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Numerical Simulation and Stability Analysis of Grouting in Hydraulic Engineering

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ABSTRACT

Grouting, as a widely used foundation reinforcement technology in water conservancy projects, is an important engineering measure to solve problems such as dam foundation leakage and subsidence of goaf under long-distance water transfer engineering. At present, the grouting simulation and stability analysis of hydraulic engineering are faced with key problems such as concealed geological conditions, complex slurry diffusion rules, comprehensive evaluation of grouting effect and analysis of grouting stability. Based on the dam foundation grouting engineering of hydropower station and the grouting engineering of the goaf in the long-distance water transfer project across the basin, the theory and method of numerical simulation and stability analysis of hydraulic engineering grouting based on three-dimensional fine geological model are proposed, and the above problems are further developed. The research and analysis, using ANSYS software to simulate it, discussed the influence of drilling pressure, grouting hole design apex angle, hole wall clearance and other factors on the borehole inclination, and proposed the drilling anti-slope scheme which can be used in engineering practice. The experimental results show that the quality of the installation and the diameter of the installation should be smooth and solid before the installation of the equipment. The filling part should not exceed 1/3, and the hole should be drilled according to the design direction and the diameter of the drill should be straight. The length is gradually increased to about 10m. The hole wall gap is an important factor causing the bending of the borehole. When designing the grouting hole, the shape of the grouting hole should be designed as a vertical hole or a straight hole with a small apex angle as much as possible, so as to ensure that the drilling tool has a good anti-slanting effect; the use of a multi-drilling tool can be greatly reduced. The contact between the drill and the well wall reduces the phenomenon of stuck or differential pressure stuck.

INTRODUCTION

The problem of foundation leakage in water conservancy projects not only causes economic loss of the project, but also seriously affects the safety and stability of the project. According to incomplete statistics, more than 50% of water conservancy project damage accidents are caused by improper foundation treatment. In the early days of construction, the Oroville Dam in the United States ignored the safe disposal of foundation cracks, resulting in a 40-foot-deep damage surface at the beginning of 2017, causing 188,000 residents to evacuate overnight. The Teton dam breach in the United States and the dam foundation damage of the Puente gravity dam in Spain are also closely related to the improper treatment of the foundation (Deng et al. 2016). At the same time, China's water conservancy project construction is developing in the direction of higher dam project, cross-basin long-distance water transfer project, such as larger scale, more complicated geological conditions, and more difficulty in ground-based safety treatment. Due to the existence of complex fractures in the dam foundation rock and the existence of underlying goafs along the water transfer project, the foundation grouting research of hydraulic engineering can not only effectively reduce the permeability of the foundation, but also improve the stability of the foundation. It is an effective technical means for dealing with ground leakage problems and ensuring long-term safe and stable operation of water conservancy projects (Hao et al. 2016).

Grouting refers to the use of a gelling slurry or chemical solution, according to a certain ratio or concentration, by means of the pressure of the mechanical or slurry weight, to the joints in the foundation rock, cracks and other weak parts that need to be grouted to fill the slurry. Through grouting, the fissure development zone and the percolation channel, which have weak local conditions in the foundation, are improved. This improves the integrity and compactness of the foundation, reduces the permeability of the foundation, and enhances the ability of the foundation to resist seepage damage, and the safety and stability of the entire project is improved. However, due to the concealment of the grouting process, the filling of the slurry in the formation cannot be assessed intuitively, and the effectiveness of grouting and the stability of the engineering cannot be accurately judged. The irritation medium existing in the rock mass of the water conservancy project can be divided into fissures, porous media, etc. The flow patterns and ways of the slurry in different kinds of irritation medium are different, and the geological modelling theory and grouting simulation theory involved are different (Dong-Yang et al. 2016). Due to the large scale of water conservancy projects, the geological environment involved in grouting reinforcement treatment is complex. Therefore, this paper takes two typical grouting projects of dam foundation fractured rock mass grouting and inter-basin long-distance water transfer engineering under the goaf for porous media grouting as an example. Simulation study on grouting diffusion process in underlying goaf of dam foundation and inter-basin long-distance water transfer project, effective evaluation of grouting effect, and fluid-solid coupling method for reasonable analysis of grouting stability, which is also to ensure water conservancy engineering, important scientific issues of foundation stability and overall engineering safety.

