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PROPOSAL OF TWO GROUT ANALYSIS METHODS

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A reliable grout analysis is important for the improvement of the grouting technology. Clarifying difficulties in developing such an analysis method, this paper proposes the Monte-Carlo simulation of fracture networks (MSFN) and the real-time inversion analysis (RTIA); the MSFN predicts the spatial variation of Legion values and the RTIA evaluates the water channel conditions and the grout agent flow. Input parameters of these analysis methods are geological data which are usually surveyed, and require no special measurement. The rigorous formulation of the MSFN and RTIA together with the explanation of a rock mass model to which the analysis method is applied.

Key Words : *grout analysis, permeable flow, fracture network, inversion*

1. INTRODUCTION

Recently, it is requested to construct structures in cites which have relatively cracked rock masses. The key issue is to secure the safety, for instance, on the impermeability. Grouting is essential[1] to this end[1),10),12),17)]. The grouting technology ought to be improved such that the construction becomes more secured and economical, and can be applied to inexperienced regions.

The grouting technology is mainly based on data and experiences which have been accumulated through the construction of previous sites. For the improvement of the grouting technology, one strategy is to develop an analysis method which can provide quantitative information. Such a grout analysis is aimed at predicting the rock improvement for given specifications, or evaluating conditions of grouting which is being applied.

There are the following three major problems[2] in developing a grout analysis:

1. difficulty in identifying water channel
2. unclarified flowing and hardening processes
3. rational evaluation of grouting effects

We are not expecting that these problems are fully solved as available geological and hydrological data are usually limited. It may be sufficient if a grout analysis is reasonably accurate in view of the uncertainty and limitation of these data.

In this and accompanying papers, we propose two analysis methods for grouting, namely, the *Monte-Carlo simulation of fracture networks* (MSFN) and the *real-time inverse analysis* (RTIA). The MSFN is aimed at predicting the rock improvement for a given specification, through the permeable flow analysis of grout agents in fracture networks[2),9),5)] generated according to the geological data. The RTIA evaluates the range and distance of intruded grout agents, using grout pressure and amount of flow which are continuously measured at a grout nozzle. **Table 1** summarizes the two grout analysis methods.

The content of this paper is as follows: First, the requirements of the grouting analysis is clarified in Section 2. Then, we present the MSFN and the RITA in Sections 3 and 4, respectively, paying attention to that these methods satisfy the requirements. It should be mentioned that the MSFN and the RTIA are to solve *well-set* problems of grouting; the well-set means that all input parameters are usually measured without requesting special measurement. Models and assumptions are made in developing these analysis methods, such that the three major problems are solved by taking best advantage of available data.

2. REQUIREMENT OF GROUT ANALYSIS

We set the basic request for a grout analysis as to answer the following questions:

1. What are the most suitable grouting specification for a target site?
2. Is the designed improvement actually achieved at each stage?

[1] Grouting will play a key role in constructing deposits of highly contaminated nuclear wastes, in order to prevent the environmental contamination in a long time span; see, for instance, [3),11),14),16)].

[2] See also [10),17)].

Table 1 TWO GROUT ANALYS METHODS

	MSFN	RTIA
objective	predict rock improvement	evaluate grout intrusion
input	geological data grout specification	crack width pressure and amount of flow
output	spatial distribution of Legion values	range and distance of intruded grout agents
model	fracture network of disk-shaped joints	partially open parallel disk

The proposed MSFN and RTIA are for the first and second questions, respectively. We consider countermeasures for the three major problems which were mentioned in the preceding section, in developing a grout analysis, such that the MSFN and the RTIA can provide answers to these questions.

Regarding to the first problem (water channel identification), it is not necessary to measure each water channel. The overall connectivity of the channels should be estimated to stop permeable flow or leaking by grouting. The MSFN uses a Monte-Calro simulation of fracture networks to simulate the overall connectivity; a probabilistic distribution of fractures is estimated from geological data of cracks which are ordinarily measured. The RTIA uses an alternative model for the water channels, one thin disk into which the permeable flow runs. The disk is not necessarily saturated with the grouting agent, which accounts for the connectivity. More complicate modeling may not be acceptable, as available data are limited.

