the asymmetric elliptical (AE) diffusion of fissured dynamic water grouting, meaning that the diffusion of fast curing grouting in dynamic water could be described by a time-variant AE curve. The curves of parameters in the AE diffusion were fitted based on the grout/water flow rate ratio. The reverse diffusion distance and diffusion opening are proportional to the grout/water flow rate ratio, while the forward diffusion distance is negatively related to the grout/water flow rate ratio. A transient equation is developed to describe the grouting diffusion in dynamic water.

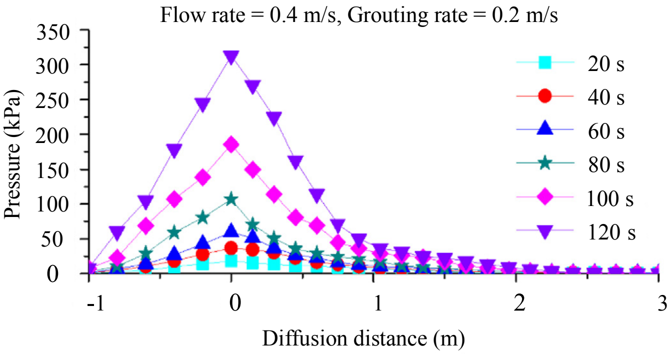
At low dynamic flow rates, fast curing grouts show high retention rate; at high dynamic flow rates, the retention rate decreases drastically. The grouting pressure exhibits nonlinear degradation from the grouting borehole outwards, while the degradation rate decreases gradually. As the grouting continues, a significant variation is observed on the pressure field in the vicinity of the grouting borehole, while the pressure field at the flow exited exhibits negligible variations. To achieve effective plugging by the grouting at a certain moment, the following conditions should be satisfied:

(1) Grouting diffusion opening is equal to the fissure width, and

(a) Transient diffusion patterns of fast curing grout under dynamic water condition.



(b) Variations of dynamic water flow (v is the initial dynamic water flow velocity).



(c) Spatiotemporal evolution of pressure fields.

Fig. 4. Diffusion of fast curing grouts: (a) Transient diffusion patterns of fast curing grout in dynamic water grouting; (b) Variations of Dynamic water flow; and (c) Spatiotemporal evolution of pressure fields.

(2) The compressive strength and plastic shear stress of cured grout at the flow cross-section boundary are larger than the hydrostatic pressure so that grout plug is induced.

The grouting borehole pressure is lower than the designed ultimate grouting pressure, the maximum allowable grouting pressure, and the critical pressure for wall rock stability. The effects of groundwater (flow rate and pressure), grouting techniques (grouting pressure and grout flow rate), and properties of grouts (curing) on the water-plugging by grouting are included. The mathematical equations are written as follows:

(1) The criterion for diffusion opening

The diffusion opening can be expressed as

$$B_{\max} = 157.4\xi + 29.2 = W \tag{1}$$

where $B_{\max}$ is the maximum diffusion opening, and W is the width of crack.

(2) The criterion for yield shear stress

The yield shear stress can be written as

$$\left.\begin{aligned} \tau_t &\ge p_0 + p_f \\ \sigma_t &\ge p_0 + p_f \end{aligned}\right\} \tag{2}$$

where τ_t is the plastic shear stress of the grout at time t, σ_t is the compressive strength of cured grout at time t, p_0 is the static

Fig. 5. Image of the 3D simulation experimental set-up.

pressure of groundwater, and p_f is the additional pressure caused by grouting.

(3) The criterion for grouting pressure

The grouting pressure can be expressed as

$$p_c \le \min(p_d, \sigma_c, p_s) \tag{3}$$

where p_c is the grouting pressure at time t, p_d is the grouting pressure designed, σ_c is the critical stress of wall rock, and p_s is the maximum grouting pressure provided by the equipment used.

2.3. Water-rich faulted zone reinforcement by grouting and wall rock stability

As a good candidate for reinforcement, water-plugging, and anti-leakage applications, grouting has been widely used in transportation, mining, land development, and heritage preservation. As the grouting process is affected by the grouting medium, geological environment, grouts, and grouting techniques, the diffusion of grout is a complicated process. The reinforcement by grouting shows significant spatial variability. Hence, it is extremely challenging to investigate the stress, deformation and stability of rocks in the grouting process using conventional analytical and numerical methods. In order to overcome this limitation, a 3D simulation experimental set-up (as shown in Figs. 5 and 6) has been proposed (Zhang, 2014). In this set-up, multi-borehole, sequenced prototype curtain grouting was applied to the water-rich faulted zone. By monitoring the displacement, seepage volume force and soil pressure, the deformations of grouting rocks and wall rocks of faulted zone were investigated to obtain the effectiveness and reliability of reinforced rocks. The 3D simulation experimental set-up can describe the faulted zone vibration, curtain grouting reinforcement, and excavation to facilitate the evaluation of grouting process and wall rock stability. This experimental set-up consists of

