Hindawi
Shock and Vibration
Volume 2020, Article ID 8811028, 9 pages
https://doi.org/10.1155/2020/8811028

Research Article

Study on Penetration Grouting Mechanism Based on Newton Fluid of Time-Dependent Behavior of Rheological Parameters

Yi Ding[1], **Zhi-Quan Yang**[1], **Yi Yang**[1], **Ying-Yan Zhu**[2], **Yong-Fa Guo**[3], **Jie Zhang**[4], and **Xin-Gui Chen**[5]

[1]*Faculty of Public Safety and Emergency Management, Kunming University of Science and Technology, Kunming, Yunnan 650093, China*
[2]*Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences and Ministry of Water Resources, Chengdu, Sichuan 610000, China*
[3]*Kunming Survey Design and Research Institute Co. Ltd. of CREEC, Kunming, Yunnan 650200, China*
[4]*Yunnan Institute of Geological Environment Monitoring, Kunming, Yunnan 650216, China*
[5]*The Third Engineering Co., Ltd. of China Railway Seventh Bureau Group Corporation, Xi'an, Shaanxi 710032, China*

Correspondence should be addressed to Zhi-Quan Yang; yzq1983816@kust.edu.cn

Received 3 September 2020; Revised 28 September 2020; Accepted 20 October 2020; Published 24 November 2020

Academic Editor: Gang Zhou

Grouting mechanism is one of the important factors on the grouting effects of practical projects. At present, the vast majority of Newton fluid penetration grouting mechanisms are considering that the viscosity of Newton fluid during the grouting whole process was constant, so the theoretical diffusion radius calculated by them is far greater than the actual measurements in the grouting engineering. Carrying out theoretical analysis and experimental research, the rheological equation and seepage motion equation for Newton fluid of time-dependent behavior of rheological parameters were established; then, the penetration grouting mechanism of them was deduced. What is more, they were validated by means of designing the grouting verifying experiments. Experiment results show that the theoretical diffusion radius calculated by the formula of diffusion radius of penetration grouting mechanism based on Newton fluid of time-dependent behavior of rheological parameters was in accordance with the change regulation of the actual measurement diffusion radius by grouting experiments. Their difference within the range of 15% is far less than about 80% change between the theoretical diffusion radius calculated by the Maag formula and the actual measurement radius. In general, it can reflect the grout infiltration laws that Newton fluid changes with time. Therefore, research achievements may not only be able to provide a strong theoretical basis for perfecting the penetration grouting mechanism but also play a reference guiding role for the theoretical research, design, and construction in the grouting technique.

1. Introduction

Grouting, as a widely used geotechnical reinforcement and water shutoff technology, has been used in practical engineering fields involving buildings, highways, subways, mines, tunnels, hydropower services, military applications, railways, and stratum treatments [1]. According to different rheological constitutive formulas, the grouting fluids are divided into three types: Newton fluid, Bingham fluid, and power-law fluid [1–3].

The grouting mechanism delivers a great and important influence on grouting effects; for example, the diffusion model of grouting is one of the significant ways to provide theoretical support and guidance for actual grouting construction. Presently, abundant research achievements have been made with respect to the penetration grouting mechanism based on Newton fluid, which are also widely used in practical grouting engineering, such as Maag spherical theory, sleeve valve, and cylinder diffusion models [1]. Additionally, Jiacai [4] studied the formula for maximum diffusion radius of Newton fluid in the fracture surface; Baker [5] deduced the calculation formula for maximum diffusion radius of Newton fluid in the rock mass fracture; Jinfeng et al. [6] explored the diffusion law of Newton fluid in the plane, radial, and circular fracture; Lie

Weile [7] deduced the diffusion formula of Newton fluid in the two-dimensional rough fracture; and Weicheng [8] explored the cylindrical diffusion mechanism based on Newton fluid under horizontal and vertical drilling conditions. As for the progress of the time-dependent behavior of grouts. Wenjun [9] built the rheological models of different types of grouts with the effect of time; Quansheng et al. [10] studied the variation of the rheological parameters of cement grouts with time; Roussel [11] investigated the thixotropy and flow behavior of fresh cement grouts; Zhuguo and Cao [12] studied the rheological behaviors of concrete in the vibrated state.

