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PREDICTION AND CONTROL OF GROUTING PROCESS IN PREPLACED AGGREGATE CONCRETE BY GREEN'S FUNCTIONS

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SYNOPSIS

In preplaced aggregate concrete practice, the process that the voids of coarse aggregate become filled with grout varies with the shape and dimensions of forms and performance conditions. A theoretical method for predicting this process was researched, and calculation results for a wall, four rectangular blocks and a cylinder were compared with experiments under different conditions. Furthermore, a practical procedure for selecting proper conditions of performance was offered.

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1. INTRODUCTION

Preplaced aggregate concrete method has been used in certain types of construction where the proper placement of conventional concrete would be difficult or impossible, and particularly well adapted for underwater constructions. In fact a number of foundations for the bridges in Kojima-Sakaide route expected to link Honshū and Shikoku across the Inland Sea of Japan in 1988 have been built by this method. Special considerations, however, are necessary to fill perfectly the voids of coarse aggregate with grout of good quality in a large-scale underwater work; for instance, the shape and dimensions of the forms to be grouted, fluidity of the grout, void characteristics of the coarse aggregate, the arrangement and injection sequence of grout pipes, and the rate and duration time of grouting for each pipe should be properly selected. One of the successful ways of producing homogeneous concrete is injecting the grout slowly, but it would lead to prolong the work and to increase a risk of grouting's being interrupted because of change in job conditions such as properties of the grout, the weather and a state of the sea. It is therefore quite important to estimate the influences of these factors on the state of filling of the grout so that the work may be performed rapidly as well as adequately.

The problem concerning the flow of grout through the voids of a preplaced coarse aggregate mass was first basically studied by Koba and Ariyoshi (1). Fig. 1 shows the test apparatus developed by them to determine the coefficient of permeability of grout through the voids of coarse aggregate by measuring efflux times with and without aggregate in the aggregate container. Through the analysis of the data, it was concluded that the grout flowed approximately in accordance with Darcy's law.

Experimental studies on grouting have been made by Port and Harbor Research Institute(1,2), Japan Railway-Construction Public Corporation(3,4), Honshū-Shikoku Bridge Authority(5), Research Institute of Shimizu Construction Co. Ltd.(6), and so forth. In these experiments, surface shapes and segregation states of grout were observed. Their conclusions may be summarized as: when the coarse aggregate was 24 mm in effective diameter with a void content of 43 percent, a proper rate of injection was less than 17 l/min(2); with a large size crushed stone aggregate from 80 to 150 mm, the rate of injection and the area to be grouted per pipe might be 400 l/min and 100 square meters respectively(5); with an aggregate from 40 to 60 mm in minimum size, grouting would be successfully performed at a rate of less than 150 l/min.

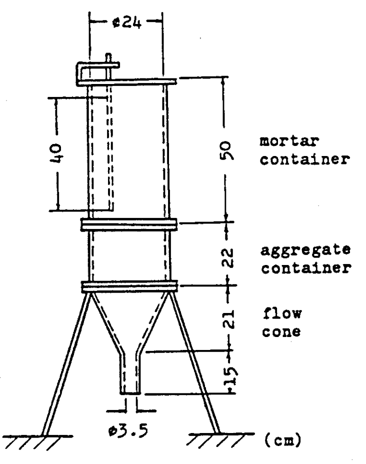

Fig. 1 Permeability test apparatus

Formerly, the flow of grout through the voids of preplaced coarse aggregate had been regarded as a three-dimensional problem, the author took note of the fact that the flow of grout seemed to obey Darcy's law as shown by Koba et al. By transforming the level of the grout surface into hydraulic pressure, the level at an arbitrary time and place could be obtained as a solution of the two-dimensional equation of diffusion instead of solving a three-dimensional equation of motion. Then, the surface of grout was to be described by a set of the levels at lattice points. This made it possible to predict the filling process of grout by calculation, even in the case that the conditions of performance were varied during the intrusion work.

This paper describes the theoretical basis for the problem, the equations to be used in the numerical calculation, the verification of validity of the theory, and the practical application of the method.

2.THEORETICAL BASIS

2.1 Basic law and differential equation

To the flow of liquid through a porous medium Darcy's law are usually applied. While, the grouting mortar has a yield stress of finite value, so that it may not flow strictly in accordance with the law. However, the grout surface in the voids of coarse aggregate has a tendency to settle toward horizontal after the injection is stopped(2). Furthermore, if the shearing rate of flow was sufficiently small, grout would keep flowing even under a stress below the yield stress determined as a Bingham body(8). Considering these experimental results as well as the study by Koba et al(1), Darcy's law may be applicable to the flow of grout through the voids of coarse aggregate.