Several phenomena have been considered for the second problem (flowing and hardening processes); for instance, the turbulence flow, the choice of particular channels, the damaging of cracks, or the diffusion and stacking of grout agents are pointed out. While some basic researches are necessary, simple modeling of these phenomena are essential in developing a grout analysis. As shown later, the MSFN considers some models which account for phenomena leading to the non-linearity. The RTIA does not use any special model, since the non-linearity can be reproduced to some extent by considering the local variation of the water channel connectivity.

In order to solve the third problem (grouting effect evaluation), we must set a certain computable quantity such that the rock improvement is quantified. The Legion value, which is a measure of in-site permeability, is a candidate for such a quantity, and the MSFN predicts the spatial variation of the Legion values. The RTIA evaluates the range and distance of grout agents as the target of the analysis. It should be mentioned that the MSFN takes care of the variance of the Legion values; it can predict the mean and standard deviation of the Legion values.

3. MSFN FOR GROUTING EFFECT PREDICTION

As mentioned, the MSFN solves[3] the three major problems considered in Section 1 in the following manner:

1. Water channels are modeled as fracture networks which are fully determined by geological data.
2. The three mechanisms are assumed for the non-linear flowing and hardening processes.
3. The reduction of the Legion value is computed by the amount of grout agents fulfilling fractures.

The assumed mechanisms are the local connectivity of fractures, the deformation and damage of fractures due to grout pressure, and the hardening and stacking of grout agents. In the following subsections, these three features of the MSFN are explained.

(1) Fracture Network Model

It is reported that permeable flow runs through cracks forming pipe-like[4] water channels. Since geological data for cracks are the dip and strike angles the opening width, and the spacing, the best modeling of such water channels are a fracture network consisting of circular-disk-shaped joints. The permeable flow runs from one intersections of joints to another if the joint edges are impermeable.

In the MSFN, all joints are a common circular-disk of the radius a and the thickness h. The joint radius is determined by a parametric study, and the density ρ is determined[5] by using this a and the measured crack spacing d. For each joint, the dip and strike angles, (ϕ, θ), are randomly chosen from the measured ones, and the location is randomly determined in a target rock mass. **Table 2** summarizes the joint parameters which can be determined from the geological data.

We assume the slow quasi-steady state of the permeable flow, i.e, the Poiseulle flow. The governing equation is a two-dimensional Laplace equation, and a simple linear relation can be derived. To show this, we consider a joint Ω with n intersections Π^α from which fluid goes in and out. In **Fig. 1**, for instance, a

[3] See also 6),7).

[4] See, for instance, 12); see also 4),13),15) for the permeable flow in rock masses and porous media.

[5] For instance, $\rho(\pi a^2 \cos\phi) = d$ holds when the dip angle ϕ is given.

Table 2 Parameters of Joint

(ϕ, θ)	dip and strike angles
h	crack-opening width
a	joint radius determined from parametric study
ρ	crack density determined from crack spacing

joint at the left side has two intersections, and a joint at the center has three intersections. Taking the x and y axes in the plane of Ω, we have a pressure field $p = p(x, y)$ satisfying

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = 0 \quad \text{in}\Omega; \tag{1}$$

Eq. (1) is the continuity equation for the fluid pressure in Ω, and hence it does not account for some portion of the fluid which hardens. Effects of hardening on the permeable flow are considered as the change in the fluid viscosity, as will be explained in the next subsection. When the pressure along Π^α is constant and given as P^α, i.e.,

$$p = P^\alpha \quad \text{on } \Pi^\alpha, \tag{2}$$

Eqs. (1) and (2) together with zero flux conditions on the boundary $\partial\Omega$ pose a boundary-value problem for p. Once p is determined, we can compute the amount of flow in the x and y-direction, q_x and q_y, as

$$\begin{bmatrix} q_x \\ q_y \end{bmatrix} = -\frac{h^3}{12\mu} \begin{bmatrix} \frac{\partial p}{\partial x} \\ \frac{\partial p}{\partial y} \end{bmatrix}, \tag{3}$$

where μ is the viscosity of the fluid. Due to the linearity, the total amount of flow running in or out through Π^α, denoted by Q^α, is expressed in terms of P^α's as

$$Q^\alpha = \sum_{\beta=1}^{n} k_{\alpha\beta} P^\beta. \tag{4}$$

Here, an n-by-n matrix $[k_{\alpha\beta}]$ is called a *joint permeability matrix*; see Appendix for the analytic computation of $[k_{\alpha\beta}]$ when the configuration of Ω is given.