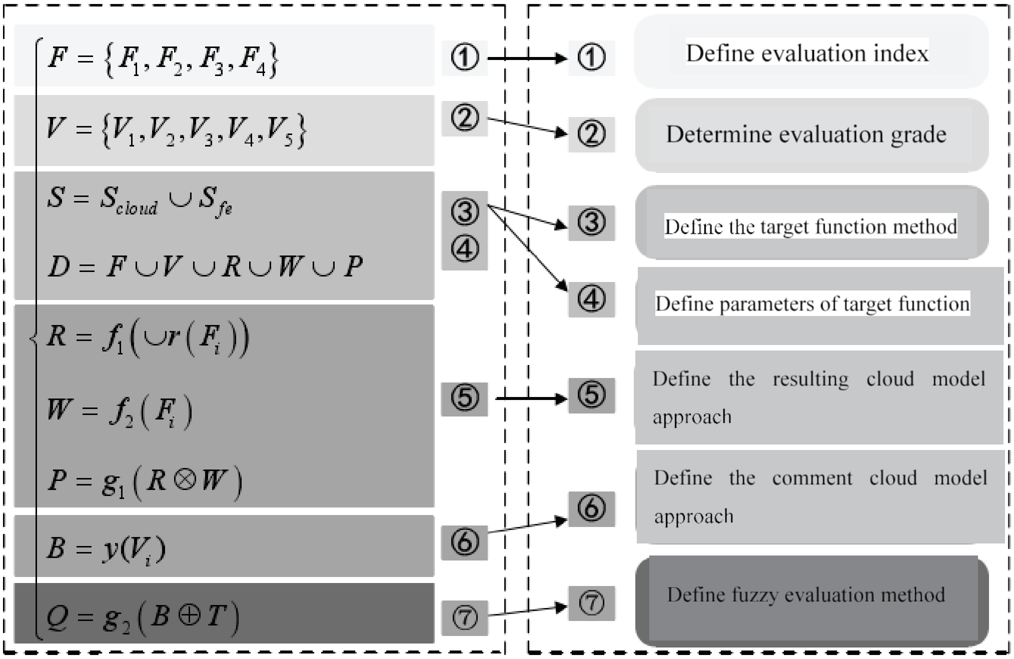
EARLIER STUDIES

In 1974, Baker derived the formula for the filling of Newtonian fluid under ideal single-fracture conditions. Since then, many scholars have used Newtonian fluid or Bingham fluid model to simulate the slurry flow process in a single fracture from different angles (Wang et al. 2018). Subsequently, in 2001 an analytical solution of the Bingham-type slurry was derived, when it was unsteadily flowing between two parallel smooth plates (Zhang et al. 2017). On the basis of this, Iwasaki et al. (2016) studied the flow diffusion law of Bingham-type slurry fluid between parallel smooth plates under different grouting flows, and used the Laplace transform method to derive the slurry for unsteady flow, velocity distribution characteristics and pressure gradient. A study on the calculation method of the infiltration distance of one-dimensional runoff and two-dimensional radial flow in parallel plate cracks (Lai et al. 2016). Based on the parallel plate fracture model, Gordeeva et al. (2017) studied the forward ratio of cement slurry radial flow, and proposed that the cement slurry advancement state depends on the grouting time and the grouting pressure or flow control. Previous study proposed a high arch dam grouting model with single fracture to optimize grouting time, control grouting pressure, and control lift deformation, which can effectively reduce high arch dam lifting and related cracking risk (Meng et al. 2016). A recent study discussed the flow-diffusion law of Bingham-type slurry in a two-dimensional channel network rock mass (Shao-Feng et al. 2017).

MODEL DESIGN METHOD

Research framework: A fuzzy comprehensive evaluation method for grouting effect based on cloud model is proposed. Firstly, the index system of comprehensive evaluation of grouting effect is introduced, including water permeability, sonic wave velocity, fracture filling rate and irritability in post-irrigation rock. The measured values of these evaluation indexes are respectively measured by water pressure test, acoustic wave test and core drilling, in-hole video and grout recorders. Secondly, the fuzzy comprehensive evaluation method of grouting effect is introduced. The cloud model theory is used to consider the fuzziness and randomness in grouting effect evaluation. The fuzzy entropy is introduced and the complexity of evaluation grade attribution is considered. Based on the cloud model-based fuzzy comprehensive evaluation method of grouting effect, the comprehensive evaluation of the dam foundation grouting effect of a large hydropower project in China is carried out.