As is well known Darcy's law is expressed by following equation:

$$dQ=-k\frac{\partial h}{\partial s}dA\,dt=-\frac{k}{\rho}\frac{\partial p}{\partial s}dA\,dt$$

where dQ is the quantity of the grout flowing through area dA perpendicular to the flow in time dt, and

k : coefficient of permeability
ρ : unit weight of the grout
$\partial p/\partial s$: pressure gradient along a stream-line

Here, a very small cubic element at a point P(x,y,z) with sides dx,dy,dz parallel to the co-ordinates axes x,y,z respectively is to be considered. If the pressure at P for an instant t is p(x,y,z,t), the quantity of the grout being estimated to be stored in the element in the direction of the y-axis in time dt is

$$dQ_y=\frac{k}{\rho}\frac{\partial^2 p}{\partial y^2}(dx\,dy\,dz)dt$$

Similarly in the directions of the z-and x-axes

$$dQ_z=\frac{k}{\rho}\frac{\partial^2 p}{\partial z^2}(dx\,dy\,dz)dt$$

$$dQ_x=\frac{k}{\rho}\frac{\partial^2 p}{\partial x^2}(dx\,dy\,dz)dt$$

Consequently, the total quantity of storage(dQ) is

$$dQ = dQ_x + dQ_y + dQ_z$$
$$= \frac{k}{\rho}\left(\frac{\partial^2 p}{dx^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2}\right) dx\, dy\, dz\, dt$$

The gain in pressure due to the storage dQ may be given by

$$dp = \frac{dQ}{q_0 (dx\, dy\, dz)}$$

where q_0 is the quantity of the grout necessary for raising the pressure by unit value per unit volume of the element. From these two relations, the following equation is obtained:

$$q_0\, dx\, dy\, dz\, dp = \frac{k}{\rho}\left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2}\right) dx\, dy\, dz\, dt$$

$$\frac{\partial p}{\partial t} = \frac{k}{q_0 \rho}\left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2}\right) = a \Delta p \quad \cdots\cdots\cdots\cdots (2)$$

where symbol Δ represents $\partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$

$$a = k / q_0 \rho \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

2.2 The general expression of the surface shape of grout by Green's function

(1) Transformation from pressure into the level of grout surface

The solution of Eq.(2) is given by

$$p = \iiint G(\xi_1, \xi_2, \xi_3, t, \xi_1', \xi_2', \xi_3') \times f(\xi_1', \xi_2', \xi_3') dV' \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where G is a Green's function dependent on the co-ordinate system and the boundary conditions, and f is the function expressing the pressure distribution at t=0.

In the two-dimensional case with x,y co-ordinates, the pressure at a point P(x,y) is expressed in the following form:

$$p = \iint G(x, y, t, x', y') \cdot f(x', y') dx'\, dy'$$

Now, assuming that a column with the base of unit area at the point P(x,y) in the coarse aggregate is injected with grout as much as q_0 , the level of the grout will be

$$h_0 = q_0 / \varepsilon$$

As the pressure is equal to unity

$$\rho h_0 = \rho q_0 / \varepsilon = 1$$

$$q_0 = \frac{\varepsilon}{\rho} \quad \cdots\cdots (5)$$

In view of the relation:

$$p = \rho h \quad \cdots\cdots (6)$$

the following equation is obtained:

$$h = \frac{p}{\rho} = \left(\frac{q_0}{\varepsilon}\right) p = \frac{q_0}{\varepsilon} \iint G \cdot f \, dx' \, dy' \quad \cdots\cdots (7)$$

In this formula, the initial condition f can be determined by use of Eq.(6) in the case that the surface shape of the grout at t=0 is known.

(2) The surface shape of grout during injection

Since p satisfies the diffusion equation (2) which has the same form as the conductional equation of heat, the theories with regard to heat conduction can be applied to the present case. For this purpose, one has only to replace the generation of heat with the injection of grout and the temperature with the pressure. Then the substitutions of the parameters are as follows:

$$\lambda \rightarrow k/\rho, \quad c\gamma \rightarrow q_0$$

where λ is heat conductivity, c is specific heat, and γ is weight per unit volume. In underwater grouting, through the conversions of parameters as

$$q_0 = \varepsilon/(\rho - 1), \quad a = k/q_0(\rho - 1) = k/\varepsilon, \quad h = p/(\rho - 1) = (q_0/\varepsilon)p,$$

the equation of h is reduced to the same form as Eq.(7).

According to the theory of heat conduction, when the quantity of heat generated in a body with an initial temperature of 0°C is $Q(\tau)$ per unit time at $t=\tau$ the temperature is given by

$$\theta(x, y, t) = \frac{1}{c\gamma} \int_0^t G_\tau(x, y, \tau, x', y') \cdot Q(\tau) d\tau$$

where x′, y′ are the co-ordinates of the heat source, and t is the duration time of heating. Through the transformations above stated, the equation of the pressure is expressed as

$$p(x, y, t) = \frac{1}{q_0} \int_0^t G_\tau \cdot Q(\tau) d\tau$$

and the level of grout surface under injection is

$$h_q=\left(\frac{q_0}{\varepsilon}\right)p=\frac{1}{\varepsilon}\int_0^t G_T\,Q(\tau)d\tau \cdots\cdots\cdots\cdots\cdots (8)$$

When using multiple grout pipes, the equation will be

$$h_q=\frac{1}{\varepsilon}\sum_{i=1}^{N_p}\int_0^t G_T(x,y,\tau,x_{pi},y_{pi})\cdot Q_i(\tau)d\tau \cdots\cdots\cdots (9)$$

where N_p is the number of the grout pipes, x_{pi} , y_{pi} and Q_i are the co-ordinates and the rate of injection of the i th pipe. Thus, the grout surface may be described by a set of the levels at lattice points.