When a fracture network contains N joints and M intersections, the permeable flow in the network can be computed by using joint permeability matrices for N joints. Suppose that two joints, Ω with n intersections and Ω' with n' intersections, are connected through a common intersection, which is the α-th for Ω and the α'-th for Ω'. Since the flow going to (or coming from) Ω equals the flow running from (or going to) Ω', the following relations hold:

$$\sum_{\beta=1}^{n} k_{\alpha\beta} P^\beta + \sum_{\beta'=1}^{n'} k_{\alpha'\beta'} P^{\beta'} = 0, \tag{5}$$

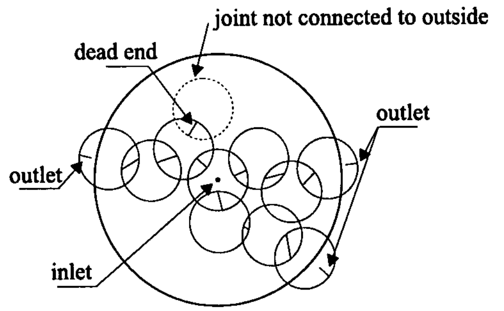

Fig. 1 Boundary Conditions

where $[k_{\alpha\beta}]$ and $[k_{\alpha'\beta'}]$ are the joint permeability matrices of Ω and Ω'. Hence, numbering M intersections suitably and using the joint permeability matrices, we can rewrite Eq. (5) for all intersections as

$$[K_{IJ}][P_J] = [0]. \tag{6}$$

This M-by-M matrix is called a *global* permeability matrix.

As shown in **Fig. 1**, some intersection pressures are prescribed; an intersection to a grouting hole is an inlet with the nozzle pressure, whereas an intersection to the target domain boundary is an outlet with zero pressure. As the quasi-static state is assumed, using the solution of Eq. (6) incrementally, we can compute the permeable flow which changes as the intrusion time goes. When a joint is initially saturated with water, the water is run out as the grout agent flows into the joint. In this manner, we can compute the flow process (which can be viewed as a moving boundary problem for grout agents) using the quasi-static state solution. **Figure 2** shows a case when fluid runs to an empty network; a white joint is fully saturated with fluid whereas a darker joint is less saturated. If $[k]$'s and $[K]$ change depending on the flowing and hardening processes, it results in the non-linearity of the permeable flow; see the next subsection.

It should be mentioned that Eq. (6) is of the same form as used in the finite element method (FEM) for solid mechanics. For instance, intersection pressure and flow correspond to nodal displacement and forces, as a joint and a intersection corresponds to an element and a node; see **Table 3**. As one advantage of the FEM is a simple computation of element stiffness matrices, the MSFN has the joint permeability matrices which can be determined mainly by analytic computation.

(2) Flowing and Hardening Processes

The local connectivity of joints in the MSFN can cause some non-linear relation between the applied pressure and the intruded flow. To show this, consider two cases when one joint is connected to one and two,

