Harmonising Rock Engineering and the Environment – Qian & Zhou (eds)

Numerical modeling for the evaluation of grout penetration in fractured rock masses

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ABSTRACT: Grouting aims to reduce the permeability of rock mass below the required value and has been widely used in rock engineering field for a long time. However, the injection procedure needs several empirical decision makings and it is rather difficult to reliably confirm the achievement of improvement, because the grout penetration process is not sufficiently clarified. This study proposes a stochastic prediction method of spatial distribution of rock hydraulic properties after grouting in fractured rock mass by using the grout penetration process model. The goal achievement probability under the specific target permeability is computed with the help of geostatistical interpolation method. The applicability of the method is verified through the several field applications.

Subject: Modelling and numerical methods

Keywords: numerical modelling, Rock joints, fluid flow, site characterization

1 INTRODUCTION

The materials stored in underground rock storage facility have gradually diversified over time (e.g. high-pressure gas storage, high level radioactive waste repository, etc.). In order to store these materials, a more reliable storage functioning is required and rock hydraulic properties around the cavern must be improved sufficiently. Especially, it is important to predict and evaluate the spatial distribution of rock hydraulic properties after grouting in fractured rock mass for the reliable groundwater control.

Grouting aims to reduce the permeability of rock mass below the required value and has been widely used in rock engineering field for a long time. However, the injection procedure needs several empirical decision makings and it is rather difficult to reliably confirm the achievement of improvement, because the grout penetration process is not sufficiently clarified.

This study proposes a stochastic prediction method of spatial distribution of rock hydraulic properties after grouting in fractured rock mass by using the grout penetration process model. The applicability of the method is verified through the several field applications.

2 NUMERICAL MODELING OF GROUT FLOW

2.1 *Modeling*

Considering the balance between the gravity force of a cement particle in suspension and drag force of a cement particle (Date, 2003, Aoki, 2003), terminal settling velocity of cement particle in suspension v is calculated by

$$v = \sqrt{\frac{4}{3}\frac{1}{C_D} g d_p \frac{\delta_p - \delta}{\delta}} \tag{1}$$

where d_p = diameter of particle; δ_p = specific gravity of particle; δ = specific gravity of suspension; and $C_D = 24/R_e$ = drag coefficient in the case of turbulent flow; R_e = Reynolds number.

Since volume of sediments in parallel plates produced in a unit period of time is constant, we have

$$s(0)d(0) = s(t)d(t) = const. \tag{2}$$

where $s(t)$ = width of sediments produced during the period from t to $t + \Delta t$, which is proportional to v; and $d(t)$ = range of sedimentation during the period from t to $t + \Delta t$.

Based on the law of conservation, $s(t)$ can be written as,

$$s(t) = \frac{d(0)}{d(t)} s(0) = \frac{Fd(0)}{Fd(t)} s(0) = \frac{E(0)}{E(t)} s(0) \tag{3}$$

where, $E(t)$ = kinetic energy of particles in suspension at t; and F = drag force of suspension.

On the other hand, obeying cubic law, flow rate $q(t)$ during the period from t to $t + \Delta t$ is given by,

$$q(t) = \frac{gb(t)^3}{12v} i \tag{4}$$

where $b(t)$ = distance between plates (aperture) at t; and i = hydraulic gradient. Velocity of suspension at t, $u(t)$ is given by

$$u(t) = \frac{q(t)}{b(t)} \tag{5}$$

From equations (3)(4) and (5), finally we can have

$$s(t) = \frac{q(0)u(0)^2}{\sum_{\tau=0}^{t} q(\tau)u(t)^2} s(0) \tag{6}$$

Substituting equation (6) for

$$b(t+1) = b(t) - s(t) \tag{7}$$

and substituting equation (7) for (4)(5)(6), we can obtain $q(t+1)$, $u(t+1)$ and $s(t+1)$. Thus, the change of flow rate as a function of time, total grout take, total time for injection, and so on can be simulated by following such iteration procedure until aperture $b(t)$ becomes 0.

The above process expresses the suspension flow near the borehole. To express the suspension flow in rock mass, the radial flow model is introduced. The suspension flow decreases in velocity in inverse proportion to distance form the centre of borehole. The discrete elements are established along the radial lines to analyze the penetration of suspension. In each element, flow rate and grout width are calculated by the iteration using equations (4) (5) (6) and (7) .