(3) The surface shape of grout after the interruption of injection

Assuming that the time of the interruption is T, the level of grout surface at the instant will be determined by

$$h_1(x',y')=\frac{1}{\varepsilon}\sum_{i=1}^{N_p}\int_0^T G_T(x',y',\tau,x_{pi},y_{pi})\times Q_i(\tau)d\tau \cdots\cdots\cdots\cdots\cdots (10)$$

In consideration of the following relation:

$$h_1(x',y')=\frac{1}{\varepsilon}f(x',y') \cdots\cdots\cdots\cdots\cdots (11)$$

the level after the interruption is expressed as

$$h_r(x,y,t)=\iint h_1(x',y')\times G(x,y,t-T,x',y')dx'\,dy' \cdots\cdots\cdots (12)$$

In general, Eq.(12) is numerically integrated.

(4) The surface shape under varying conditions of grouting

When the secondary injection is resumed after a certain period of pause, the level of the grout (h_s) may be estimated as follows. Though the conditions such as the number and arrangement of grout pipes, the rate of injection of each pipe are not necessarily the same as those in the previous injection, yet, for the purpose of simplifying the discussion, one grout pipe is to be used.

If the interruption and resumption times of injection are T_1 and T_2 respectively the level of the grout at the instant of the interruption is

$$h_1(x',y')=\frac{1}{\varepsilon}\int_0^{T_1} G_T(x',y',\tau,x_p,y_p)\cdot Q_1(\tau)d\tau \cdots\cdots (13)$$

During the pause of injection, the surface of the grout changes in accordance with the following formula:

$$h_r(x,y,t)=\iint h_1(x',y')\times G(x,y,t-T_1,x',y')dx'\,dy'$$

Further, the additional change due to the secondary injection is

$$h_s(x,y,t)=\frac{1}{\varepsilon}\int_{T_2}^{t-T_2} G_r(x,y,\tau,x_p,y_p)\cdot Q_2(\tau)d\tau \quad \cdots\cdots(14)$$

Finally, the level of the grout surface during the secondary injection is given by

$$h(x,y,t)=h_r+h_s \quad \cdots\cdots(15)$$

In the case that the grouting conditions will be repeatedly varied, one has only to repeat these procedures.

3. FORMULAS TO BE USED IN CALCULATION

3.1 For wall shaped structures

In the case that the formwork has a wall shape of length L and thickness B, x-axis is to be taken in the longitudinal direction of the wall.

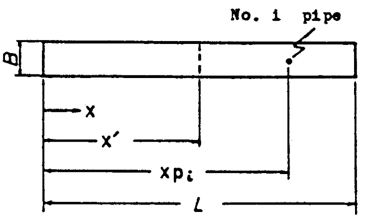

Fig. 2 Wall.

Then, no outflow will occur at x=0 and L, that is, the boundary conditions are

$$\left[\frac{\partial h_q}{\partial x}\right]_{x=0}=\left[\frac{\partial h_q}{\partial x}\right]_{x=L}=0$$

Green's function in this case is given by

$$G_x=\frac{1}{L}+\frac{2}{L}\sum_{n=1}^{\infty}\exp\left\{-\left(\frac{n\pi}{L}\right)^2 a\tau\right\}\times\cos\frac{n\pi x}{L}\cos\frac{n\pi x'}{L} \quad \cdots\cdots(16)$$

Consequently, the following formula may be derived from Eq.(9):

$$h_q(x,t)=\frac{1}{\varepsilon}\sum_{i=1}^{N_p}\int_0^t\frac{q_i(\tau)}{L}\left[1+2\sum_{n=1}^{\infty}\exp\left\{-\left(\frac{n\pi}{L}\right)^2 a\tau\right\}\cos\frac{n\pi x}{L}\cos\frac{n\pi x_{pi}}{L}\right]d\tau$$

where $q_i(\tau)$ is the rate of injection of the i th pipe per unit thickness of the wall, that is, $q_i(\tau)=Q_i/B$. Assuming that Q_i is not changed from t=0 to t=t, integration of this equation yields

$$h_q=\frac{1}{\varepsilon BL}\sum_{i=1}^{N_p}Q_i\left[t+2\sum_{n=1}^{\infty}\frac{1}{a}\left(\frac{L}{n\pi}\right)^2\left\{1-\exp\left(-\frac{an^2\pi^2}{L^2}t\right)\right\}\cos\frac{n\pi x}{L}\cos\frac{n\pi x_{pi}}{L}\right]$$

In a similar way, after the interruption of injection

$$h_r=\int_0^L h_1(x')\left[1+2\sum_{n=1}^{\infty}\exp\left\{-a\left(\frac{n\pi}{L}\right)^2(t-T_1)\right\}\cos\frac{n\pi x}{L}\cos\frac{n\pi x'}{L}\right]dx' \qquad (t>T_1)$$

where T_1 is the time at the instant of the interruption, and $h_1(x')$ is the level of the grout at $t=T_1$.