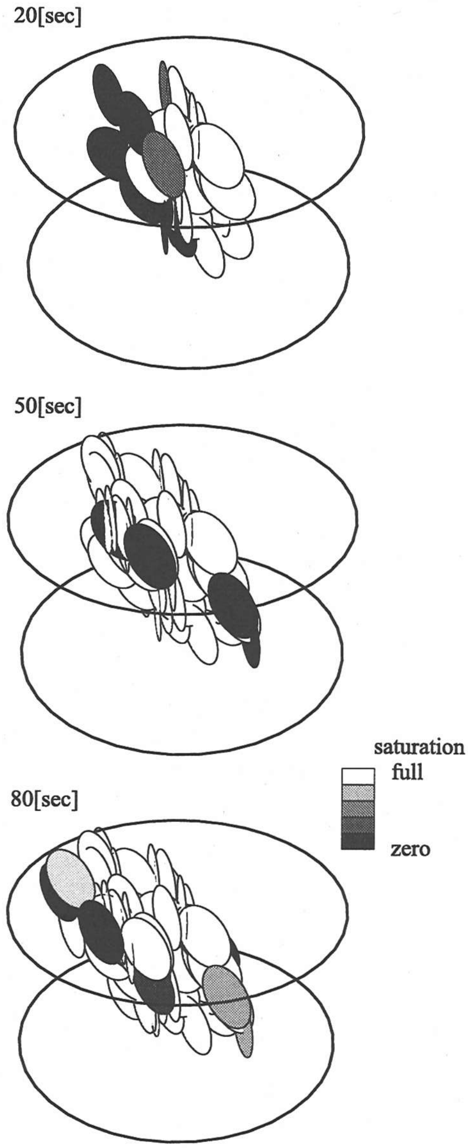

Fig. 2 Permeable Flow in Fracture Network

as presented in **Fig. 3**. When a constant pressure is given at one end intersection, the pressure gradient decreases as the flow runs to further joints. The amount of flow that is intruded from the end intersection decreases for the case of one to one. However, it increases for the case of one to two, as the number of outlets increases as the flow runs further. Indeed, we can compute the change of the intruded flow as

$$\text{(amount of flow)} \propto \begin{cases} 1/\ln t & \text{one to one} \\ t/\ln t & \text{one to two} \end{cases}$$

where t is the intrusion time. This explains one mechanism of the non-linear change in the intruded flow

Table 3 Comparison of FEM and MSFN

FEM	MSFN
element	joint
node	intersection
nodal displacement	average pressure
nodal force	amount of flow
element and global stiffness matrices	joint and global permeability matrices

with respect to time, which is caused by the number of intersections in a joint.

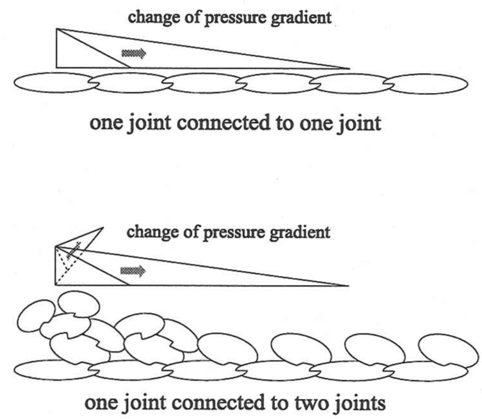

Fig. 3 Two Examples of Connected Joints

There are other mechanisms which induce the non-linearity in the permeable flow, beside the inherent non-linearity due to the connectivity. The effects of turbulence, which occurs in high velocity regions, is one mechanisms, though they are not considered in the MSFN as it assumes the Poiseulle flow. When the grouting pressure is relatively high, we consider that the deformation and damage of cracks is another mechanisms. The permeability of a thin plate depends on the cubic of its thickness, as shown in Eq. (3). Slight change of thickness, therefore, can cause large difference in the permeability and the non-linear behaviors.

The deformation of a joint is computed by using a penny-shaped crack model. When subjected to a uniform fluid pressure p, the deformation is

$$[w](x,y) = \sqrt{a^2 - x^2 - y^2}\,\frac{8(1-\nu^2)p}{\pi E}, \tag{7}$$

where $[w]$ is the opening of the joint, and E and ν are Young's modulus and Possion's ratio of the rock mass. While $[w]$ varies place to place, we assume that the average of $[w]$ gives the increase of the thickness, Δh, and set the following relation:

$$\Delta h(\sigma_n) = \begin{cases} \frac{16(1-\nu^2)a}{3\pi E}\sigma_n & \sigma_n > 0, \\ 0 & \sigma_n < 0, \end{cases} \tag{8}$$

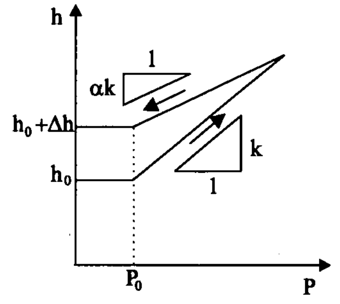

Fig. 4 Model for Joint Deformation

where σ_n is the nominal pressure given by the difference of the average flow pressure to the ground stress.