In applying the above procedure to rock mass, aperture distribution of the fractures intersecting the injection hole must be required in order to determine $b(0)$. However, if all apertures can be represented as a mean value, the flow rate of the rock mass can be expressed as

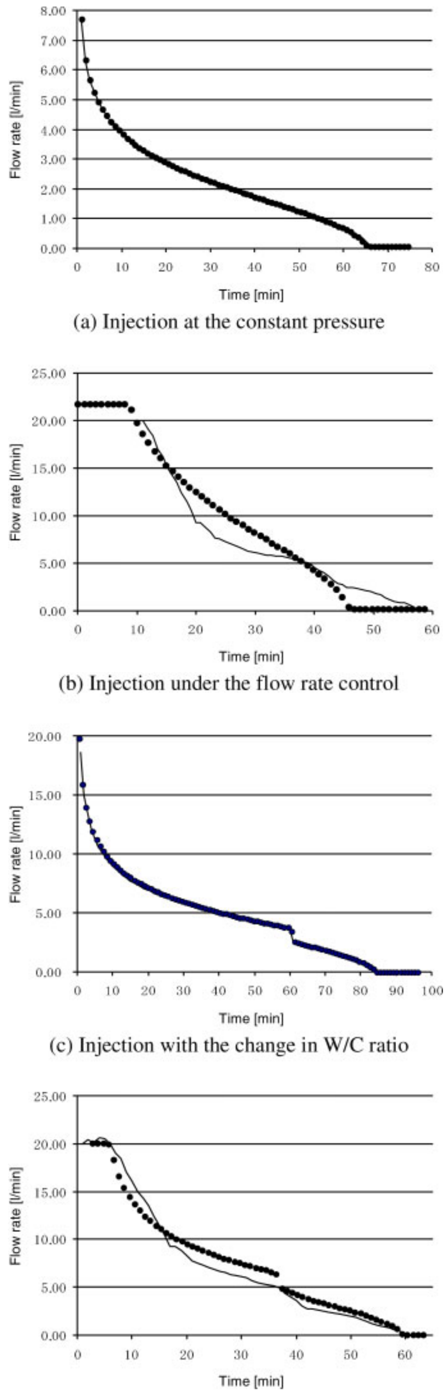
$$Q_{RM}(t) = N \sum \{ f_B(b) Q(t | b(0) = b_M) \} \tag{8}$$

where N = number of the fractures intersecting the injection hole; $f_B(b)$ = probability density function of aperture, b_M = averaged aperture.

As a result, the flow rate in the field tests can be simulated using equation (8). The number of fractures is determined by referring the fracture spacing data from borehole television system. Averaged aperture can be obtained from cubic law with the spacing data.

2.2 *Model validation*

The applicability of the proposed grout penetration model is examined through the several field applications. Figure 1 shows the illustrations of the comparison between the theoretical plots of flow rate obtained from the analysis with the proposed model and the actual field data. Figure 1(a) shows the injection case at the constant pressure. Figure 1(b) shows the injection case in the high permeable rock mass under the flow rate control. Figure 1(c) shows the injection case with the change in W/C ratio during the injection. As shown in the figures, the theoretical plots are closed to the field data. Figure 1(c) shows the compound case under the conditions of (b) and (c). Thus, it is found that the flow behaviors of suspension can be simulated by the iteration procedure using equations (4) (5) (6) and (7). Thus the proposed model is validated.



(a) Injection at the constant pressure

(b) Injection under the flow rate control

(c) Injection with the change in W/C ratio

(d) Injection under the compound conditions

Figure 1. The illustrations of comparison between the theoretical plots of flow rate obtained from the analysis with the proposed model and the actual field data (line).

3 PREDICTION METHOD OF IMPROVEMENT

In this section, the authors propose a stochastic prediction method of spatial distribution of rock hydraulic properties after grouting by using grout penetration process model developed in Section 2.

3.1 *Geostatistical estimation of hydraulic conductivity*

Ordinary Kriging, one of geostatistical interpolation method is employed to estimate the spatial distribution of hydraulic