However, the time-dependent behavior of rheological parameters of most of the achievements for the penetration grouting mechanism for Newton fluid is not considered currently, and the rheological parameters are considered to be constants in the whole grouting process while calculating theoretical diffusion size. Then, the calculated theoretical diffusion size is far greater than the measured value in actual grouting. Therefore, the diffusion of grouts in engineering mainly depends on the workers' experience, which brings uncertainty to engineering grouting and makes it difficult to meet the requirements for engineering practices. Consequently, the penetration grouting mechanism based on Newton fluid of time-dependent behavior of rheological parameters is studied in this paper to provide theoretical support for actual grouting construction.

2. Study on Penetration Grouting Mechanism Based on Newton Fluid of Time-dependent Behavior of Rheological Parameters

2.1. Seepage Motion Formula for Newton Fluid of Time-Dependent Behavior. The basic rheological formula of Newton fluid is

$$\tau = \eta\gamma. \tag{1}$$

According to the literature [9], the time-dependent behavior of rheological parameters of Newton fluid (dynamic viscosity) formula is

$$\eta(t) = \eta_0 e^{kt}. \tag{2}$$

The rheological formula for Newton fluid of time-dependent behavior can be obtained by combining formulas (1) and (2):

$$\tau = \eta(t)\gamma = \eta_0 e^{kt}\gamma, \tag{3}$$

where τ is the shear stress; γ is the shear rate $(\gamma = -dv/dr)$; η is dynamic viscosity; η_0 is the initial value of dynamic viscosity of Newton fluid, and it approximately equals the fixed dynamic viscosity n in formula (1); $\eta(t)$ is the dynamic viscosity of Newton fluid at the moment of t; t is the grouting duration; and k is the time-dependent coefficient and it can be measured via the experiment.

In a circular tube with the Newton fluid of time-dependent behavior of rheological parameters, the radius is hypothesized to be r_0. Taking an infinitesimal element of the fluid column and using the tube axis as the symmetry axis, the radius satisfying $r < r_0$ and the length is dl [13]. It is hypothesized that the pressure distribution of the infinitesimal element of the fluid column dl at the left and right ends is p and $p + dp$, respectively. Therefore, the pressure difference in the infinitesimal element is dp. The shear stress acting on the surface is τ, its direction is on the left, and it is opposite to the direction of flow velocity as shown in Figure 1.

Under the condition that the gravity of Newton fluid is ignored, the force on the infinitesimal element column is shown in Figure 1 which satisfies the following equilibrium equations:

$$\pi r^2 dp + 2\pi r\tau\, dl = 0. \tag{4}$$

Shear stress on the surface of the infinitesimal element column is

$$\tau = -\frac{r}{2}\frac{dp}{dl}, \tag{5}$$

and combining formula (5) and formula (3), we can obtain

$$\gamma = -\frac{dv}{dr} = \frac{\tau}{\eta_0 e^{kt}} = \left(-\frac{1}{2\eta_0 e^{kt}}\frac{dp}{dl}\right)r. \tag{6}$$

The velocity formula of Newton fluid of the time-dependent behavior in the cross section of the circular tube can be solved and obtained at $v = 0$ by applying the method of separation of variables and considering the boundary conditions $r = r_0$ of the pipe wall for formula (6):

$$v = -\frac{1}{4\eta_0 e^{kt}}\frac{dp}{dl}\left(r_0^2 - r^2\right). \tag{7}$$

The flow Q_P of Newton fluid of the time-dependent behavior for the laminar flow in the circular tube can be obtained:

$$Q_P = \int_0^{r0} 2\pi r v\, dr. \tag{8}$$

By substituting formula (7) into formula (8), the following results can be obtained:

$$Q_P = -\frac{\pi r_0^4}{8\eta_0 e^{kt}}\frac{dp}{dl}. \tag{9}$$

Therefore, the average velocity of Newton fluid of time-dependent behavior on the cross section of the pipe is shown as follows:

$$\overline{v} = \frac{Q_P}{\pi r_0^2} = -\frac{r_0^2}{8\eta_0 e^{kt}}\frac{dp}{dl}. \tag{10}$$

Then, the average seepage velocity of the fluid in the grouted medium holds formula $V = \phi\overline{v}$, and, according to literature [13],

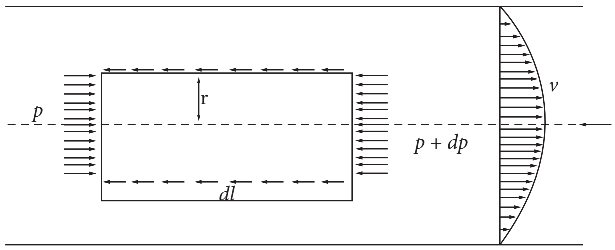


FIGURE 1: Flow diagram of Newton fluid of time-dependent behavior in the circular tube.