3.2 For rectangular structures

For the case that the formwork has a rectangular shape of length L and width B, x,y co-ordinates are to be taken as Fig.3.

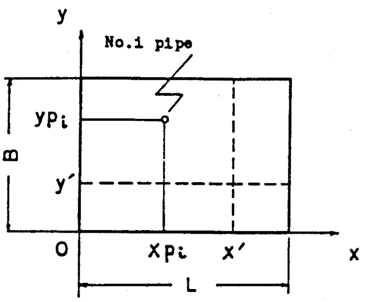

Fig. 3 Rectangular block.

Then, no outflow exists at x=0,L and at y=0,B. Accordingly, the Green's function is given through the multiplication of solutions by

$$G_{xy}=G_x\cdot G_y$$

where G_y is the equation obtained by replacing x, x', L and n in Eq.(16) with y, y', B and m respectively. Then equation (9) is rewritten as

$$h_q(x,y,t)=\frac{1}{\varepsilon}\sum_{i=1}^{N_p}Q_i\int_0^t G_{xy}\,d\tau$$

Through integration, this equation may finally have the following form:

$$h_q(x,y,t)=\frac{1}{\varepsilon BL}\sum_{i=1}^{N_p}Q_i(t+2S_x+2S_y+4S_{xy}) \cdots\cdots(17)$$

in which

$$S_x=\sum_{n=1}^{\infty}\frac{1}{a}\left(\frac{L}{n\pi}\right)^2\left\{1-\exp\left(-\frac{an^2\pi^2}{L^2}t\right)\right\}\times\cos\frac{n\pi x}{L}\cos\frac{n\pi x_{pi}}{L}$$

$$S_y=\sum_{m=1}^{\infty}\frac{1}{a}\left(\frac{B}{m\pi}\right)^2\left\{1-\exp\left(-\frac{am^2\pi^2}{B^2}t\right)\right\}\times\cos\frac{m\pi y}{B}\cos\frac{m\pi y_{pi}}{B}$$

$$S_{xy}=\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\frac{1}{a\left\{\left(\frac{n\pi}{L}\right)^2+\left(\frac{m\pi}{B}\right)^2\right\}}\left[1-\exp\left\{-\left(\frac{an^2\pi^2}{L^2}+\frac{am^2\pi^2}{B^2}\right)t\right\}\right]\cos\frac{n\pi x}{L}\times\cos\frac{n\pi x_{pi}}{L}\cos\frac{m\pi y}{B}\cos\frac{m\pi y_{pi}}{B}$$

During the interruption $(t>T_1)$

$$h_r(x,y,t)=\iint h_1(x',y')(1+2\Sigma_x)\times(1+2\Sigma_y)dx'\,dy' \cdots\cdots\cdots\cdots(18)$$

where

$$\Sigma_x=\sum_{n=1}^{\infty}\exp\left\{-\frac{an^2\pi^2}{L^2}(t-T_1)\right\}\times\cos\frac{n\pi x}{L}\cos\frac{n\pi x'}{L}$$

$$\Sigma_y=\sum_{m=1}^{\infty}\exp\left\{-\frac{am^2\pi^2}{B^2}(t-T_1)\right\}\times\cos\frac{m\pi y}{B}\cos\frac{m\pi y'}{B}$$

and $h_1(x',y')$ may be obtained by substituting T_1 for t in Eq.(17).

If the grouting operation is resumed at t= T_2 , the additional change of the grout level due to the secondary injection is obtained by substituting $t-T_2$ for t in the equation of h_q as

$$h_s(x,y,t)=h_q(x,y,t-T_2)$$

Thus, the level of the grout surface during the secondary injection can be calculated by

$$h(x,y,t)=h_q(x,y,t-T_2)+h_r(x,y,t)\cdots\cdots\cdots\cdots(19)$$

3.3 For cylindrical structures

In the case that the formwork has a circular cross section of radius R, and that grouting is performed through a pipe inserted in the center of the forms, polar co-ordinates are to be taken with the origin at the position of the pipe. Then, Green's function for this case is given by

$$G_r=\frac{1}{\pi R^2}\left\{1+\sum_{n=1}^{\infty}\exp(-a\mu_n^2\tau)\times\frac{J_0(\mu_n r)J_0(\mu_n r')}{J_0^2(\mu_n R)}\right\}$$

and Eq.(8) may be written in the following form:

$$h_q(r,t)=\frac{Q}{\pi R^2\varepsilon}(t+\Sigma_1)\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(20)$$

in which

$$\Sigma_1=\sum_{n=1}^{\infty}\frac{J_0(\mu_n r)}{a\mu_n^2J_0^2(\mu_n R)}\{1-\exp(-a\mu_n^2 t)\}$$

where μ_n is the n th positive solution of $J_1(\mu_n R)=0$.
At the instant of the interruption $(t=T_1)$:

$$h_1(r,T_1)=h_q(r,T_1)\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(21)$$