Cracks are damaged when subjected to an excessive grout pressure, and this leads to the increase of the permeability. To account for the crack damage, we modify Eq. (8) considering the inelastic deformation of the joint. The simplest modification is to replace E with a smaller value as the damage makes the rock mass softer. As the reduction of E is not easily evaluated, we introduce one parameter, α, and rewrite Eq. (8) for the case of $\sigma_n > 0$ as

$$\Delta h(\sigma_n, \Delta\sigma_n) = \begin{cases} \frac{16(1-\nu^2)a}{3\pi E}\sigma_n & \Delta\sigma_n > 0, \\ \frac{16(1-\nu^2)a}{3\pi\alpha E}\sigma_n & \Delta\sigma_n < 0, \end{cases} \tag{9}$$

where $\Delta\sigma_n$ is the change of the nominal pressure. **Figure 4** shows Eq. (8) and Eq. (9).

The flowing and hardening processes of grout agents in water channels are not fully clarified; for instance, the stacking and de-hydration of grout agents and the non-uniform fulfillment of cracks are often reported. As no quantitative information is available, we make the simplest model at the current stage, without assuming complicated phenomena and introducing many parameters which require further measurements.

The possibility that the stacking of grout agents occurs increases as the agent flows a longer distance in thinner water channels. Modeling this as the increase of the viscosity, we assume that the viscosity increases proportionally to the intrusion time t and the inverse of the joint thickness h. Introducing a parameter β, we set the following form of the viscosity:

$$\mu(h,t) = \mu^o \left(1 + \beta\frac{t}{h}\right), \tag{10}$$

where μ^o is the initial viscosity.

(3) Grouting Effects

As the Legion value is only one parameter which is commonly used, we evaluate the grouting effects using the spatial variation of the Legion value. The MSFN computes Legion values carrying out a fictitious Legion test which makes a grout hole at a location of interest and simulates the intrusion of water.

Table 4 Parameters Used in MSFN

α	reduction of Elasticity due to damage
β	viscosity change due to stacking
γ	joint closing due to grout fulfillment

The principle mechanism that the grouting improves the impermeability is the fulfillment of cracks by cement. We model the fulfillment as the decrease of the joint thickness, depending on the amount of intruded cement. The saturation ratio, denoted by S, is defined as the volume fraction of the cement, i.e., the ratio of the intruded cement volume, V_C, to the current joint volume, $V_J = \pi a^2 h$,

$$S = \frac{V_C}{V_J}. \tag{11}$$

The value of V_C can be computed even when various W/C's are used; if there is v volume of a grout agent of W/C=a, it contributes $v/(1+a)$ to V_C. We assume the simplest linear relation between S and the decrease of the joint thickness, $\Delta h'$. Introducing a parameter γ for this linear relation, we set

$$\Delta h' = \gamma S. \tag{12}$$

Once a fracture network is generated, the non-linear flowing and hardening processes in each joint are computed by using Eqs. (8) and (9) together with Eq. (10), and the reduced thickness is determined from Eq. (12). Fictitious Legion tests are simulated by using the same fracture network with reduced joint thickness. The spatial variation of Legion values is then computed, and can be used as a measure[6] of the grouting effects. It should be noted that since only the joint thickness is changed in the MSFN, the effects of the grouting up to the n-th grouting are expressed as the sum of the reduced thickness at each grouting,

$$\Delta H^n = \Delta H^{n-1} + \Delta h'^n, \tag{13}$$

where $\Delta h'^n$ is the reduction of the n-th grouting and ΔH^n is the sum of the reduction up to the n-th grouting.

The three parameters, α, β and γ, are introduced in the MSFN; see **Table 4**. These parameters are determined by a parametric study such that measured data can be reproduced well.

[6] We can evaluate a grouting specification for the target rock mass, carrying out this MSFN using that specification.