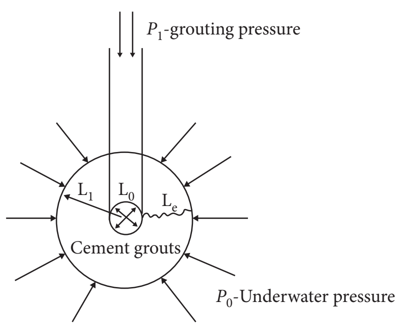


FIGURE 2: Spherical diffusion model of Newton fluid of time-dependent behavior.

$$K = \frac{\phi r_0^2}{8\mu}, \tag{11}$$

$$\beta = \frac{\eta_0}{\mu}. \tag{12}$$

The seepage formula based on Newton fluid of time-dependent behavior of rheological parameters can be obtained by simultaneous formulas (10), (11), and (12):

$$V = e^{-kt}\left(\frac{K}{\beta}\right)\left(-\frac{dp}{dl}\right), \tag{13}$$

where ϕ is the porosity of the grouted medium; μ is the viscosity of water; V is the average seepage velocity of Newton fluid of time-dependent behavior in the grouted medium; and other symbols are the same as above.

2.2. Penetration Grouting Mechanism of Newton Fluid Based on Time-Dependent Behavior of Rheological Parameters. According to [13–16], the following assumptions are adopted in this paper while studying the penetration grouting mechanism based on Newton fluid of time-dependent behavior of rheological parameters:

(1) The grouted medium or material is isotropic and homogeneous

(2) The fluid is incompressible and its flow pattern remains unchanged during grouting

(3) The dynamic viscosity of Newton fluid is time-dependent (increased with time), and the dynamic viscosity is exponentially related to time

(4) The flow velocity was small, and the grout flow is laminar except that the local area around the grouting hole is turbulent

(5) The tampering method is used for grouting, and cement grout is grouted into the grouted medium from the bottom of the grouting pipe orifice and diffuses in a spherical shape

(6) The gravity effect of fluid is ignored in the grouting process

The spherical diffusion model for penetration grouting mechanism based on Newton fluid of time-dependent behavior of rheological parameters studied in this paper is shown in Figure 2.

In Figure 2, p_1 is the grouting pressure; p_0 is the groundwater pressure at the grouting point; l_1 is the diffusion radius of Newton fluid of time-dependent behavior at the time of t; and l_0 is the radius of grouting pipe.

The total grouting volume Q of Newton fluid of time-dependent behavior in the grouting process meets the following formula:

$$Q = VAt, \tag{14}$$

where A is the total diffusion surface area of Newton fluid of time-dependent behavior in the grouting area. The total diffusion surface area of the diffusion model is shown in Figure 2 and expressed as follows:

$$A = 4\pi l^2. \tag{15}$$

By substituting formulas (14) and (15) into formula (13), the following formula is derived:

$$dp = -\frac{e^{kt}Q\beta}{4\pi tK} l^{-2} dl. \tag{16}$$

For formula (16), the boundary conditions of grouting are taken into account while the integral of separation of variables method is used, namely, $l = l_1$ holds when $p = p_1$, and $l = l_0$ when $p = p_0$:

$$\Delta p = p_1 - p_0 = \frac{e^{kt}Q\beta}{4\pi tK}\left(\frac{1}{l_0} - \frac{1}{l_1}\right), \tag{17}$$

and combining grouting volume $Q = (4/3)\pi l_1^3 \phi$ into formula (16),

$$\Delta p = p_1 - p_0 = \frac{e^{kt}\beta\phi l_1^3}{3tK}\left(\frac{1}{l_0} - \frac{1}{l_1}\right). \tag{18}$$

In practical engineering, $l_1 \gg l_0$ is established, that is, $(1/l_0) - (1/l_1) \approx (1/l_0)$; formula (18) is simplified to be

$$\Delta p = p_1 - p_0 = \frac{e^{kt}\beta\phi l_1^3}{3tKl_0}. \tag{19}$$

Formula (19) is the formula for the penetration mechanism of spherical diffusion based on Newton fluid of time-dependent behavior of rheological parameters.