During the interruption :

$$h_r(r,t)=\int_0^R h_1(r')G_r\cdot(2\pi r'dr')$$

By substituting Eq.(21) for $h_1(r')$ in this equation and by performing integration, the following formula may be obtained as the final form:

$$h_r(r,t)=\frac{Q}{\pi R^2\varepsilon}(T_1+\Sigma_2\Sigma_3)\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(22)$$

where

$$\Sigma_2=\sum_{n=1}^{\infty}\frac{J_0(\mu_n r)}{J_0^2(\mu_n R)}\exp\{-a\mu_n^2(t-T_1)\}$$

$$\Sigma_3=\sum_{m=1}^{\infty}\frac{1}{a\mu_m^2}\{1-\exp(-a\mu_m^2 T_1)\}$$

Eq.(22) is calculable without performing numerical integration.

After the resumption of the grouting ($t>T_2$):

$$h(r,t)=h_q(r,t-T_2)+h_r(r,t)\cdots\cdots\cdots\cdots\cdots\cdots(23)$$

4. THE VERIFICATION OF VALIDITY BY EXPERIMENTAL RESULTS

4.1 Verification by laboratory tests

(1) Procedure

The forms used in the tests had a wall-shape of 50 cm x 20 cm x 35 cm in height, and its facade consisted of a trasparent panel ruled into 5 cm squares.

The coarse aggregate was river gravel. Its characteristics are shown in Table 1, and the coefficients of permeability in the table are the average values of three measurements.

Table 1 Properties of aggregate

Aggr No.	Grading (mm)	Voids (%)	Permeability (cm/s)
A1	15-20	36.17	4.12
A2	20-30	39.06	6.07
A3	30-60	40.56	10.49

Properties of the grout used were as follows.

C:F:S:W=1:0:1:0.552
water reducing agent=C x 0.5 %
efflux time=15.1 s

The injection of the grout was performed through one or two pipes by gravity in air. Since it was difficult to maintain the rate of injection at the planned value, the actual rate was determined later from the photographs taken of the filling process of the grout.

(2) The estimation of the state of filling

The two-dimensional equation (17) was used to calculate the level of the grout surface at 286 lattice points by dividing L into twenty five equal parts and B into ten parts.

As for the parameters used in calculation, void contents of coarse aggregate and coefficiet of permeability were measured values and rates of injection were slightly increased from the average rates calculated in such a manner as previously mentioned, because the grout surface of the inner part of the forms was thought to be higher than that which had been observed through the transparent facade of the forms.

The first three terms of the infinite series were added on the basis of the following considerations.

First, the calculation results showed a curved surface with a peak at the injec tion point, which had a tendency to sharpen with increase of the number of terms added (N), while the results about the other points were little affected by N. Second, the grout pipe occupied a certain area, so that, the peak was actually lower than the calculated value for N=100, and closer to that for N=3.

Comparison of the results for N=3, 10, and 100 is seen in Fig. 4.

(3) Comparison of the experimental results with the calculation results

The calculated and experimental results with different gradings of coarse aggregate and arrangements of grout pipes are shown in Fig. 4, 5 and 6.

Conditions of grouting are summarized in Table 2, together with those of the experiments performed in the past, which will be stated in detail next in 4.2.

As is seen in the table, from case No.1 to No.3, the grading of coarse aggregate was varied and two grout pipes were used in case No.3 (Fig. 6).

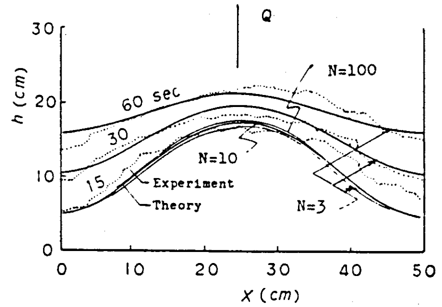

Fig. 4 Comparison of the theory with experimental results.

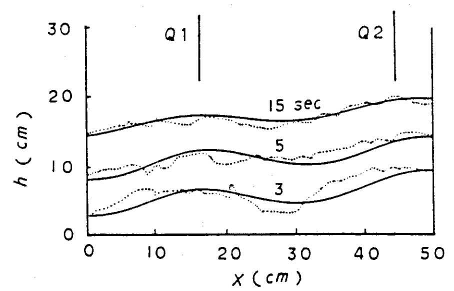

Fig. 6 Theoretical and experimental results for grouting with two pipes.