Mathematical model: At present, a few independent studies on the comprehensive evaluation of grouting effect are single-factor independent evaluation, and the randomness in grouting effect evaluation is neglected. In this paper, the cloud model theory is introduced for the uncertainty in grouting effect evaluation, and the comprehensive evaluation of grouting effect is established. In the construction of comprehensive evaluation system of grouting effect, four indexes of water permeability, sonic wave velocity, filling rate and potability are comprehensively considered. Secondly, considering the importance scale and membership degree in the evaluation of grouting effect, it is easy to be subject to personal experience and based on the influence of subjective factors, a fuzzy comprehensive evaluation method based on cloud model is proposed. The fuzzy features and randomness are combined organically by using the digital features of the cloud model. Again, it is based on a single evaluation level as a comprehensive grouting effect. The evaluation results are difficult to fully and truly reflect the grouting effect, and the fuzzy entropy is introduced as the auxiliary evaluation of the comprehensive evaluation of grouting effect. The two-dimensional evaluation results are constructed from the level and complexity, and the grouting effect is evaluated. The mathematical model for comprehensive evaluation of grouting effect is shown in Fig. 1. The mathematical model clarifies the indicator set, evaluation level set, method set and parameter set of the comprehensive evaluation of grouting effect.



(a) Fuzzy comprehensive evaluation mathematical model of grouting effect based on cloud simulation

(b) Mathematical modeling

Fig. 1: Mathematical model for fuzzy comprehensive evaluation of grouting effect based on cloud model.

The above mathematical model consists of 6 parts, and the meanings and functions of each part of the parameters are as follows:

1. The index set {f} of the evaluation system is defined as the basis for the comprehensive evaluation of the grouting effect, including water permeability (f1), acoustic wave velocity (f2), crack filling rate (f3), and unit injection amount (f4).
2. Combined with the experience of grouting engineering and the acceptance criteria of each evaluation index, the grade set {v} and interval division criteria of each evaluation index are determined, including five grades, very good (v1), better (v2), general (v3), poor (v4), very poor (v5).
3. Define a comprehensive evaluation method set S for grouting effects, including cloud-based fuzzy comprehensive evaluation method (Scloud) and fuzzy entropy solving method (Sgray).
4. The parameter set d for solving the objective function is defined, including the evaluation index set f, the evaluation level set v, the fuzzy membership degree matrix r, the index weight set w, and the evaluation result set p.
5. A method set for solving the evaluation result cloud model is defined, including a method for solving the membership degree cloud model (R), a method for solving the evaluation index weight cloud model (W), and a method for solving the evaluation result cloud model (P); where r(Fi) represents the membership of the cloud model of the indicator Fi, f1 is a function for establishing the matrix model matrix R of the membership degree, and f2 is a function for establishing the weight model cloud model W of the evaluation index. For the coupling operator, g1 is the coupling condition.
6. Define a method set for solving the comment set cloud model, and y is a function for creating the comment set cloud model B.
7. Define a method set for solving fuzzy comprehensive evaluation, and g2 is a function of the coupled grouting effect evaluation result cloud model and the comment set cloud model. For the coupling operator.

Cloud Model Generator: The cloud generator includes a forward cloud generator and a reverse cloud generator. The Forward Cloud Generator (FCG) is a qualitative to quantitative mapping that generates cloud droplets based on the

Fig. 2: Schematic diagram of the forward generator and reverse generator.

digital features C(Ex, En, He) of the cloud, mapping qualitative concepts to quantitative locations in the numerical space. Achieving the conversion of qualitative concepts to quantitative values. The Back Cloud Generator (BCG) is the inverse process of the forward cloud generator, which realizes the conversion model from the quantitative value to the qualitative concept. According to the cloud drop that matches a certain distribution, the digital feature C corresponding to the cloud model is obtained. The forward cloud model and the reverse cloud model generator are specifically shown in Fig. 2.