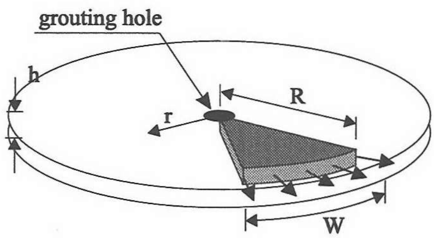

Fig. 5 Partially Open Parallel Disk

4. RTIA FOR GROUT INTRUSION EVALUATION

The RTIA predicts the water channel conditions and the grout filling, using only real-time data of the grouting pressure and flow. In view of the quantity of these data, the RTIA assumes the simplest model for a water channel, a partially open parallel disk. The thickness of the disk is determined from measured crack-opening width, and fluid flows in a radial manner from the center to regions where the disk is open. The range of the direction corresponds to the water channel condition, i.e., as the channel has better connectivity, the range becomes larger. The distance at which grout agent reaches can be computed once this range is determined.

(1) Partially Open Parallel Disk Model

The partially open parallel disk model with thickness h is shown in **Fig. 5**. The range of the open part is W, and the head of the liquid is located at R; W is a function of the distance from the center, r, and R is a function of the intrusion time, t. Note that W is $W = 2\pi r$ for a fully connected water channels, whereas W is constant or decreases with respect to r for poorly connected water channels.

The partially open parallel disk model cannot tell the number of cracks intersecting the grout hole or the change of the disk width. If there are more than one cracks, W/r becomes larger than 2π. While it is possible to set the number of cracks as an unknown number or to set the disk thickness as a variable, we fix the crack number and the thickness for simplicity in the this paper, and admit $W/r > 2\pi$.

(2) Flow in Partially Closed Parallel Disk Model

Based on the same assumptions as in the MSFN, we set the following field equation for the pressure and velocity fields, $p(r,t)$ and $v(r,t)$, when the fluid runs to $r = R(t)$:

$$v(r,t) = \begin{cases} -k'\frac{\partial p}{\partial r}(r,t) & 0 < r < R(t), \\ -k\frac{\partial p}{\partial r}(r,t) & R(t) < r, \end{cases} \tag{14}$$

where k' and k are the permeability of the intruded and pre-existing liquids. The continuity condition is expressed in terms of v as

$$hW(r)v(r,t) = const. \quad 0 < r < R(t). \tag{15}$$

The boundary conditions at $r = 0$ and $r = R$ are

$$\begin{cases} p(r,t) = P(t) \;\&\; hW(r)v(r,t) = Q(t) & \\ \qquad\qquad\qquad\qquad\qquad\qquad r = 0, & \\ v(r,t) = \dfrac{\mathrm{d}R}{\mathrm{d}t}(t) \qquad\qquad r = R(t). & \end{cases} \tag{16}$$

where P and Q are the grouting pressure and the amount of flow.

Suppose that W is known. As R increases with respect to t, Eq. (14) and Eq. (15) with Eq. (16) pose a moving boundary value problem. However, they can be solved by first assuming R, which leads to two equations for P and Q, separately. To show this, deleting v from Eq. (14) and Eq. (16) as

$$v(r,t) = \frac{Q(t)}{h}\frac{1}{W(r)},$$

we derive

$$\begin{cases} -\dfrac{Q}{k'h}\dfrac{1}{W(r)} = \dfrac{\partial p}{\partial r}(r,t) & 0 < r < R(t), \\ -\dfrac{Q}{kh}\dfrac{1}{W(r)} = \dfrac{\partial p}{\partial r}(r,t) & R(t) < r. \end{cases}$$

Integration of these relations from 0 to r and from r to ∞, respectively, leads to

$$\begin{cases} p(r,t) - P(t) = -\dfrac{Q}{k'h}\displaystyle\int_0^r \frac{1}{W(r)}\mathrm{d}r & \\ \qquad\qquad\qquad\qquad\qquad 0 < r < R(t), & \\ -p(r,t) = -\dfrac{Q}{kh}\displaystyle\int_r^\infty \frac{1}{W(r)}\mathrm{d}r & \\ \qquad\qquad\qquad\qquad\qquad R(t) < r. & \end{cases}$$

As p is continuous at $r = R$, the following equation is derived:

$$P(t) = \frac{Q(t)}{h}\left(\frac{1}{k'}\int_0^{R(t)} \frac{1}{W(r)}\mathrm{d}r\right) + \frac{Q(t)}{h}\left(\frac{1}{k}\int_{R(t)}^\infty \frac{1}{W(r)}\mathrm{d}r\right). \tag{17}$$

Another relation between P and Q is derived from the boundary condition, $v = \mathrm{d}R/\mathrm{d}t$ at $r = R$, as,

$$\frac{Q(t)}{h}\frac{1}{W(R)} = \frac{\mathrm{d}R}{\mathrm{d}t}(t). \tag{18}$$

Equations (17) and (18) determine P and R for given Q (or Q and R for given P), if W is prescribed.