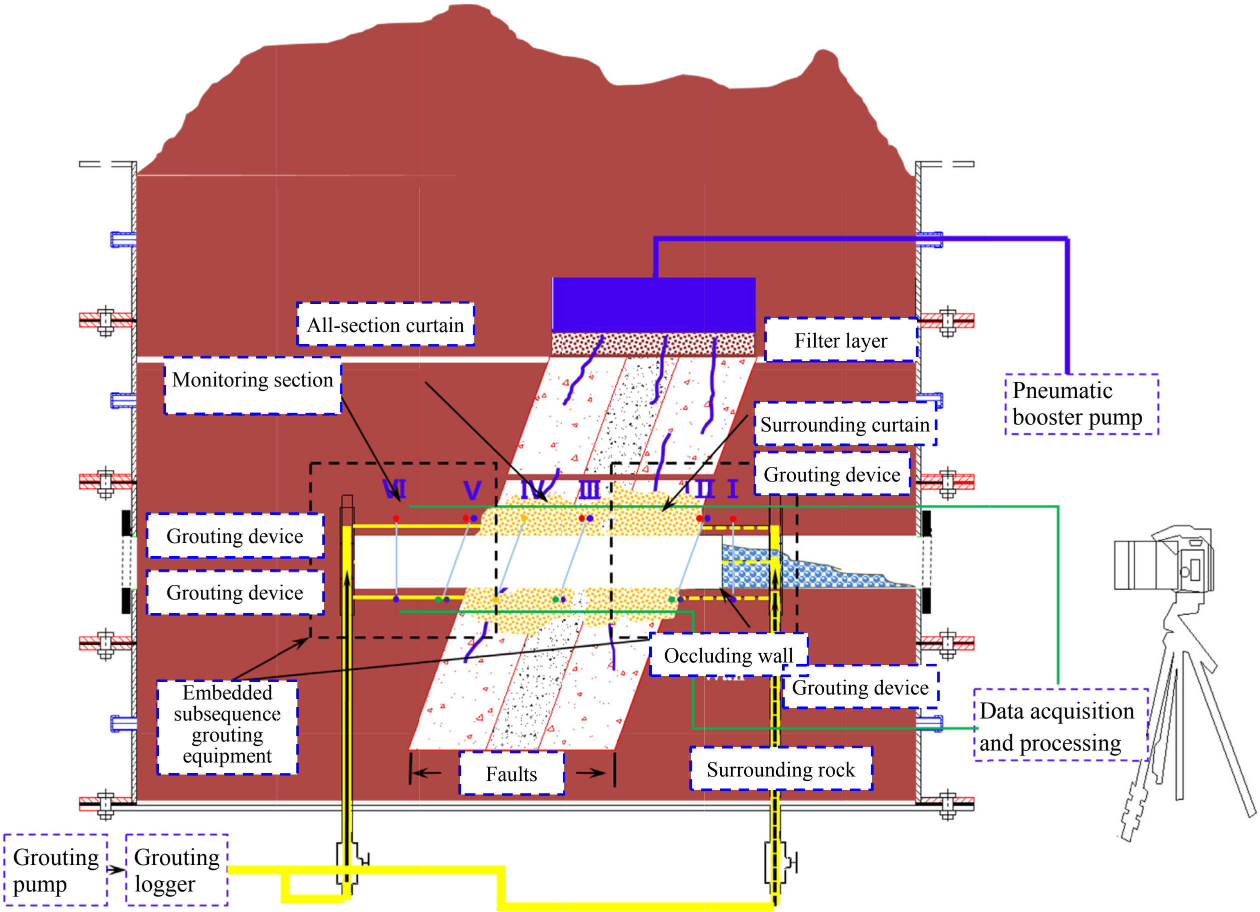


Fig. 6. Schematic of the 3D simulation experimental set-up.

a stand, a water supply system, a double-grouting system, a multi-parameter monitoring system, and a real-time image capturing system. The internal structure size of the set-up was $\phi 1.5$ m × 1.2 m (height).

Based on multi-parameter data and analyses (as shown in Figs. 7 and 8), the soil pressure, the seepage volume force, and the displacement can be investigated. The spatiotemporal effect of load transfer is demonstrated, and the preferred channels of grouting diffusion are revealed. It shows that both the soil pressure and seepage volume force increase drastically with the grouting pressure, and the response time of seepage volume force is significantly shorter than that of the soil pressure. The response time and intensity of the monitoring point are dependent of the relative position of this point and the diffusion route of grouts. Specifically, the relative position of the monitoring point is dominant in undisturbed grouting cases, while the preferred diffusion route of grouts has a significant effect on these parameters in vibrational grouting cases. The reinforcing modes in undisturbed grouting and vibrational grouting are penetration-fracture grouting and filling-compaction-fracture grouting (a supporting cement cavity is observed). The preferred diffusion routes are the top and bottom of the tunnel vault.

The soil pressure, osmotic pressure and displacement under vibration and cascaded head pressures are monitored to investigate the stability of faulted zone reinforced by grouting. The results reveal that the stability of rocks in the faulted zone is markedly improved, although further improvements are essential. Grouting weak areas containing preferred diffusion channels are observed at the intersection of wall rocks and faulted zone. The safety degree

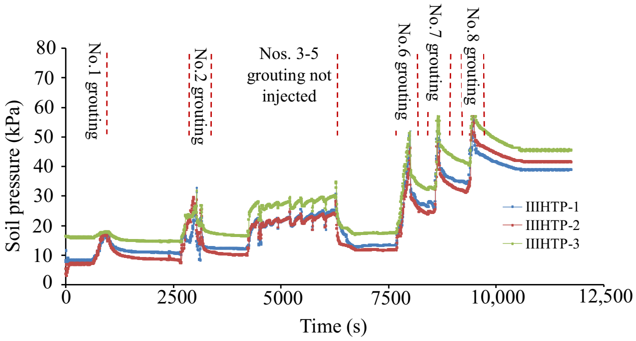


Fig. 7. Soil pressure of the faulted zone.