Forward cloud generator algorithm:

Input: The digital features Ex, En, He of a qualitative concept, and the number N of given cloud drops.

Output: The quantitative position of n cloud drops in the number domain space and each cloud drop represents the certainty of the concept.

Algorithm:

1. Generate a normal random number Eni′ with the expected En and the standard deviation of He;
2. Generate a normal random number xi expecting Ex and standard deviation Eni';
3. Let x be a specific quantitative value of the qualitative concept, called cloud drop;
4. Calculation: $u_i = \exp[-(x_i - Ex)^2 / 2(En_i')^2]$
5. Let μ_i be x the certainty of the qualitative concept;
6. Combine (x_i, μ_i) to form 1 cloud drop;
7. Repeat the above steps until the required n drops are generated.

ANALYSIS OF RESULTS

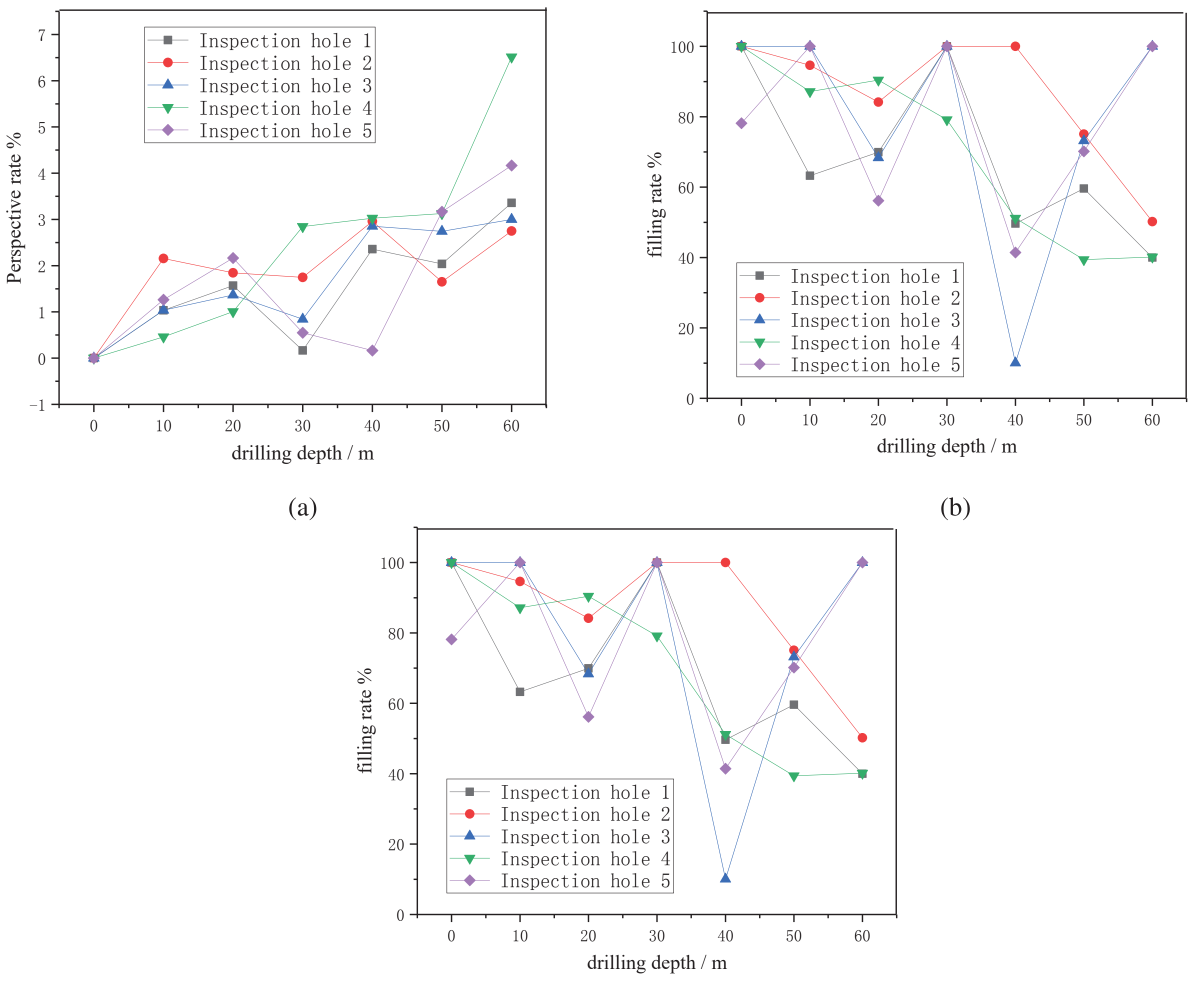
Establishment of evaluation index system: The effect of grouting directly affects the safe and stable operation of hydraulic engineering. However, due to the concealment of the project, the evaluation of grouting effect is often limited. The comprehensive evaluation index system of grouting effect should be based on a series of complementary indicators of organic factors. Establishing a complete evaluation index system can objectively and accurately reflect the grouting effect of the area, so establish a reasonable evaluation index system for grouting effect. It is the basis for studying the effect of grouting. This paper establishes an index system for evaluation of grouting effects including target layer, criterion layer and index layer, as shown in Table 1. There are three levels from the top to the bottom. The first layer is the target layer t, that is, the target is the comprehensive evaluation of the grouting effect, the second layer is the criterion layer c, and the permeability and compactness of the post-irrigation rock mass are used as the evaluation criteria. The third layer is the index layer f, which includes four indexes of water permeability, acoustic wave velocity, crack filling rate and potability of the rock mass after irrigation.