(3) Inversion of Closeness and Range of Flow

When P and Q are continuously measured, we can determine W and R using Eq. (17) and Eq. (18).

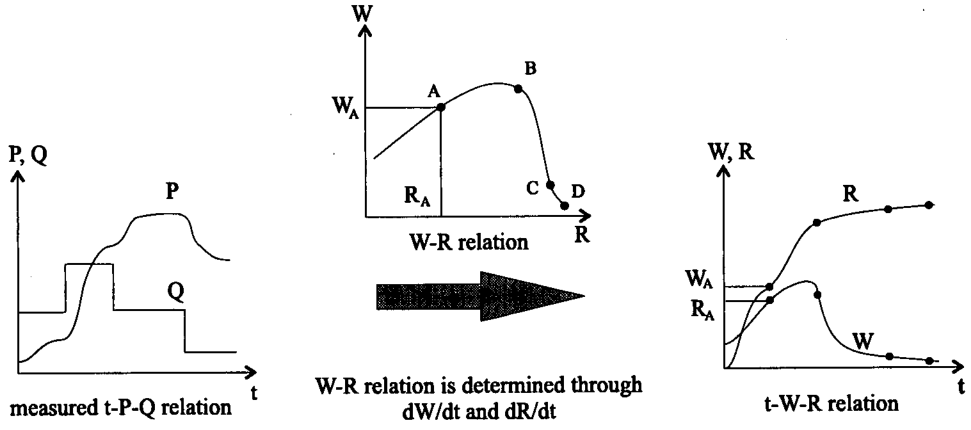

Fig. 6 Concept of Inversion from t-P-Q to t-W-R

Table 5 Input Data for RTIA

h	constant crack-opening width
P	grout pressure at time t
Q	amount of grout at time t

This is an inverse problem of W and R for given P and Q. Indeed, dividing both sides of Eq. (17) with Q and taking derivative with respect to t, we have

$$h\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{P(t)}{Q(t)}\right) = \left(\frac{1}{k'} - \frac{1}{k}\right)\frac{1}{W(R)}\frac{\mathrm{d}R}{\mathrm{d}t}(t).$$

It then follows from this equation and Eq. (18) that $\mathrm{d}R/\mathrm{d}t$ and Q are given by

$$\frac{\mathrm{d}R}{\mathrm{d}t}(t) = \sqrt{\left(\frac{1}{k'} - \frac{1}{k}\right)^{-1} Q(t)\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{P(t)}{Q(t)}\right)}, \quad (19)$$

and

$$W(R) = \sqrt{\left(\frac{1}{k'} - \frac{1}{k}\right)\frac{1}{h^2}\frac{Q(t)}{\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{P(t)}{Q(t)}\right)}}. \quad (20)$$

In view of Eqs. (19) and (20), we can summarize the procedure of the RTIA, as follows:

1. determine $\mathrm{d}R/\mathrm{d}t$ from Eq. (19)
2. compute R integrating $\mathrm{d}R/\mathrm{d}t$ with respect to t
3. compute W from Eq. (20) using this R

As is seen, the RTIA can evaluate the connectivity of the water channels (W) and the distance to which the grout agents flow (R) only from data obtained by continuous monitoring of the pressure and the amount of flow; see **Fig. 6** for the basic concept of the RTIA. **Table 5** presents the input data which are used in the above procedures of the RITA.

5. CONCLUDING REMARKS

The two analysis methods for grouting, the MSFN and the RTIA, are presented in this paper. Both the MSFN and the RITA accounting for the three major difficulties in developing a grout analysis, even though idearized models of water channels are used and simple mechanisms are considered for complicated flowing processes.