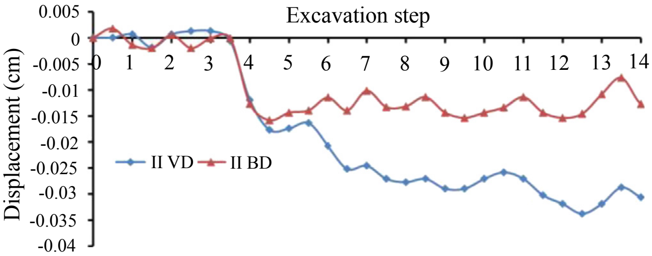
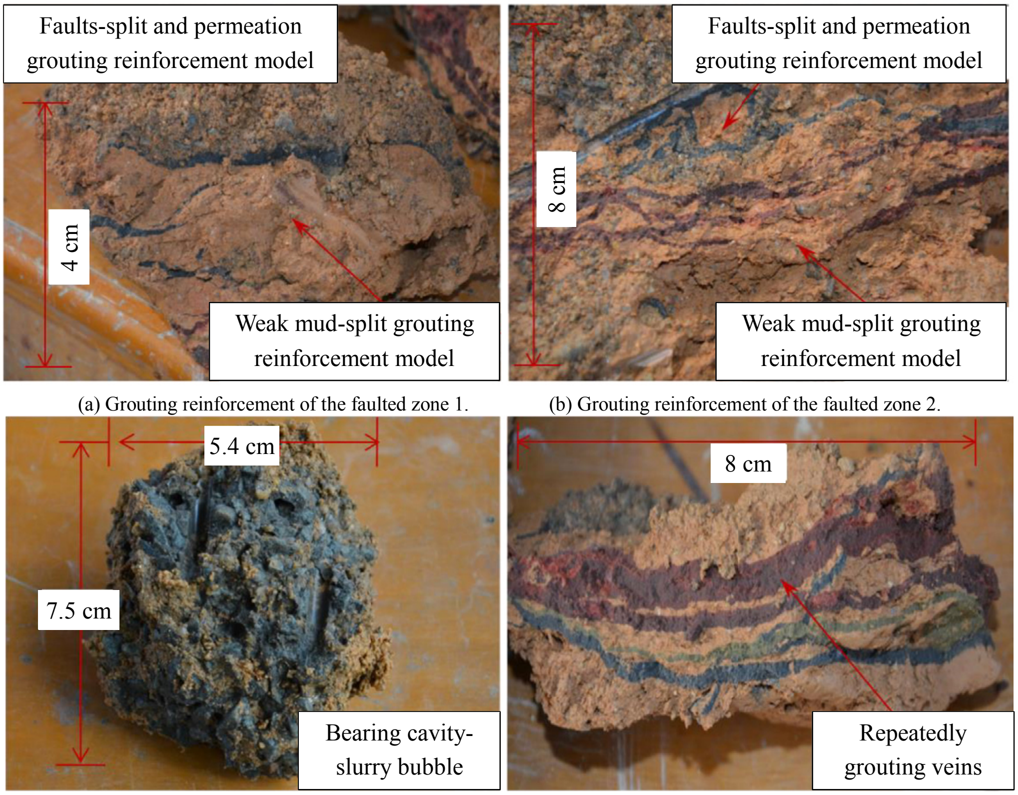


Fig. 8. Vertical displacement of the monitoring points on the cross-section II.



(a) Grouting reinforcement of the faulted zone 1. (b) Grouting reinforcement of the faulted zone 2.

(c) Grout bubbles in the faulted zone in vibrational grouting. (d) Layered fracture grout vein.

Fig. 9. Parts reinforced by grouting: (a) Grouting reinforcement of the faulted zone 1, (b) Grouting reinforcement of the faulted zone 2, (c) Grout bubbles in the faulted zone in vibrational grouting, and (d) Layered fracture grout vein.

(*K*), which is an indicator of the overall grouting process, is 4.5 in this case, indicating good grouting effects.

As shown in Fig. 9, no clear shape is observed for the grouting reinforced parts in the faulted zone and the reinforcing area is 1–3.1 times the radius of drilling hole. Filling grout bubbles are observed in the supporting cavities of vibrational zone. Connected to the major grouting veins at the top and bottom of tunnel vault, the supporting cavities are not properly attached to the wall rocks, resulting in grouting weak areas. Additionally, lamination is observed in the major grout veins, demonstrating the repeated fractures in multi-sequenced grouting.

3. Advances in equipment and materials

Dynamic water grouting refers to the control of water and mud inrush, which is a challenging process requiring excellent performance of grouts. Grouts currently used can be categorized into chemical grouts and cement-based fast curing grouts. However, these materials are limited by short service life due to the continuous interactions with the dynamic water. Targeted at common issues such as water inrush and water-rich strata/channel in weak faulted zone, novel grouts and techniques have been proposed and optimized based on on-site measurements.

3.1. Cement-based high early strength water-plugging materials

In underground engineering, the groundwater flow conditions in weak water-rich faulted zone are altered by vibrations from field excavation, resulting in interstitial flow, channel flow or even large-scale inrush of pressured groundwater. Grouting and water-plugging can effectively improve the strength and overall performance of rock masses in the weak water-rich faulted zone. However, as direct plugging is challenging and may lead to collapse of wall rocks, reinforcement is basically employed in most cases, while this technique requires high cost and long construction durations. Therefore, a novel high early strength reinforcing/plugging grout (Table 2 and Fig. 10) is proposed. Besides the high early strength, this material exhibits rapid increase in the strength (e.g., the 1 d compressive strength is 8.5 times higher than that of conventional 42.5 silicate cement) and good adhesive strength. As a result, the stability and wash resistance of rocks in this zone are significantly improved, resulting in rapid water-plugging.