Acquisition of evaluation indicators: Pressing the water test on the fractured rock mass and obtaining the permeability value of each hole section on the site is the most commonly used means for judging the permeability of the rock mass and the effect of grouting and seepage prevention. It can directly judge the effectiveness of grouting in each hole section. However, as more and more high dams are put into construction, the results of conventional pressure water tests often cannot effectively reflect the permeability characteristics of rock masses. Therefore, the results of a single pressurized water test cannot be used as the sole basis for determining the grouting effect. On the basis of the water pressure test, more and more geophysical monitoring technologies have emerged, and as an auxiliary means to test and evaluate the grouting effect. The acoustic wave detection method in the hole has the characteristics of fast and timely. The sonic wave velocity has been used for tracking and rapid detection of grouting construction in many hydropower projects such as Ertan and Xiluodu in China. In addition, through the core drilling and digital drilling imaging method, the filling of the slurry in the crack can be directly observed, which is intuitive and reliable, and is not restricted by the formation. Therefore, the crack filling rate can also be used as an effective index in the evaluation of grouting effect. Therefore, in recent years, the water permeability test value of the water pressure test, the acoustic wave velocity result in the post-irrigation rock, and the crack filling condition are effective and reasonable evaluation indexes for the evaluation of grouting effect.

Table 1: Index system for evaluation of grouting effect.

Destination layer T	Comprehensive evaluation of grouting effect			
Criterion layer C	Permeability C1		Compactness C2	
Index level F	Permeable rate F1	Acoustic wave velocity F2	Fracture fill rate F3	Filling can be F4

Case Study-Fuzzy Comprehensive Evaluation of Curtain Grouting Effect of Dam Foundation: Taking a large-scale hydropower project in the upper reaches of the Minjiang River as the research object, comprehensive evaluation of grouting effect was carried out, and the research scope of grouting effect evaluation was selected. In order to carry out a reasonable inspection of the quality of the grout, the scope of the study set up five construction quality third-party inspection holes, including 70 sections, with a distance of approximately 25 m along the axis of the dam. According to the contents of the previous section, the comprehensive evaluation index of grouting effect selected in this paper includes four indexes: water permeability, acoustic wave velocity, crack filling rate and irrigation. The first three indicators are obtained according to the inspection hole water pressure test, the sound wave detection in the inspection hole, the borehole imaging, and the coring method. The wave velocity value and the filling rate value in each unit hole segment are calculated by the arithmetic average method based on the detection result. The specific results are shown in Fig. 3. The water permeability distribution range of each hole of the inspection hole is 0.22~10Lu, the distribution range of the acoustic wave velocity is 4.12~6.02km/s, and the distribution range of the crack filling rate is 0~100%.



(a) (b)

(c)

Fig. 3: Calculation results of the evaluation indicators of each unit of the inspection hole.

Table 2: Irrigation area division and RI value.