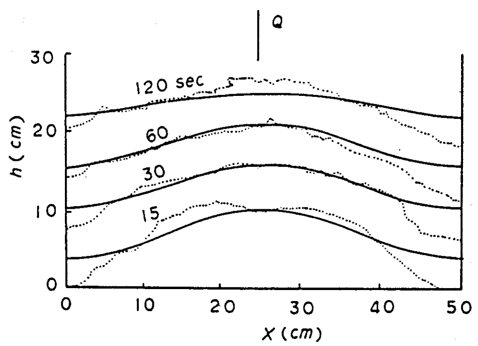

Fig. 5 Rectangular form of 20 cm by 50 cm.

Table 2 Grouting conditions.

Case No.	Fig No.	Dimensions	Coarse aggregate	Location of pipes	Grout time	Grouting rate Q1	Q2	Remarks
1	4	L=50cm B=20cm	A1	Center	15s 30 60	16.8 l/min 11.7 6.9	- - -	Rectangular
2	5	L=50cm B=20cm	A2	Center	15 30 60 120	11.9 10.8 8.1 4.6	- - - -	
3	6	L=50cm B=20cm	A3	xp1=16.7cm xp2=44.4cm yp1=yp2=10	3 5 15	37.7 38.8 17.2	30.1 25.9 11.5	
4	8	L=2m B=0.2m	20-30mm V=43.3% k=8.96	Center	1min \~ 7	11.5	-	Wall shaped Underwater
5	9	L=5m B=5m	40-80mm V=48.1% k=9,12,15	Center	0.5h 1 2	120	-	Square Underwater
6	10	R=1.5m	40-150mm V=48.5% k=15cm/s	Center	0-1 1-2	60.4 -	- 51.7	Grouting rate changed at 1 h

Fig.7 is a perspective feature of the grout surface in case No.3 at t=5 s.

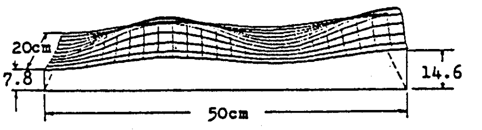

Fig. 7 Perspective drawing of mortar surface calculated for case No. 3 at 5 s.

4.2 Verification by experimental results in the past

(1) Wall

Underwater grouting tests had been carried out by Port and Harbor Research Institute by use of 200 cm x 20 cm x 80 cm forms with the facade of glass. Since the coefficient of permeability and the void content determined by measurements had been reported in the paper(1), calculation could be made.

Grouting conditions are listed in Table 2 as case No.4. Rates of grouting are values estimated in the same way as described in 4.1,(1). Eq.(17) was used with the first three terms to be added.

Fig.8 shows the features of the grout surface coming up along the glass plate. In the figure, the observed surface (dotted lines) seem to agree fairly well with the calculated results (solid lines), except that the actual spread of the grout is narrower than the estimated especially in an early stage of grouting. This disagreement might be caused by underwater grouting because the coefficient of permeability was determined by tests in air.

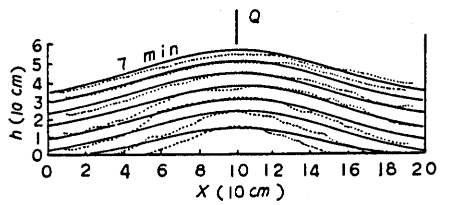

Fig. 8 Results for the wall-shaped form grouted at a constant rate 11.5 l/min.

(2) Square and cylindrical cases on a large scale

Field experiments of grouting had been performed by Japan Railway-Construction Public Corporation(3). There, the progress of filling was observed by sounding the surface of grout through well pipes inserted in the coarse aggregate. Two cases of the experiments are compared with calculated results in Fig. 9 and Fig.10.

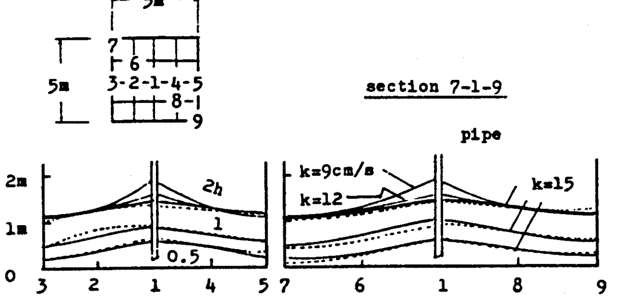

Fig. 9 5 m square form.

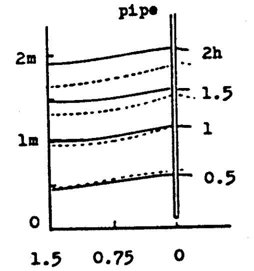

Fig. 10 Cylindrical form ; grouting rate changed at 1 h.

The experimental data recorded in the report were such as grading of crushed stone aggregate, efflux time of grout, the average grouting rate, injection rate of each batch, the number of the batches injected, and the level of grout surface at the scheduled times. Therefore, some of the parameters to be used in calculation, that is, void content of the coarse aggregate, coefficient of permeability, and injection rate were estimated from the experimental data in the following manner.

Void content — volume ratio of the injected grout to grouted portion

Coefficient of permeability — because of difficulty in measurement due to the excess of aggregate size for the test apparatus, three values of 9, 12 and 15 cm/s, in consideration of test result on 30-60 mm aggregate (6.8 cm/s), were used.