Maag formula for penetration grouting based on Newton fluid may be deduced from (19), without considering the time-dependent behavior of rheological parameters of Newton fluid:

$$\Delta p = p_1 - p_0 = \frac{l_1^3 \beta \phi}{3Ktl_0}. \tag{20}$$

The spherically theoretical diffusion radius of Newton fluid of time-dependent behavior of rheological parameters in the grouted medium can be obtained by formula (19):

$$l_1 = \sqrt[3]{\frac{3(p_1 - p_0)tKl_0}{e^{kt}\beta\phi}} = \sqrt[3]{\frac{3\Delta ptKl_0}{e^{kt}\beta\phi}}. \tag{21}$$

3. Application Scope and Parameter Determination

3.1. Application Scope. Formula (19) or (21) was derived on the basis of laminar flow, so it was concluded to be non-applicable to the turbulent flow.

According to [17, 18], the laminar or turbulent flow state of Newton fluid of time-dependent behavior was determined by Reynolds number (Re). Newton fluid was in a turbulent state when Reynolds number >4000; Newton fluid was in a mixed state of turbulent flow and laminar flow when $2000 < \mathrm{Re} < 4000$ held; and Newton fluid was in a laminar flow state when $\mathrm{Re} < 2000$ held. The Reynolds number could be obtained by calculating thee following formula:

$$\mathrm{Re} = \frac{\overline{v}d}{\eta}, \tag{22}$$

where $\overline{v}$ is the average velocity of Newton fluid of time-dependent behavior in the grouted medium or material; d is the spatial range size of the flow of Newton fluid (e.g., pipe radius or diameter, and it means the pore size of the flow of Newton fluid in the grouted medium in this paper); and the meaning denoted by η is shown in the above-mentioned text.

3.2. Parameters Determined. The methods for obtaining each parameter in equation (19) or (21) are determined as follows:

The porosity ϕ denotes the ratio of pore volume to total volume in the grouted medium or material, and it can be obtained with the following formula:

$$\phi = \frac{\gamma_s(1+\omega) - \gamma}{\gamma_s(1+\omega)}, \tag{23}$$

where ω is the water content of the grouted medium or material; γ is the density of the grouted medium or material; and γ_s is the volumetric weight of soil. Such parameters may be determined according to [19].

The permeability coefficient K of the grouted medium or material reflects its penetration behavior, and it may be determined by an indoor or on-site measurement method. However, the on-site water injecting experiment technique is normally used to obtain such a coefficient in order to truly reflect the permeability of the grouted medium or material.

The initial dynamic viscosity η_0 and time-dependent behavior coefficient k can be obtained by one of the following two methods:

(1) It can be obtained on the research results of rheological parameters of Newton fluid of time-dependent behavior, such as [2] and [17];

(2) The rheological parameters of Newton fluid can be measured by a rotating viscometer.

The grouting time t can be designed and selected according to the actual engineering situation, and the radius of the grouting pipe can be determined by directly measuring the grouting pipe.

On the basis of obtaining the porosity and permeability coefficient of the grouted medium or material and inquiring the viscosity value of water at different temperatures, then the β value can be calculated by formulas (11) and (12).

Now that all the parameters required to be obtained in formula (19) or formula (21) are completely determined and the theoretical diffusion radius l_1 of Newton fluid of time-dependent behavior in the grouted medium or material can be obtained under the condition of known grouting pressure and groundwater pressure difference at the grouting point, on the contrary, the theoretical grouting pressure differential Δp can be obtained when the grouting pressure l_1 is known.

4. Grouting Experiment

In order to verify the applicability of formula for penetration grouting mechanism based on Newton fluid of time-dependent behavior of rheological parameters derived above (i.e., formula (19) or formula (21)), an indoor grouting experiment was designed to verify the formula).

4.1. Grouting Experimental Device. The grouting experimental device is composed of the experiment chamber, pressure supply device, and grouting storage container as shown in Figure 3. The experiment chamber, composed of the steel support and plexiglass plate, has an appearance size of $600 \times 600 \times 600$ mm, and it is used to place the grouted medium, as shown in Figure 3(a). The nitrogen installed in the pressure supply device offers pressure for grouting. The grouting pressure can be monitored by a pressure monitor installed at the upper end of the grouting pipe. Through the nitrogen pressure reducer and grouting control switch, the precise grouting pressure and grouting time can be controlled, as shown in Figure 3(b). The grout storage container is mainly composed of the closed steel cylinder and circular-shaped iron frame, in which the closed steel cylinder is sized with a bottom diameter of 15 cm and a height of 40 cm; it is designed to bear the pressure at 2.5 MPa. The container opened at the top and bottom, respectively. A metal joint is welded to hold Newton fluid of time-dependent behavior. When the experiment is conducted, the metal joint is put into a circular iron frame, the pressurized nitrogen enters the grout storage container from the top through the pipe, and then the grouted fluid is applied with the pressure and enters into the grouted medium. The electronic scale at the lower

(a) (b) (c)

Figure 3: Physical photos of grouting experiments device. (a) Experiment chamber. (b) Pressure supply device. (c) Grout storage device.

part is capable of accurately measuring the volume of Newton fluid in the whole grouting experiment process as shown in Figure 3(c).