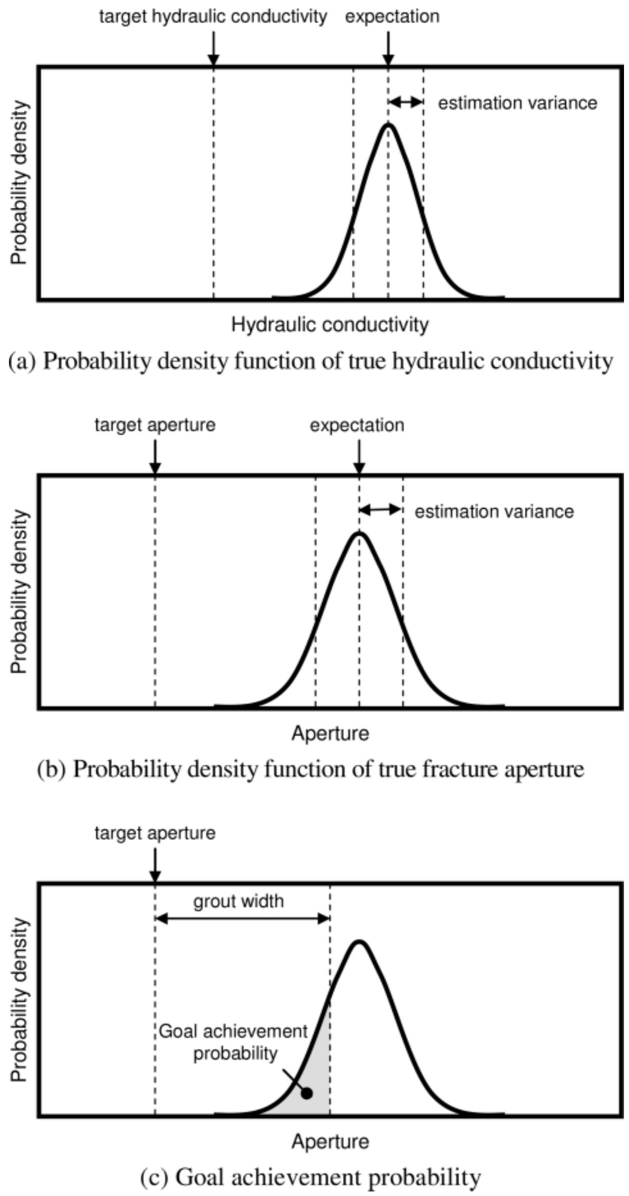


Figure 2. The calculation method of goal achievement probability.

conductivity before grouting. Logarithm of hydraulic conductivity data observed in the injection holes are used as the input data. Ordinary Kriging provides not only the estimated value but also the estimation variance everywhere in the space. This means we can have the confidence intervals of hydraulic conductivity at the arbitrary point in the space.

3.2 *Calculation of goal achievement probability*

It is impossible to grasp the real spatial distribution hydraulic conductivity because the estimated value generally includes error. Thus we consider obtaining the probability that hydraulic conductivity at the arbitrary point is under the required value (target hydraulic conductivity: e.g. target Lugeon value).

Figure 2 shows the concept of the method. At first, we can have probability density function of true hydraulic conductivity as shown in Figure 2(a) from the estimated value and the estimation variance calculated by Ordinary Kriging. In this figure, the target hydraulic conductivity is also plotted.

Assuming fracture spacing can be obtained, we can have probability density function of true fracture aperture and the target aperture as shown in Figure 2(b) by applying cubic low to the values shown in Figure 2(a).

From the grout penetration process model, we can have the grout width after grouting at the arbitrary point. Therefore, the area of distribution under sum of target aperture and grout width is the goal achievement probability by grouting as shown in Figure 2(c).

Thus, we can obtain the probability that hydraulic conductivity at the arbitrary point is under the required value.

4 VERIFICATION OF THE PRIDICTION METHOD

The proposed prediction method is verified through the field applications. The 84 values of hydraulic conductivity after grouting at 5 different sites are predicted by the proposed method and then the values of goal achievement probability under the specific goal achievement values are computed. The study sites are as follows;

– N dam (granite)
– O dam (rhyolite)