Injection rate — for case No.5, the average rate: for case No.6, Q_1 was taken as the average rate from the start to 1 hr and Q_2 the average rate from 1 hr to 2 hr.

Though the calculation results were obtained by partly use of the estimated values, they satisfactorily agree with the experiments. Naturally a certain extent of local disorder due to the variations of the fluidity and the injection rate of the grout, and the irregularity of the voids may exist, however, as far as the grout flows smoothly as a whole, the theory might be valid.

5. PRACTICAL APPLICATIONS

5.1 Planning and prediction of grouting process for a foundation slab

For a flat and wide structure like the base slab of a dry dock, it is difficult or uneconomical to grout simultaneously over the whole area. Therefore the grouting is usually performed with grout pipes being shifted from one side to the other of the forms. Case No.7, as an example, a foundation slab of 4 m by 6 m by 1 m was taken. The arrangement of the pipes is shown in Fig. 11. Injection sequence was from left to right row by row in five steps. Accordingly, the grouting would be performed through three or two pipes simultaneously, and there would be no pause between the steps.

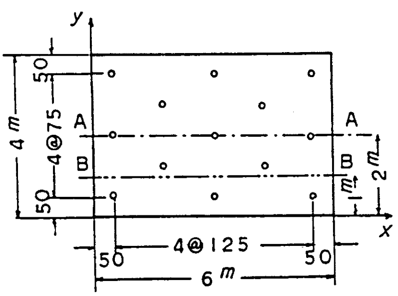

Fig. 11 Arrangement of the grouting pipes.

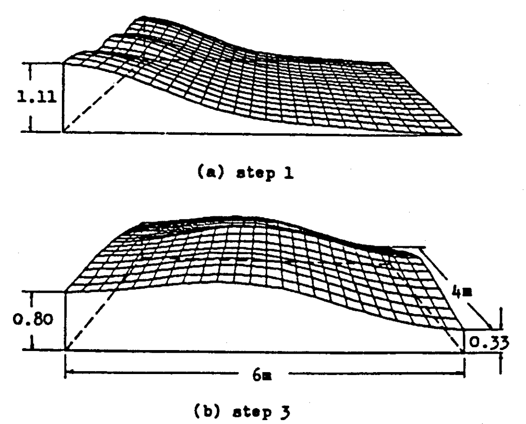

Fig. 12 Perspective drawings of mortar surface for case No. 7 when step 1 (a) and step 3 (b) were finished.

Rate and duration time of injection in each step are shown in Table 3. They were selected so that the grouting might steadily progress in approximately 1 m depth from the left side of the forms. Pipe No.2 in the table is identical to a pipe situated on the line AA in Fig. 11.

Table 3 Grouting conditions of case No. 7.

Step	Pipe No.1			Pipe No.2			Grouting time(min)	V (%)	k(cm/s)
	xp (m)	yp (m)	Q(l/min)	xp (m)	yp (m)	Q(l/min)			
1	0.50	0.50	30.0	0.50	2.00	15.0	40		
2	1.75	1.25	30.0	-	-	-	20		
3	3.00	0.50	30.0	3.00	2.00	15.0	15	40	6.00
4	4.75	1.25	30.0	-	-	-	10		
5	5.50	0.50	30.0	5.50	2.00	15.0	5		

Void content of coarse aggregate and coefficient of permeability were assumed 40 percent and 6.00 cm/s respectively.

Since the grouting conditions were changed several times, Eq.(17), (18) and (19) were used repeatedly. The level of grout surface was calculated at 425 lattice points by dividing L into twenty four equal parts and B into sixteen.

Fig.12(a) and (b) are the estimated states of filling when step 1 and step 3 are completed.

Fig. 13 shows the progress of the filling in section BB with the advance of the step.

For this case the fluidity of the grout was assumed unchanged. If it lowered after the completion of the step, the constant $k(=k_2)$ included in the equations of h_r , Eq.(15),(19),(23), might be chosen of a smaller value than $k(=k_1)$ in h_s or h_q .

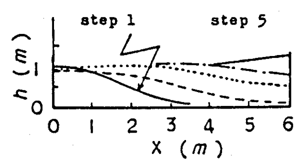

Fig. 13 Change of mortar surface at section B with the advance of grouting steps.

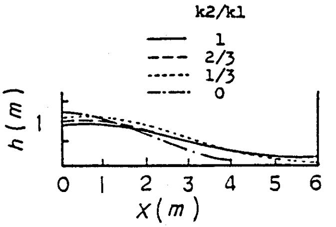

Fig. 14 Influence of k_2 on the shape of mortar surface.

Fig. 14 shows the surface shapes in section AA at the instant of the completion of step 2 with varying k_2/k_1 ratio.