4.2. Grouting Materials and Grouted Medium. In this paper, gravel (sand) stone bodies with particle size respectively distributed within the range of 1–3 mm, 3–5 mm, and 5–10 mm were selected as the grouted medium for the verifying experiment. To make the grouted gravel (sand) body met the hypothesis for isotropy and homogeneity, the gravel (sand) stone bodies had been washed out in clear water for 3 times before start the grouting experiment.

The properties of three types of grouted gravel (sand) stone bodies are shown in Table 1.

By referring to GB/T50123-1999 Standard for Soil Experiment Method issued by the Ministry of Water Resources of China, the proportion γ_s and water content ω of gravel (sand) stone bodies in Table 1 can be obtained by specific indoor experiment. Density is designed by the actual grouting experiment; then, according to formula (23), the porosity of gravel (sand) body can be calculated. The permeability coefficient was obtained by using type 70 permeameter (the inner diameter of the type 70 permeameter is 100 mm and the maximum particle diameter of the injected gravel (sand) body is 10 mm in this experiment; therefore, $\varphi/d = 10 > 5$, and it meets the requirements of grouting permeability test), and the experiment is shown in Figure 4.

Ordinary Portland cement with a grade of #32.5 produced by Kunming Cement Plant was selected as the grouting material. In the verifying experiment of this paper, the grout with a water-cement ratio of 2.0 was used for the grouting verifying experiment. According to [20, 21], such a grout was a typical Newton fluid, and its rheological formula of time-dependent behavior of rheological parameter can be found in the research results of [20].

4.3. Working Principle and Steps. The working principle of the experiment is shown in Figure 5.

The experiment steps are shown as follows:

(1) According to the density and porosity in Table 1, the volume of grouted gravel (sand) stone body in the experiment chamber (3) was calculated. Four layers of gravel (sand) stone body were designed and laid from the bottom of the experiment chamber, and the pave height of each layer was designed to be 15 cm; then, the theoretical mass of each layer of gravel (sand) stone body in each group of grouting verifying experiment was calculated as shown in Table 2 according to the predetermined density in Table 1.

(2) Assemble experiment chamber (3) according to the design requirements, lay a plastic film (to prevent grout leakage during grouting), and mark the height of each 15 cm from the bottom to the top, so as to accurately control the soil laying of each layer.

(3) Lay the gravel (sand) stone body according to the theoretical mass of each layer in Table 2, and compact the gravel (sand) stone body on each layer within the marked volume range. Ensure that the density and porosity meet the specified requirements in Table 1; then lay the grouting pipe simultaneously.

(4) Prepare cement grouts (5) with a water-cement ratio of 2.0, weigh the required materials, and mix them for over 5 minutes to ensure the uniformity of the grouts.

(5) Pour the mixed grout into a grout storage container (2) and install the grouting pipe (7).

(6) Check the above steps and prepare for grouting.

(7) Start grouting. Turn on the grouting control switch, and start nitrogen pressure reducer (4) to make the grouting pressure quickly hit the designed value;

Table 1: Elementary properties of three grouted gravel (sand) stone body.

Particle sizes	Proportion γ_s	Water content ω (%)	Density γ (g/cm^3)	Permeability coefficient K (cm/s)	Porosity ϕ (%)	Number
1~3 mm	2.63	7.61	1.70	0.65	39.93	Material 1
3~5 mm	2.65	9.88	1.60	2.11	45.05	Material 2
5~10 mm	2.72	11.95	1.50	8.94	50.74	Material 3

Figure 4: Physical photos of the coefficient of permeability experiments on the grouted gravel (sand) stone body.

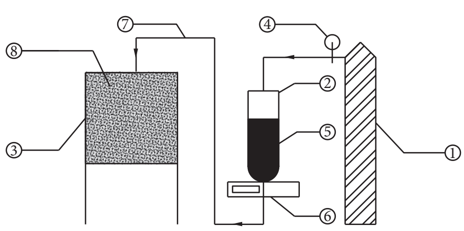


Figure 5: Schematic diagram of the operation principle of the grouting experiments. (1) Pressure supply device. (2) Grout storage container. (3) Experiment chamber. (4) Nitrogen pressure reducer and grouting control switch. (5) Newton fluid, grout of time-dependent behavior of rheological parameter. (6) Electronic scale. (7) Grouting pipe. (8) Gravel (sand) stone body with a uniform grain size.

then, make sure the grouting pressure in the entire grouting process is the designed value (as shown in Table 2). Observe the flow and diffusion of the grout.