3.2. High expansion polyurethane for water-plugging

As a major issue in underground constructions in karst areas, the channel water inrush leads to severe risks in underground engineering. Due to the hidden channels networks, underground rivers and cavities, the groundwater can easily rush into underground structures in karst areas. As a result, the channel water inrush is regarded as the dominant cause of geological catastrophes in underground engineering (e.g., tunnels, mines, hydropower stations). Additionally, the early stage of water inrush is usually the release of static reserves such as hidden rivers and other water body resources, and the flow rate and hydrostatic pressure of flows in these cases are relatively high. Water-plugging using conventional grouts are not effective due to the poor wash resistance of these materials. Therefore, a high pressure polymer water-plugging grout (see Table 3 and Fig. 10) is proposed. This material exhibited rapid reaction (cured plugger in 30–50 s), high expansion ratio (e.g., 30), negligible water-dependence, low amount required, and non-toxicity.

Table 2
Cement-based high early strength water-plugging/reinforcement materials.

Material	Flexural strength/Compressive strength (MPa)		
	t = 1 d	*t* = 3 d	*t* = 7 d
42.5 Silicate cement	0.21/0.67	1.23/6.83	2.92/14.21
New materials	1.62/5.71	2.93/12.62	4.67/19.62

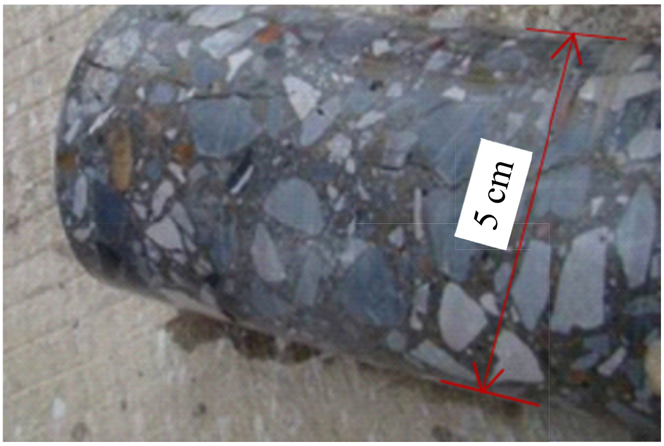


Fig. 10. Schematic illustration of water-plugging/reinforcement by grouting.

Table 3
Performances of high expansion polyurethane for water-plugging.

Flow time (s)	Curing time (s)	Combustibility	Toxicity	Expansion ratio	Water-dependence
10–30	30–50	Non-combustible	N.A.	20–30	N.A.

3.3. Strong penetration silicone for grouting

Upon grouting, the initial fissures and some structural fissures in the wall rocks are intermittently distributed, resulting in limited water conducting capability. However, the stress conditions are significantly changed by the underground constructions and fissure propagations due to the hydraulic fracturing effect observed. These large fissures can act as water channels and water inrush issues occur. On the other hand, water-rich strata with high porosity and connectivity (e.g., porous sandstone and micro-crack rocks) are also frequently encountered in underground engineering. In this case, the injection of conventional grout is not effective due to the micro-sized pores/fissures. To overcome this difficulty, a nano-scale silicon grout (see Table 4 and Fig. 11) with strong penetration (minimum fissure size of 0.01 mm), tunable curing time, and ultra-low viscosity (10 mPa s) is proposed.

Table 4
Performances of strong penetration silicone for grouting.

Curing time	Initial viscosity at 20 °C (mPa s)	Minimum grouting fissure (mm)	Impermeability pressure (MPa)	7 d compressive strength (MPa)	pH value
10 min–7 h	10	0.01	4.5	45	9.8

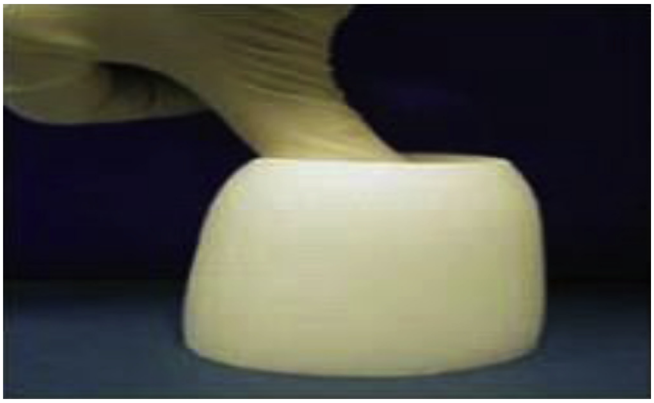


Fig. 11. Strong penetration silicone for grouting.

3.4. Grouting equipment and techniques

Conventional grouting equipment shows reduced effectiveness in projects with complicated conditions of the groundwater flow and grouting, and a dynamic yet accurate tuning of fluid ratio is not achieved. Hence, two specified pumps for grouting have been introduced:

(1) Continuous tuning high pressure pneumatic grouting pump (Fig. 12a)

This pump shows high rated pressure (12.5 MPa), high pulse frequency (1 cycle/s at 10 MPa), and tunable fluid ratio between 1:5 and 5:1, thus real-time adjustment of grouts can be realized.

(2) High-pressure, large-flow fully hydraulic grouting pump (Fig. 12b)

This pump shows high pressure (21 MPa), large flow (100 L/min), and large tuning range of fluid ratio (1:0 to 1:1), thus achieving rapid plugging in large flow cases.