It should be emphasized again that the MSFN and the RTIA solve their own well-set problems which do not require special measurements of the rock geology or hydrology. In another word, the target problems of the MSFN and the RITA are posed such that full advantage is taken of geological and flow data which are ordinarily measured.

APPENDIX: JOINT PERMEABILITY MATRIX

The joint permeability matrix can be computed analytically by using complex potentials. Suppose that Ω is regarded as a unit circle in a two-dimensional palne. When Ω has one hole at the origin and another at (x^1, y^1) and a unit volume of fluid runs from (x^1, y^1) to the origin, the pressure is given as

$$\begin{aligned} p(z, z^1) = \Im\{&(2\imath - z^1 - z^{1\prime})\ln z \\ &- ((\imath + z^1)^2/z^1)\ln(z - z^1) \\ &- ((\imath + z^{1\prime})^2/z^{1\prime})\ln(z - z^{1\prime})\}, \end{aligned}$$

where $z = x + \imath y$, $z^1 = x^1 + \imath x^1$ and $z^{1\prime} = 1/\overline{z^1}$ and $\Im\{\}$ stands for the imaginary part. Recall that zero flux conditions along the boundary are used.

The integration of $p(z, z^1)$ with respect to z^1 along a certain arc Π in Ω gives a pressure field for flow coming from Π and going out to the origin. Now, we coming from Π and going out to the origin. Now, we assume that Ω has n intersections. When a unit flow comes from, say, Π^β and goes to the origin, We can compute the average pressure on, say, Π^α, as

$$P^{\alpha\beta} = \frac{1}{\Pi^\alpha \Pi^\beta} \int_{\Pi^\alpha} \mathrm{d}z \int_{\Pi^\beta} \mathrm{d}z^1 p(z, z^1).$$

While the above setting is not realistic, we can compute a joint permeability matrix analytically using $P^{\alpha\beta}$. By definition, $P^{\alpha\beta} - P - 1\beta$ gives the pressure at Π^α when the unit flow runs from Π^β to Π^1 ($\beta \neq 1$). Hence, the joint permeability matrix must satisfy

$$\begin{bmatrix} -1 \\ 1 \\ 0 \\ \cdots \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & k_{13} & \cdots \\ k_{21} & k_{22} & k_{23} & \cdots \\ k_{31} & k_{32} & k_{33} & \cdots \\ \vdots & \vdots & \vdots & \cdots \end{bmatrix} \begin{bmatrix} 0 \\ P^{2\beta} - P^{1\beta} \\ P^{3\beta} - P^{1\beta} \\ \vdots \end{bmatrix}.$$

Forming an $n-1$-by-$n-1$ matrix (with component of $P^{\alpha\beta} - P^{\alpha 1}$ for $\alpha, \beta = 2, 3, \cdots, n$), we can compute

$$[k_{\alpha\beta}] = [P^{\alpha\beta} - P^{\alpha 1}]^{-1},$$

for α, β = 2, 3, $\cdots$, n. Since constant pressure at all intersections does not produce permeable flow, we have

$$k^{1\beta} = -\sum_{\alpha=2}^{n} k_{\alpha\beta},$$

for $\beta = 2, 3, \cdots, n$. Finally, according to the reciprocal theorem, we have $k^{\beta 1} = k^{1\beta}$ and $k^{11} = -\sum_{\beta=2}^{n} k^{1\beta}$.

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二つのグラウト解析手法の提案

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グラウト技術の向上のためには合理的で信頼できる解析手法が必要である．解析手法開発上の問題点を整理した上で，本論文は，モンテカルロシミュレーションを利用したフラクチャーネットワーク解析 (MSFN) とリアルタイムインバージョン解析 (RITA) を提案した．MSFN は，多数のフラクチャーネットワークの解析により，与えられたグラウト仕様からルジオン値の空間分布を推定する．RITA は，常時計測されているグラウト孔の圧力と注入量の関係の逆解析により，水みちの状態やグラウト剤の到達距離を推定する．入力データは計測されている地質データである．解析手法の対象となる水みちモデルや仮定を説明し，解析手法を厳密に定式化している．