(7) Stop grouting. When the grouting duration hits the designed time in Table 2, stop grouting.

(8) Mould removal and measurement. When the grout is completely consolidated with the grouted gravel (sand) stone body, measure the three-dimensional diffusion radius of the grouting body.

(9) Analyze the experimental data and draw a conclusion.

4.4. Grouting Verifying Experiment

4.4.1. Experiment Design. The grouting verifying experiments designed in this paper are shown in Table 2. PVC pipe with a diameter of 15 mm is to be used for the grouting test. Namely, the radius grouting pipe is $l_0 = 0.0075$ m. Both the indoor environment temperature and water temperature for the experiment are 20 °C (the water viscosity at 20 °C is $\mu = 1.01\times10^{-3}$ Pa·s), and some corresponding basic grouting parameters can be calculated by the formula introduced above, as shown in Table 3.

Physical photos of the grouting verifying experiments are shown in Figure 6.

4.4.2. Determination on Flow State of Newton Fluid of Time-Dependent Behavior. Utilize formula (22) to determine the flow state of Newton fluid of time-dependent behavior in the grouted gravel (sand) body before starting the experiment.

Calculate the Reynolds number Re_b of the instantaneous mixed cement grouts. Reynolds number of Newton grout of time-dependent behavior in Experiment 1, Experiment 2, and Experiment 3 satisfied $\mathrm{Re}_{G1b} = 25.9$, $\mathrm{Re}_{G2b} = 32.51$, and $\mathrm{Re}_{G3b} = 38.02$. When their viscosity gradually increased, the pore size and path space became smaller or were even completely blocked; also the average movement speed of the grout decreased gradually. Then, the instantaneous Reynolds number of grout decreased in the grouting process. Namely, the instantaneous Reynolds number of Newton grout of time-dependent behavior satisfied the relationship $\mathrm{Re}_b < 2000$. This result showed that the Newton grout of time-dependent behavior with a water-cement ratio of 2.0 in the grouting process of gravel (sand) stone body coincided with the theoretical basis of the laminar flow state.

4.4.3. Determination on Diffusion Radius of Grouting and Analysis on Grouting Stone Body. It is found from Figure 6 that Newton grout of time-dependent behavior in the grouted gravel (sand) stone body showed a semiellipsoid diffusion shape, which was close to the theoretical diffusion shape (the completely hemispherical diffusion shape). In order to analyze and compare the difference between actual diffusion shape and theoretical diffusion shape in a better way, the diffusion radii of axis x, axis y, and axis z of the grouting stone body were measured and analyzed.

When the grouting test is completed, disassemble the experiment chamber, measure the diffusion radius of grouting stone bodies in axis x, axis y, and axis z with the ruler at least three times each, and take the average value.

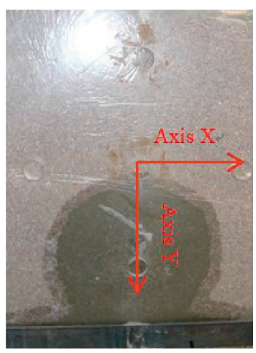
The comparative analysis results of the diffusion radius of grouting stone body in axis x, axis y, and axis z directions are shown in Table 4.

Table 2: Design parameters of grouting experiments.

Grouted medium							
Experiment number	Water–cement ratio	Volume of gravel (sand) stone body to be laid on each layer (cm^3)	Material grade	Designed density (g/cm^3)	Theoretical mass of gravel (sand) stone body to be laid on each layer (kg)	Grouting pressure (MPa)	Grouting duration (s)
G1			Material 1	1.70	91.8		300
G2	2.0	54000	Material 2	1.60	86.4	0.04	200
G3			Material 3	1.50	81.0		120

Table 3: Some basic penetration grouting parameters about the grouting verification experiments.

Experiment number	l_0 (m)	M (Pa·s)	β	r_0
G1				1.15×10^{-2}
G2	0.0075	1.01×10^{-3}	4.65	1.95×10^{-2}
G3				3.77×10^{-2}



(a)

(b)

Figure 6: Physical photos of the grouting verifying experiments. (a) Flow pattern. (b) Consolidated stone body.

Table 4: Analysis and comparison of the diffusion radius on x-, y-, and z-axis directions of grouting stone body.