Additionally, a series of auxiliary devices has been reported. These devices include double-fluid grouter, plugger for inrush borehole, real-time pressure meter for the grouting pressure, pressured penetration grouter, and large-flow aggregate feeder. Together with these devices, novel grouting equipment and materials enable the effective control of severe water inrush accidents.

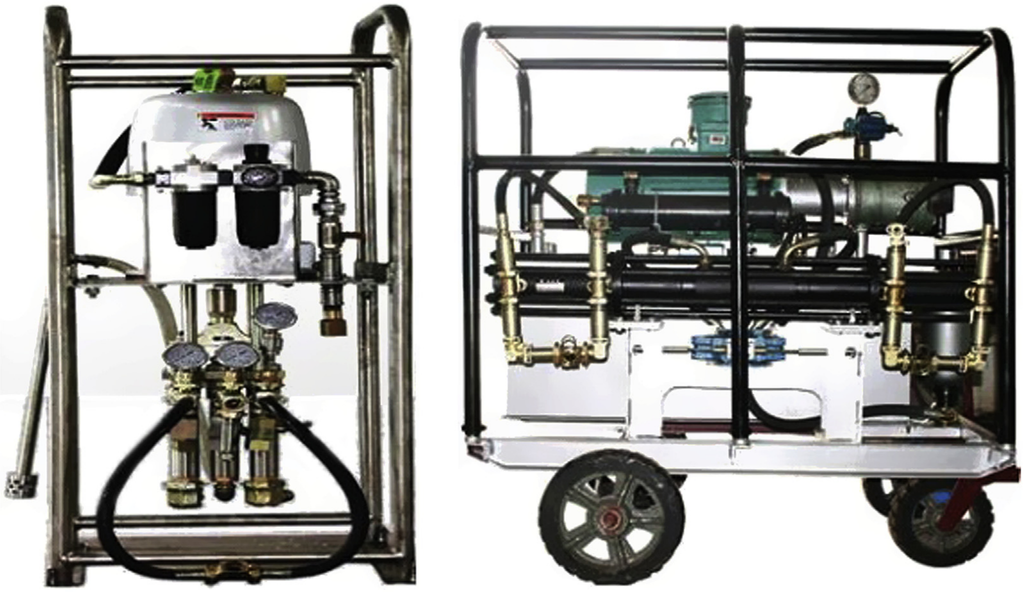
4. Water inrush control and grouting design

4.1. Full-life, multi-purpose water inrush control

A full-life, multi-purpose water inrush control approach refers to as an approach involving detections of water channels and a control plan considering the safety of constructions in their entire service lifetime. The design of the key borehole (Zhang, 2011) is optimized and the approach is designed based on the feedback-optimization pattern.

Based on accurate channel detection, key borehole design and safety control techniques, an effective and reliable approach for the dynamic control of water inrush issues is proposed (see Fig. 13). Previous grouting techniques rely on empirical data and cases, and theoretical guidance is absent. To address this issue, an approach based on key borehole optimization is developed for dynamic control of water inrush. As a result, the plugging effectiveness is improved at a significantly reduced cost. The supporting capability of wall rocks can be significantly increased by borehole far-end plugging, thus eliminating secondary water inrush and other secondary accidents. The key points are described as follows:

(1) The 3D pattern and flow field characteristics of water channels are obtained by accurate detection and flow calculation.



(a) (b)

Fig. 12. Novel grouting equipment: (a) Continuous tuning high pressure pneumatic grouting pump, and (b) High-pressure, large-flow fully hydraulic grouting pump.