Area	Segment number	Water conductivity (m^2/s)	Ash injection measured value (kg)	Ashing amount 1D calculated value (kg)	Ashing amount 2D calculated value (kg)	Irrigable area	RI
1	1	1.11E-06	23.4	5.91	154.42	Irrigation area - normal grouting	0.559
	2	3.85E-07	8.6	6.97	209.60	Non-irrigating area - no need to grout	1.000
	3	2.52E-06	93	40.32	1656.74	Irrigation area - normal grouting	0.516
	4	3.69E-06	170.5	88.90	5227.72	Irrigation area - normal grouting	0.508
	5	3.80E-06	140.9	129.62	10805.51	Irrigation area - normal grouting	0.501
	6	3.53E-06	138.5	118.05	9677.76	Irrigation area - normal grouting	0.501
	7	6.63E-07	409.8	2.77	83.12	Non-irrigating area - no need to grout	1.000
	8	5.06E-06	317	171.24	7991.88	Irrigation area - normal grouting	0.510
	9	5.01E-06	267.9	172.87	14619.60	Irrigation area - normal grouting	0.503
	10	4.74E-06	283.2	163.62	7560.01	Irrigation area - normal grouting	0.508
	11	5.31E-06	200.7	186.30	16104.03	Irrigation area - normal grouting	0.500
	12	3.55E-06	114.4	119.75	9904.30	Non-irrigating area - can be improved	0.478
	13	3.62E-06	107.6	118.21	9435.99	Non-irrigating area - can be improved	0.455
	14	9.22E-07	94.1	7.49	496.91	Non-irrigating area - no need to grout	1.000

Since the irritability index is determined according to the quantitative relationship between the ash injection amount and the hydraulic conductivity of each section of the grouting hole, the inspection hole and the grouting hole do not coincide, so the monitoring result of the grouting hole closest to the inspection hole is selected as the irritability index calculation. The input parameters, combined with the inspection of the water permeability, the acoustic wave velocity and the crack filling rate, determine the filling effect in the vicinity of the inspection hole. Using the Moye formula, the hydraulic conductivity of each grouting section can be converted from the water permeability of the pre-irrigation water test.

$$T = \frac{Q_w \rho_w g}{2\pi * \Delta P_w}\left[1 + \ln\left(\frac{L}{2r_b}\right)\right] \qquad \ldots(1)$$

Where, Q_w is the pressure water flow, L/min; ρ_w is the density of water, kg/m^3; g is the acceleration of gravity, m/s^2; ΔP_w is the effective pressure water pressure, MPa; L is the pressurized water test section length, m; r_b is the radius of the grouting hole, m. According to the judgment method of the irrigability judgment and the RI value described above, the theoretical calculation value of the ash injection amount in the one-dimensional and two-dimensional flow of the slurry in each hole section is calculated, and the grouting area to which it belongs is determined and the RI value is calculated. The specific content is shown in Table 2.

CONCLUSIONS

Based on the slurry diffusion law obtained by grouting simulation of porous media, considering the difference of slurry concentration in different regions and the insufficiency of grouting pressure, the theory and method of stability analysis of grouting engineering based on fluid-solid coupling theory are proposed.

1. A mathematical model for the analysis of grouting stability in the goaf under the cross-basin long-distance water transfer project based on fluid-solid coupling is proposed. The slurry concentration field data is applied to the analysis of grouting stability to reasonably determine the physics of the filling body formed after grouting reinforcement.
2. Taking the analysis of grouting stability in the undercutting area of the long-distance water transfer project across the basin as an example, based on the fluid-solid coupling method, the engineering deformation mechanism and deformation characteristics under the influence of multiple factors are analyzed, and the grouting engineering is discussed in detail. Stress and deformation of the entire construction and operation of the building.
3. The results show that under the various pressures, the maximum principal stress and the minimum principal

stress of the underlying goaf and the overlying rock layers of the water transfer project do not exceed the tensile and compressive strengths of various rock masses. No tensile or compressive failure occurred in the rock mass, and the research provided technical support for guiding the stability design and construction of the water conservancy project. The practice shows that the theory and method proposed in this paper can provide theoretical basis and technical support for the grouting simulation, grouting effect evaluation and stability analysis of the hydropower station dam foundation fissure grouting and inter-basin long-distance water transfer project.

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