Diffusion radius size of grouted and consolidated stone body				
Experiment number	Axis x (mm)	Axis y (mm)	Axis z (mm)	Difference between maximum and minimum sizes (%)
G1	98.9	100	99.5	1.10
G2	121.6	126.1	123.9	3.57
G3	162.9	170.1	166.8	4.23

It is found from Table 4 that there is an insignificant difference with respect to the size of diffusion radiuses of axis x, axis y, and axis z of grouting stone body. The size of the diffusion radius in the direction of axis y is maximum, and the size in the direction of axis x is minimum, but the difference between such two values was within 5%; this indicates that the shape of the grouting stone body is close to the theoretical model, as shown in Figure 2.

4.4.4. Result Analysis. According to the penetration grouting mechanism based on Newton fluid of time-dependent behavior of rheological parameters, the theoretically calculated value of diffusion radius, the actually measured value of diffusion radius, and the difference analysis between them are shown in Table 5. For comparison, the diffusion radius of Maag formula [1] without considering the time-dependent behavior of the viscosity of Newton fluid was calculated and the diffusion radius and difference between the Maag value and experimental value are also listed in Table 5.

To verify and analyze the applicability of formula (19) or (21) in a more effective manner, the minimum measured diffusion radius in three-dimensional directions (i.e., the diffusion radius size in the direction of axis x) is compared to the theoretically calculated value.

Analyzing Table 5, it is concluded that the theoretical value of the grouting diffusion radius calculated by the formula based on Newton fluid of time-dependent behavior of rheological parameters derived in this paper basically

Table 5: The theoretical calculation and the actual measured values of the final diffusion radius in the grouting experiment.

Experiment number	Theoretically calculated value of grouted diffusion radius/mm		Actually measured value of grouted diffusion radius/mm	Error analysis	
	To follow the formulas in this paper	To follow Maag formula		Formula in this paper (%)	Maag formula (%)
G1	113.6	458.5	98.9	12.94	78.43
G2	142.7	569.7	121.6	14.79	78.66
G3	188.6	747.3	162.9	13.63	78.20

coincides with the measured value of the grouting verifying experiment, and the difference is within 15% between the two values, which is much less than the change in 80% between the measured value and the value calculated by the Maag theoretical formula. This indicates that the penetration grouting mechanism based on Newton fluid of time-dependent behavior of rheological parameters established in this paper can reflect the penetration grouting mechanism based on Newton fluid of time-dependent behavior of rheological parameters, and the results are closer to the actual value. Such results can provide theoretical support and guidance for actual grouting construction.

There are three reasons for the theoretical diffusion radius by using the formula for penetration diffusion mechanism based on Newton fluid of time-dependent behavior of rheological parameters derived in this paper being larger than the actually measured value in grouting test.

(1) Multiple factors affect the permeability and diffusion radius of Newton fluid of time-dependent behavior of rheological parameters in the grouted medium. For example, the grout is considered to be an unstable liquid due to excessive water separation rate while being prepared, but the Newton fluid is assumed to be a stable grout liquid when the theoretical value is calculated by using the formula for penetration diffusion mechanism based on Newton fluid of time-dependent behavior of rheological parameters; for example, sedimentation and blockage may occur when the grout diffuses in the grouted medium.

(2) The gravel (sand) bodies were still different from the isotropic and homogeneous hypothesis after washing three times.

(3) Presently, although some research achievements have been made in the time-dependent behavior of Newton fluid, the research on the time-dependent behavior of the grouts is still in the experimental stage. The rheological models are instructive to the research, but their time-dependent behavior law cannot be truly reflected.

5. Conclusions

(1) On the basis of the basic rheological formula for Newton fluid and time-dependent behavior of its rheological parameters, the rheological formula of Newton fluid of time-dependent behavior is established.

(2) The seepage motion formula for Newton fluid of time-dependent behavior is studied, and the formula for penetration grouting diffusion mechanism based on Newton fluid of time-dependent behavior of rheological parameters is deduced. A specific determination method and application scope of each parameter in the formula are analyzed.

(3) The formulas for penetration grouting diffusion mechanism based on Newton fluid of time-dependent behavior of rheological parameters are verified by grouting experiments. The results show that the theoretical value of the grouting diffusion radius calculated by the formula based on Newton fluid of time-dependent behavior of rheological parameters derived in this paper basically coincides with the measured value of the grouting verifying experiment, and the difference is within 15% between the two values, which is much less than the change in 80% between the measured value and the value calculated by Maag theoretical formula. This indicates that the penetration grouting mechanism based on Newton fluid of time-dependent behavior of rheological parameters established in this paper can reflect the penetration grouting mechanism based on Newton fluid of time-dependent behavior of rheological parameters, and the results are closer to the actual value. Such results can provide theoretical support and guidance for the actual grouting construction.