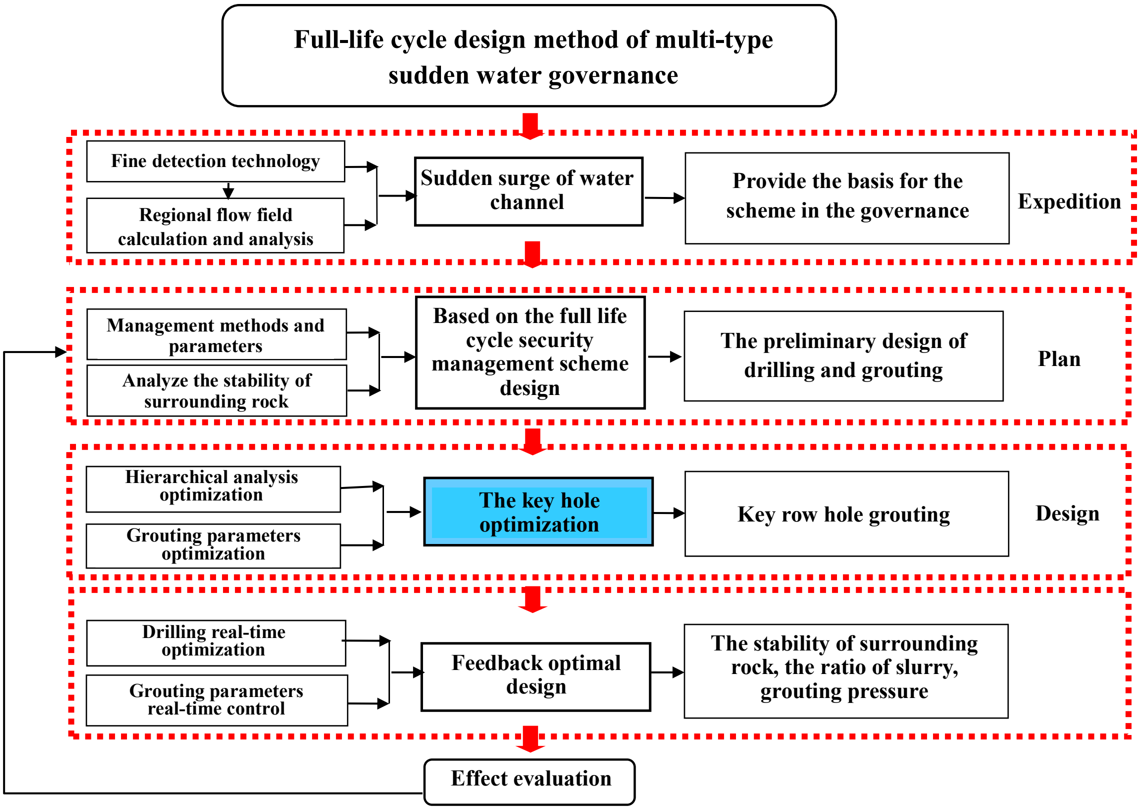


Fig. 13. Full-life water inrush control.

(2) Based on flow simulation, small-scale testing, borehole water injection, and grouting diffusion simulation, the key borehole dominating the water inrush control process is optimized.
(3) Based on the key borehole, grouting borehole, drainage borehole, diverting borehole, and testing borehole are included to develop a systematic control approach.

In conventional approaches, boreholes are developed in the vicinity of water and mud inrush sites. The borehole depth and the inter-hole distance are determined empirically and thus large efforts made to inrush incident control are required. Additionally, the insufficient effective thickness of wall rocks may lead to secondary water inrush. Based on accurate detection and selection of the key borehole, effective water-plugging can be achieved with one borehole, resulting in 70% reduction of borehole drilling efforts and increase of effective thickness of wall rocks. Additionally, the principles of gradual transition from loading to supporting of grout on wall rocks can be obtained, and a dynamic control approach (including borehole arrangement, tube length adjustment, grout gelation time, and grouting pressure control) based on wall rock monitoring can be established. In this circumstance, water inrush control is turned from an empirical process into an accurately predicted and precisely controlled process.

4.2. Key techniques for the control of typical water inrush incidents

Water inrush in tunnels and underground engineering works refers to as the cases where the breakout of groundwater with considerable flow rate which significantly affects the construction of underground structures. In some cases (e.g., large depth and extreme earth temperature), the water exhibits a high temperature. The groundwater is then defined as dynamic water. The dynamic water has a negative effect on the construction safety, the local ecosystem, and the long-term stability of underground structures. Moreover, the characteristics of dynamic water are highly dependent on the water channels involved, and no universal control approaches have been developed for all water inrush cases. Based on the frequency and control approaches proposed, the water inrush cases are divided into water-rich faulted zone inrush, karst passages inrush, joint fissure inrush, and micro-crack inrush, as shown in Fig. 14.

4.2.1. Control of water-rich faulted zone inrush

The water-rich faulted zone inrush is commonly observed in underground constructions (Zhang, 2014). In the absence of filling materials and poor cementation, the water-rich faulted zone exhibits good water induction capability, resulting in high risks of water inrush. The water-rich faulted zone inrush is time-variant and subjected to nonlinear variation of water flow. Sudden changes in flow states are also observed. The major reasons of water-rich faulted zone inrush include exposure of water-rich fractured strata and instability of rock pillars. In these cases, the faulted zone is connected with other water-bearing bodies (Ye et al., 2014). As shown in Fig. 15, the control of water-rich faulted zone inrush should be designed based on four combinations: the combination of general prospection and geological investigation, the combination of deep and shallow grouting reinforcement, the combination of support enhancement and wall rock stability monitoring, and the combination of immediate effects and long-term stability. First, far-end induction (via induction boreholes) and near-end plugging (by cement-based high early strength grouts) are employed. Then, the maximum water pressure allowed by the wall rocks can be increased by high-pressure compaction

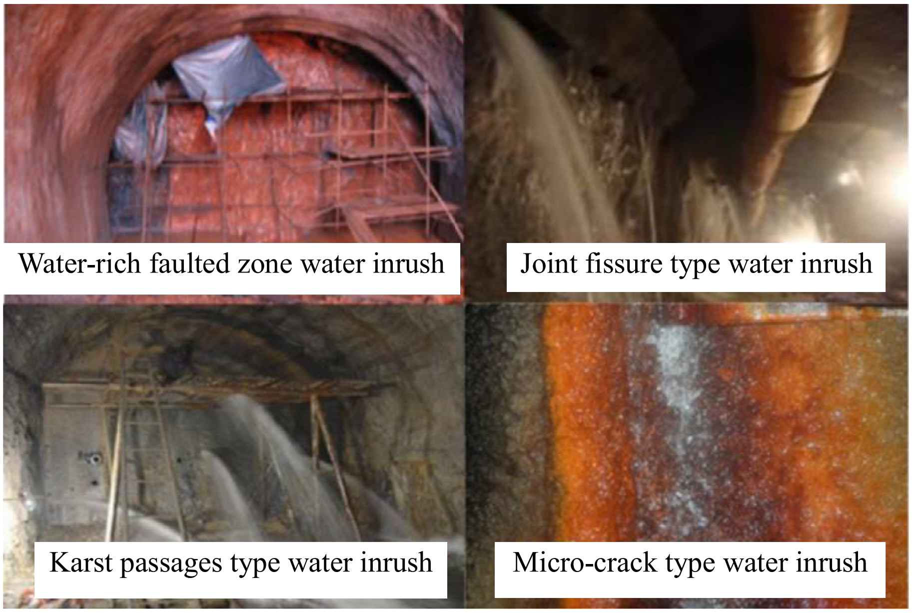


Fig. 14. Schematic illustration of different water inrush cases.