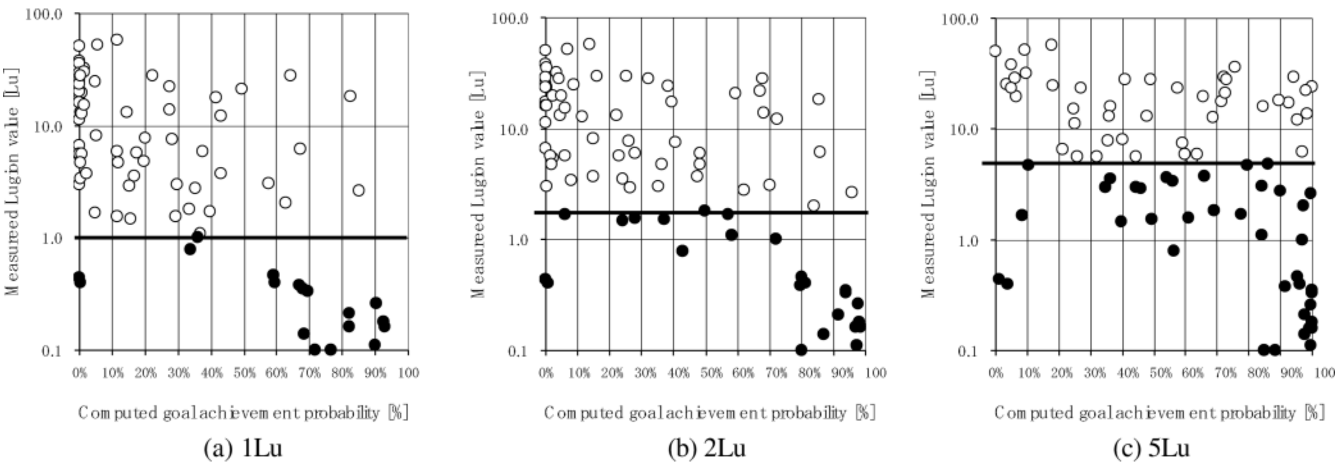


Figure 3. The computed goal achievement probability and the measured Lugeon value under the target Lugeon values of 1Lu (a), 2Lu (b), and 5Lu (c). White circles show the plots whose measured Lugeon value is greater than the target Lugeon value while black circles show those less than the target Lugeon value.

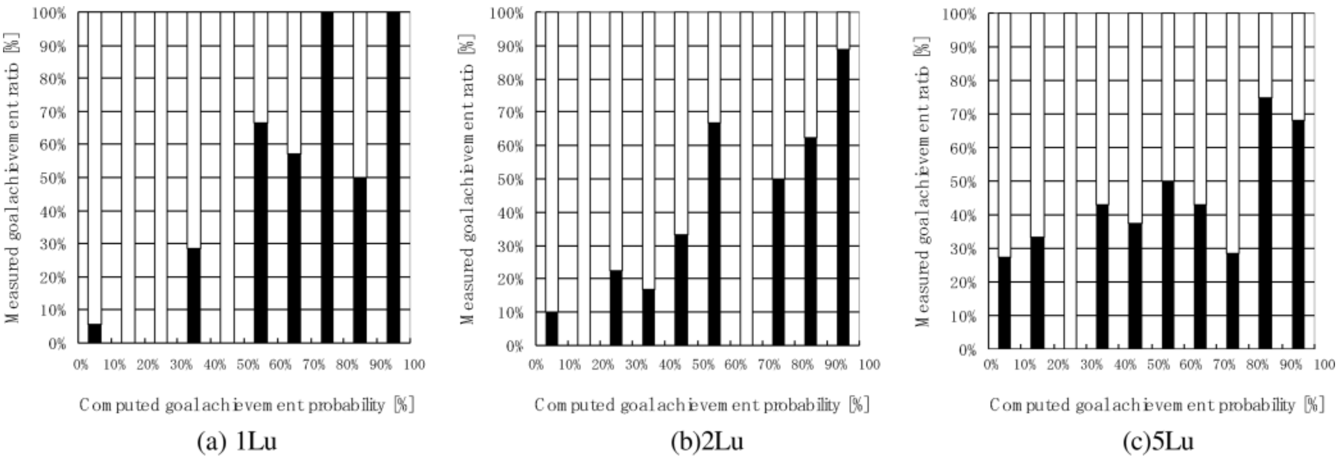


Figure 4. The computed goal achievement probability and the measured achievement ratio under the target Lugeon values of 1Lu (a), 2Lu (b), and 5Lu (c).

– C dam (andesite)
– G dam (andesite)
– M dam (conglomerate and sandstone)

The sets of Lugeon values obtained from the grouting tests for consolidation grouting are used for the verification. The goal achievement values at the secondary to quaternary holes are predicted by using the Lugeon values of primary to tertiary holes, respectively.

Figure 3 shows the computed goal achievement probability and the measured Lugeon value under the target Lugeon values of 1Lu (a), 2Lu (b), and 5Lu (c), respectively, and Figure 4 shows the computed goal achievement probability and the measured achievement ratio under the target Lugeon values of 1Lu (a), 2Lu (b), and 5Lu (c). From these figures it is found that the measured achievement ratio is almost same as the computed goal achievement probability except for that in the class consisting of small number of data irrespective of the difference of the target Lugeon value. This fact shows that the goal achievement probability at the arbitrary point, which allows performing the risk assessment, can be appropriately obtained by the proposed method.

5 CONCLUSION

This study proposed a stochastic prediction method of spatial distribution of rock hydraulic properties after grouting in fractured rock mass by using the grout penetration process model. The goal achievement probability under the specific target permeability can be computed with the help of geostatistical interpolation method. The applicability of the method has been verified through the several field applications.

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