Data Availability

All data generated or analyzed during this study are included in this manuscript.

Conflicts of Interest

The authors declare that they have no known conflicts of financial interests or personal relationships that could influence the work reported in this paper.

Acknowledgments

The authors thank National Natural Science Foundation of China (Grant no. 41861134008), Key R&D Program of Yunnan Province (Grant no. 202003AC100002), and General Program of Basic Research Plan of Yunnan Province (Grant no. 202001AT070043) for their financial support during the preparation of this manuscript.

References

[1] G. Wang, *Grouting Technology Theory and Practice*, China University of Mining and Technology Press, Beijing, China, 2000.

[2] J. Kuang, *Geotechnical Grouting Theory and Engineering Examples*, Science Press, Beijing, China, 1993.

[3] Y. Mi-jia, C. Guo-xiong, and Y. He, "The development trend and research present condition of grouting theory," *Chinese Journal of Rock Mechanics and Engineering*, vol. 20, no. 6, pp. 839–841, 2001.

[4] L. Jia-cai, "Study on crack grouting diffusion radius," in *Collection Papers of China Institute of Water Resources and Hydropower Research*, pp. 186–195, Water Resources and Electric Power Press, Beijing, China, 1982.

[5] C. Baker, *Rock Stabilization in Rock Mechanics*, Springer-Verlag, Newyork, NY, USA, 1974.

[6] Z. Jin-feng, L. Liang, and Y. Xiao-li, "Penetration radius and pressure attenuation law in fracturing grouting," *Journal of Hydraulic Engineering*, vol. 37, no. 3, pp. 314–319, 2006.

[7] L. Wei-Lie, *Theory and Practice of Grouting*, Northeast University Press, Shenyang, China, 1975.

[8] J. Wei-Cheng and N. I. Wen-yao, "Theoretical analysis and the control technology of drilling and grouting," *Coal Mine Safety*, vol. 5, no. 4, pp. 14-15, 1999.

[9] W. Ruan, "Research on diffusion of grouting and basic properties of grouts," *Chinese Journal of Geotechnical Engineering*, vol. 27, no. 1, pp. 69–73, 2005.

[10] Q. Liu, L. Chao-bo, B. Liu, and X. Lu, "Study on rheological properties of cement slurry considering the effects of temperature and hydration time," *Chinese Journal of Rock Mechanics and Engineering*, vol. 33, no. S2, pp. 3730–3740, 2014.

[11] N. Roussel, "Steady and transient flow behaviour of fresh cement pastes," *Cement and Concrete Research*, vol. 35, no. 9, pp. 189–199, 2004.

[12] L. I. Zhu-guo and G. Cao, "Rheological behaviors and model of fresh concrete in vibrated state," *Cement and Concrete Research*, vol. 120, pp. 217–226, 2019.

[13] X. Kong, *Higher Percolation Mechanics*, Press of University of Science and Technology of China, Beijing, China, 1999.

[14] D. Gao, *Engineering Fluid Mechanics*, Machinery Industry Press, Beijing, China, 1999.

[15] C. Shen and L. I. U. He-nian, *Non-Newtonian Fluid Mechanics and its Application*, Higher Education Press, Beijing, China, 1989.

[16] R. Zenit, D. L. Koch, and A. S. Sangani, "Measurement of the average properties of a suspension of bubbles rising in a vertical channel," *Journal of Fluid Mechanics*, vol. 429, pp. 2-3, 2001.

[17] W. Zhang and C. Wen-yi, *Fluid Mechanics*, Tianjin University Press, Tianjin, China, 2009.

[18] X. Zeng, *Mud Rheology and Viscosity Measurement*, The Geological Society of Hunan, Hunan, China, 1981.

[19] Ministry of Water Resources of the People's Republic of China and GB/T50123-1999, *Standard for Test Methods of Earthworks*, China Planning Press, Beijing, China, 1999.

[20] W. Ruan, *Basic Properties of Grouts and Spreading of Grouts in Rock Mass fissures*, Jilin University, Jilin, China, 2003.

[21] W. Ruan, "Spreading model of grouting in rock mass fissures based on time-dependent behavior of viscosity of cement-based grouts," *Chinese Journal of Rock Mechanics and Engineering*, vol. 24, no. 15, pp. 2709–2714, 2005.