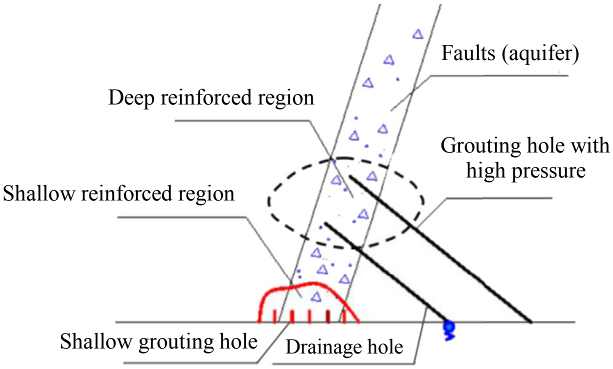


Fig. 15. Schematic illustration of deep induction and shallow grouting reinforcement.

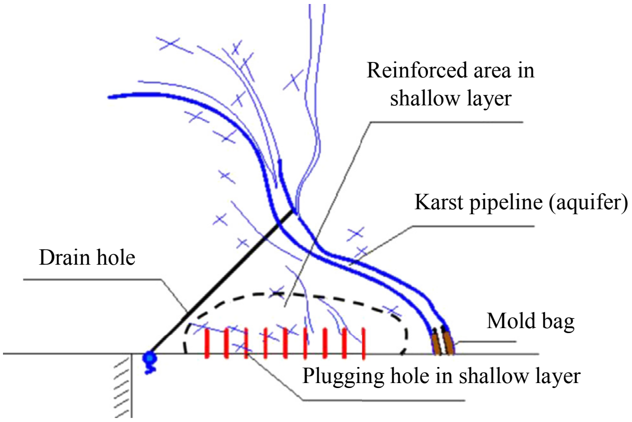


Fig. 16. Schematic illustration of water inrush control in karst areas.

grouting. In virtue of the anti-washout capability of the grouts used, near-end water channels are effectively plugged (displacement plugging). Finally, the induction boreholes are plugged to achieve complete plugging of dynamic water. Due to their key roles in this approach, the boreholes for deep induction should be properly designed and arranged based on the induction channels and wall rocks involved. The multi-section grouting techniques can be employed to improve the effectiveness and uniformity of grouting, thus eliminating grouting blind areas.

4.2.2. *Control of karst passages inrush*

As one of the dominant issues for underground engineering in karst areas (Zhang et al., 2010), the karst passages inrush may lead to severe safety problems and high risks, as well as significantly reduced construction efficiency. Generally, karst passages inrush is observed in karst areas with a huge static reserve. In this case, transient large-flow water inrush with considerable sediment contents is observed occasionally in the early stage, and the inrush is then stabilized in the late stage. The major reasons of karst passages inrush include exposure of water-rich fractured strata and instability of rock pillars or fillers. As shown in Fig. 16, for the control of karst passages inrush, distributions of water channels and conditions of wall rocks in the targeted area should be investigated first, followed by tube cementation by bag sealing and grout filling. In cases where the inrush sites show large flow pressure, installation of orifice tubes is challenging and exploration holes of considerable sizes need to be drilled in stable rocks by slewing drilling machine to diverge the water flow. Before the drilling of exploration holes, the orifice tubes should be installed, high pressure sealing should be completed, and valves should be involved at the ends to control water release. In some cases, holes can be drilled at control sites to expose the hidden water channels, followed by grouting plugging. Moreover, the grouts are selected based on their nontoxicity and durability. For instance, polymer swelling grout is appropriate candidate for water inrush in karst channels, while fast-curing grouts may be used for shallow grouting reinforcement.

4.2.3. *Control of joint fissure inrush*

As one of the most common issues in underground engineering, joint fissure inrush has been commonly observed in various cases. The fissures in wall rocks, which may be exposed in underground constructions, have a negative effect on the integrity and overall strength of the rocks. In cases where water is contained in the wall rocks, water inrush issues may be observed. With characteristics such as uniform inter-fissure distance, inhomogeneous water induction, and nonlinear changes of water influx, joint fissure inrush refers to as the water inrush caused by the exposure of fissures in water-bearing layers and the connection of these layers with surface water bodies. Based on the characteristics of joint fissure inrush, the following principles are proposed:

1. Geological investigation should be conducted before plugging.
2. Plugging should be employed together with controlled induction.
3. Boreholes should be drilled at far-ends and deep induction should be involved.
4. Key boreholes should be selected and grouted.
5. Real-time monitoring should be realized.

As shown in Fig. 17, based on fissure strike, width, dip angle, and dip direction (Liu et al., 2011b), boreholes are drilled in accordance with the spatial distribution of fissures and the inrush direction. The water-plugging is achieved using radial holes reinforced in shallow layers and key borehole grouting in deep layers. The borehole drilling evaluation and key borehole selection are achieved by multi-factor hierarchical optimization. Additionally, the water/grout ratio is accurately controlled using advanced information technologies. In some cases, induction holes can be involved to achieve the face-line-point plugging.

