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Analysis and engineering application investigation of multiple-hole grouting injections into porous media considering filtration effects

Zilong Zhou [a], Xueming Du [a,b,*], Shanyong Wang [b], Haizhi Zang [a]

[a] School of Resources and Safety Engineering, Central South University, Changsha, Hunan, 410083, China
[b] ARC Centre of Excellence for Geotechnical Science and Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan, Australia

HIGHLIGHTS

- The change of porosity decreases with increasing tortuosity dimension.
- The effective range depends not only on the diffusion pressure but also on the porosity of injected medium with filtration.
- The expense of triangular pass is less than that of rectangular pass.

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ABSTRACT

The arrangement parameters of multiple grouting holes are important issues in soil sealing and in guaranteeing the grouting effectiveness. To better understand the effects of the arrangement parameters of multiple grouting holes, including the arrangement of the pass and space between the holes (the effective range of slurry diffusion and effective porosity of the injected media), on the effectiveness of grouting reinforcement, diffusion models of single-hole grouting and multiple-hole grouting are constructed based on fractal geometry and filtration effects. Then, the parameters of the grouting hole obtained by the present model are applied to the site. After grouting, the effect of grouting reinforcement under the corresponding parameters of the hole is obtained by analysing ground-penetrating radar data for the design profile and the porosity of each observation hole. The theoretical and engineering test results show the following responses: (1) The predictions from the proposed model show good consistency with the literature data and application results. For instance, in the case with filtration, the porosity increases faster at nearer distances, beyond which there is approximately no change in porosity with increasing distance. However, in the case without filtration, there is approximately no change in porosity with increasing distance during the whole process of grouting. (2) In the case without filtration, the effective diffusion range of the slurry depends only on the diffusion pressure of each test point. However, in the case with filtration, the effective diffusion range of the slurry depends not only on the diffusion pressure of each test point but also on the porosity of the injected media. (3) Under identical parameters of grouting hole and engineering geological conditions, the grouting expense of a triangular pass is less than that of a rectangular pass to achieve the same grouting effect.

1. Introduction

Permeation grouting is an effective method used for improving soil stabilization without disturbing the original soil structure. Due to its very affordable cost and low environmental pollution emission, cement-based grout is widely used in various civil engineering applications [1,2]. The basic principle is that grouts are injected in the zone to drive up water and air in the space of soil to improve the structural properties of injected media. However, when selecting a grouting procedure, the grout material, grouting diffusion pressure, layout of grouting holes and grout volume that will achieve the desired goal in the most economic manner must be determined [3]. The arrangement parameters of multiple grouting holes play important roles in grouting engineering [4–6]. The arrangement of the pass and space between holes determines not only the quality of the grouting effect but also the economic cost of grouting. Therefore, understanding the effect of multiple-hole grouting on the effect of grouting reinforcement under the hole

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* Corresponding author at: School of Resources and Safety Engineering, Central South University, Changsha, China.

E-mail address: 2007-dxm@163.com (X. Du).

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design parameters (the effect law of the arrangement of the pass and space between holes) is of great importance in the design of grouting engineering.

As part of efforts to elucidate the effect law of multiple-hole grouting for grouting reinforcement, researchers have found that the reinforcement performance of multiple-hole grouting is influenced by two factors: the arrangement of the pass and space between holes. Jafari et al. investigated multiple-hole grouting in the laboratory on clay specimens prepared at different overconsolidation ratios and found that for a given total injection volume, the effect of grouting reinforcement under multiple-hole grouting (by injecting small amounts of grout at multiple locations) is superior to that of single-hole grouting (by injecting the whole volume at a single location). In addition, research has shown that an excessive (too large or too small) space is not conducive to the effect of grouting reinforcement [7]. Hao studied the interaction relationship between multiple-hole grouting under different pass values and proposed some valuable theoretical equations of grouting [6]. Zhao et al. analysed the design of hole arrangement for treating the deterioration of cement concrete pavement and obtained design calculation methods for the concrete disease treatment process for two-hole, three-hole, four-hole and five-hole grouting-hole layout schemes [8].

However, previous studies of multiple-hole grouting have largely neglected the filtration effect of slurry [4,5,9], and their results are only applicable to chemical grout or ultrafine cement slurry, not ordinary cement slurry. During cement-based slurry diffusion, another process (filtration process) can prevent diffusion of the grout into the pores of the porous media by clogging the porous media. In addition, even if slurry arrives at the far region from the injection point, the strength of the injected media may not achieve the design of the reinforcement strength due changes in the original properties of the slurry (continuous adsorption or deposition of particles).

To further reveal the diffusion mechanism of multiple-hole grouting, it is necessary to study the effects of the arrangement of the pass and spaces between the holes on grouting reinforcement. This paper presents a study of theory and engineering practice devoted to investigating the effects of the parameters of multiple-hole grouting, including the arrangement of the pass and spaces between the holes, on the diffusion mechanism of multiple-hole grouting considering filtration. To accomplish this, based on fractal geometry and the filtration effect, diffusion models of single-hole grouting and multiple-hole grouting considering the filtration effect are first constructed. Then, to verify the feasibility of the design parameters, the parameters of the grouting holes obtained by these models are applied to the site. Finally, the effect of grouting reinforcement under the corresponding parameters of the hole is obtained by analysing ground-penetrating radar data of the design profile and the porosity of each observation hole.