Fast-curing and anti-washout grouts should be used for joint fissure inrush due to its high pressure and large flow rate. Conventional fast-curing grouts (e.g., cement/water glass grout) are readily diluted and washed out by dynamic water, resulting in poor grouting effects. Therefore, grouts such as GT-1 should be used instead due to their controllable gelation, high early strength, washout resistance in dynamic water, good compatibility with pumps, and nontoxicity. These grouts exhibited excellent grouting effects in joint fissure water inrush cases. In addition, polymer grouts and high strength cement-based grouts (e.g., modified sulphoaluminate cement) can be used for shallow grouting reinforcement.

4.2.4. Control of micro-crack inrush

Micro-crack inrush is regarded as a key challenge in underground engineering, especially in urban subway, undersea tunnel, deep mines and underground oil storage, in which the control of micro-crack inrush is urgently needed. Due to the complicated structures and small sizes of cracks involved, these inrush cases exhibit large flux, long period, wide distribution, and frequent transfer. In most cases, micro-crack inrush comes in the surface spraying format.

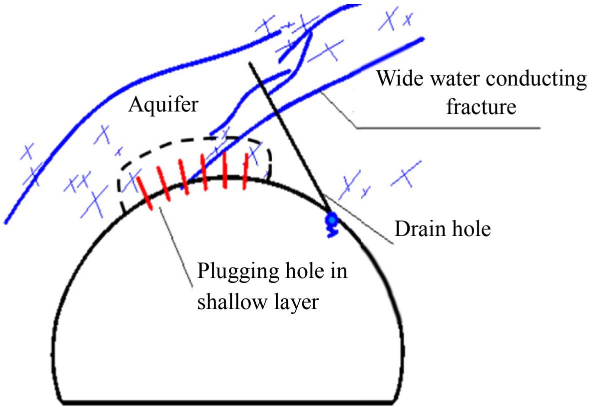


Fig. 17. Schematic illustration of joint fissure water inrush control.

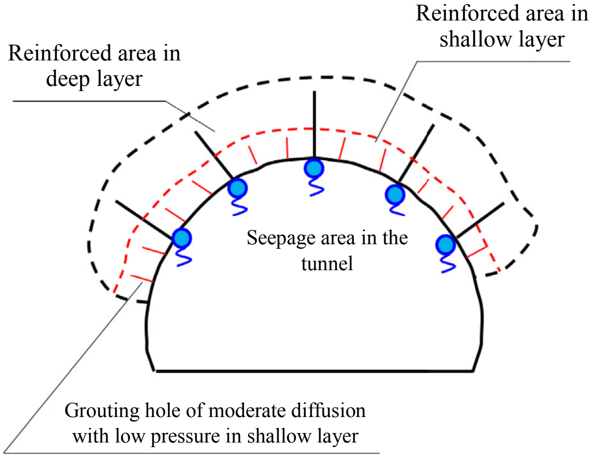


Fig. 18. Schematic illustration of micro-crack inrush control.

As shown in Fig. 18, the control of micro-crack inrush by grouting should be achieved based on investigations of the micro-scale characteristics of wall rocks and the local hydrogeological conditions. The inter-hole distance is reduced and sequent grouting is employed to achieve complete water-plugging. The grouting pressure is made of gradients: low pressure in shallow layers to facilitate grout penetration and high pressure in deep layers to achieve effective filling. On the other hand, real-time monitoring of flow rate, flow pressure and wall rock deformation should be conducted so that the grouting parameters can be adjusted timely to optimize grouting effects. The grouts for micro-crack inrush control should be selected based on the groutability, durability, strength, and flexibility of the grouts. For instance, the groutability and the penetration capability of grout particles are related to the size of cracks. In cases where the penetration ratio of the layer is smaller than 10^{-2} cm/s and the crack size is below 0.2 mm, it is difficult for conventional cement-based grouts to be injected. Therefore, ultra-fine cement particles are commonly used for layers with a penetration ratio of 10^{-2}–10^{-4} cm/s. In cases where the penetration ratio of the layer is below 10^{-4} cm/s, strong penetration silica gel is used as the grout. The parameters of radial grouting are usually determined based on the rock structure and the local hydrogeological conditions, and optimized by on-site testing. Values of parameters that are commonly used are shown in Table 5.

Table 5
Grouting parameters commonly adopted in micro-crack inrush cases.

Parameter	Designed value
Radial plugging/reinforcing thickness	(0.2–0.5)*D*
Diffusion diameter	0.5–1 m
Circumferential space	1–1.5 m
Longitudinal space	0.5–1 m
Borehole arrangement	Full-ring plum-type arrangement

Note: *D* is the hole diameter (m) of underground engineering excavation.

5. Conclusions

This review has summarized recent advances in theories of water inrush control, materials/equipment of grouting, and approaches for key control. The conclusions can be drawn as follows:

(1) Great achievements have been made in large-scale grouting simulation and theories of dynamic water grouting. A visualized model for large-scale dynamic water grouting is proposed and the plugging of dynamic water is investigated.
(2) The grouting in water-rich faulted zone is investigated and a multi-parameter, real-time monitoring system is developed. Changes in the soil pressure, seepage volume force, and the displacement are monitored to investigate the stability of the reinforcement body by grouting in fractured medium.
(3) A high early strength cream-type reinforcing/plugging grout, a high permeability nano-scale silica gel grout, and a high-expansion filling grout are 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.
(4) A novel full-life periodic dynamic water grouting with the critical grouting borehole as the core is proposed, and the key techniques for the control of water inrush in water-rich faulted zone, joint fissures and karst passages and micro-crack water inrush are developed.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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