2. Fractal characteristics of porous media

It is assumed that porous media contain a large number of capillaries [10,11], which are a set of voids or gaps separated by a solid skeleton. The cumulative number (N) of capillaries with a size of at least λ in a representative unit cell and the pore size distribution are given by the following equation [12–14]:

$$N(\geq \lambda) = \left(\frac{\lambda_{\max}}{\lambda}\right)^{D_f} \tag{1}$$

where λ is the capillary diameter, λ_{max} is the maximum capillary diameter and D_f is the fractal dimension of the capillary; in general, $1 < D_f < 2$ in two dimensions, and $2 < D_f < 3$ in three dimensions. The size of the fractal dimension represents the uniformity of the pore size distribution. The smaller the fractal dimension, the more uniform the pore size distribution.

Differentiating both sides of Eq. (1) with respect to λ gives the following:

$$-\mathrm{d}N(\lambda) = D_f \lambda_{\max}^{D_f} \lambda^{-(D_f+1)} \mathrm{d}\lambda \tag{2}$$

When liquids flow through the pores of a porous medium, the capillaries may be tortuous. These tortuous capillaries can be expressed by the following fractal equation:

$$L_t = \lambda^{1-D_T} L^{D_T} \tag{3}$$

where L_t and L_0 are the actual length of the capillary and the representative length of the capillary, respectively, and D_T is the tortuosity fractal dimension of the capillary. In general, $1 < D_T < 2$ in two dimensions, which represents the extent of tortuosity of capillary pathways for slurry flow in porous media. Note that when the tortuosity fractal dimension of capillary D_T is equal to 1, the pathway for slurry flow in the porous medium is a straight capillary path. A higher value of the tortuosity fractal dimension of the capillary corresponds to a highly tortuous pathway for the flow of slurry.

Differentiating both sides of Eq. (3) with respect to L_0 gives the following:

$$\mathrm{d}L_t = \lambda^{1-D_T} L^{D_T - 1} D_T \mathrm{d}L \tag{4}$$

3. Analysis of multiple-hole grouting considering the filtration effect

3.1. Analysis of a single hole with respect to grouting pressure and the porosity of porous media

For a Bingham fluid, the flow rate q(λ) through a single tortuous capillary can be predicted by [15,16]:

$$q(\lambda) = -\frac{\pi\lambda^{3+D_T}}{128\mu L^{D_T-1} D_T}\frac{\mathrm{d}p}{\mathrm{d}L} - \frac{\tau_0 \pi \lambda^3}{32\mu} \tag{5}$$

where τ_0 is the yield stress and μ is the viscosity of the slurry, p is the diffusion pressure of the slurry.

The total flow rate Q(λ) through a unit volume consists of a set of individual capillaries of flow rate q(λ) that cover the whole range of capillaries whose diameters are within the range between λ_{min} and λ_{max}. From Eqs. (2)–(5), we have

$$\begin{aligned} Q(\lambda) &= -\int_{\lambda_{\min}}^{\lambda_{\max}} q(\lambda)\mathrm{d}N(\lambda) \\ &= \int_{\lambda_{\min}}^{\lambda_{\max}} \left(- \frac{\pi\lambda^{3+D_T}}{128\mu L^{D_T-1} D_T}\frac{\mathrm{d}p}{\mathrm{d}L} - \frac{\tau_0\pi\lambda^3}{32\mu}\right) \\ &\quad \times D_f \lambda_{\max}^{D_f} \lambda^{-(D_f+1)} \mathrm{d}\lambda \\ &= -\frac{\pi\lambda_{\max}^{3+D_T} D_\mathrm{f} \mathrm{d}p}{128\mu L^{D_T-1} D_T (3 + D_T - D_\mathrm{f})\mathrm{d}L}\left[1 - \left(\frac{\lambda_{\min}}{\lambda_{\max}}\right)^{3+D_T-D_\mathrm{f}}\right] \\ &\quad - \frac{\pi\tau_0 D_\mathrm{f}}{32\mu(3 - D_\mathrm{f})}\lambda_{\max}^3\left[1 - \left(\frac{\lambda_{\min}}{\lambda_{\max}}\right)^{3-D_\mathrm{f}}\right] \end{aligned} \tag{6}$$

The capillary area of the unit cell can be expressed as:

$$\begin{aligned} A_P &= -\int_{\lambda_{\min}}^{\lambda_{\max}} \frac{1}{4}\pi\lambda^2 \mathrm{d}N(\lambda) \\ &= \int_{\lambda_{\min}}^{\lambda_{\max}} \frac{1}{4}\pi\lambda^2 D_\mathrm{f} \lambda_{\max}^{D_\mathrm{f}} \lambda^{-D_\mathrm{f}+1} \mathrm{d}\lambda \\ &= \frac{\pi D_\mathrm{f}}{4(2 - D_\mathrm{f})}\lambda_{\max}^2\left[1 - \left(\frac{\lambda_{\min}}{\lambda_{\max}}\right)^{2-D_\mathrm{f}}\right] \end{aligned} \tag{7}$$