5.2 The selection of performance conditions

(1) The relation between performance conditions and the maximum gradient of grout flow

a. Rectangular structures

For the case of rectangular forms of L by B with a grout pipe in the center, the co-ordinates of injection point are $x_p=L/2$, $y_p=B/2$. Considering the section $y=B/2$

Eq.(17) will be finally written as

$$h=\frac{Q}{\varepsilon BL}(t+2s_x+2s_y+4s_{xy})$$

$$s_x=-\frac{1}{a}\left(\frac{L}{2\pi}\right)^2\left\{1-\exp\left(-\frac{4a\pi^2}{L^2}t\right)\right\}\cos\frac{2\pi x}{L}$$

$$s_y=\frac{1}{a}\left(\frac{B}{2\pi}\right)^2\left\{1-\exp\left(-\frac{4a\pi^2}{B^2}t\right)\right\}$$

$$s_{xy}=-\frac{1}{a\left\{\left(\frac{2\pi}{L}\right)^2+\left(\frac{2\pi}{B}\right)^2\right\}}\left[1-\exp\left\{-\left(\frac{4a\pi^2}{L^2}+\frac{4a\pi^2}{B^2}\right)t\right\}\right]\cos\frac{2\pi x}{L}$$

The equation of gradient is

$$\frac{dh}{dx}=\frac{d}{dx}\left\{\frac{Q}{\varepsilon BL}(t+2s_x+2s_y+4s_{xy})\right\}$$

$$=\frac{2Q}{\varepsilon BL}\left[\frac{1}{a}\left(\frac{L}{2\pi}\right)\left\{1-\exp\left(-\frac{4a\pi^2}{L^2}t\right)\right\}\sin\frac{2\pi x}{L}\right.$$

$$\left.+\left(\frac{2\pi}{L}\right)\frac{2}{a\left\{\left(\frac{2\pi}{L}\right)^2+\left(\frac{2\pi}{B}\right)^2\right\}}\left\{1-\exp\left(-\frac{4a\pi^2}{L^2}t-\frac{4a\pi^2}{B^2}t\right)\right\}\sin\frac{2\pi x}{L}\right]$$

For the maximum value of dh/dx :

$$\exp\left(-\frac{4a\pi^2}{L^2}t\right)=0,\quad \exp\left\{-\left(\frac{4a\pi^2}{L^2}+\frac{4a\pi^2}{B^2}\right)t\right\}=0$$

Thus,

$$\left(\frac{dh}{dx}\right)_{max}=\frac{2Q}{a\varepsilon BL}\left(\frac{L}{2\pi}\right)\left(1+\frac{B^2}{B^2+L^2}\right)\sin\frac{2\pi x}{L}$$

As the positions where the gradient takes its maximum value are x=L/4 and 3L/4,

$$\left(\frac{dh}{dx}\right)_{max}=\frac{1}{2\pi}\frac{2Q}{a\varepsilon B}\left(1+\frac{2B^2}{B^2+L^2}\right)$$

Using the notation $L/B=\varphi$ and the relation $a\varepsilon=k$ which is derived from Eq.(3) and (5),

$$\left(\frac{dh}{dx}\right)_{max}=\frac{50}{3\pi}\frac{Q}{k}\frac{1}{B}\left(1+\frac{2}{1+\varphi^2}\right)$$

where the units to be used are cm for L and B, l/min for Q, and cm/s for k.

This formula indicates that the maximum gradient of grout flow is proportional to the rate of injection, inversely proportional to the coefficient of permeability, and that it decreases with increasing dimensions of the formwork. By use of this equation, the allowable maximum value of Q/k may be determined for a given gradient of grout flow.

Table 4 is a comparison of calculated values with the experimental results carried out by Port and Harbor Research Institute in the same manner as described in 4.2,(1).

The maximum gradients were measured from the illustrations of the grout surface in the paper.

Table 4 Comparison between calculated and experimental results

Aggr (mm)	k(cm/s)	Q(ℓ/min)	experiment	calculation
10 ~ 15	1.99	4.36	0.62	0.59
20 ~ 30	8.96	11.52	0.33	0.35
30 ~ 40	15.37	4.83	0.15	0.09

Though the readings have been subjectively obtained, they seem to agree considerably well with the calculated values.

b. Cylinders

For the case of cylindrical forms with a grout pipe in the center, Eq.(20) may be used, but it is not so easy to derive the maximum dh/dr from this equation as from that for the rectangular forms. Therefore, by dividing R, the radius of the forms, into equal parts of R/m, and using the following notations:

$$\Delta r = R/m \qquad r_{i-1} = (i-1)\Delta r \qquad r_i = i\Delta r$$

the gradient G_i between $i\Delta r$ and $(i-1)\Delta r$ may be calculated as follows:

$$G_i = |(h_i - h_{i-1})/\Delta r| = |\Delta h/\Delta r|$$

$$\frac{\Delta h}{\Delta r} = \left| \frac{Q}{\pi R^2 \varepsilon}\left[t + \sum_{n=1}^{3} \frac{J_0\{\mu_n(r+\Delta r)\}}{a\mu_n^2 J_0^2(\mu_n R)}\{1 - \exp(-a\mu_n^2 t)\}\right] - \frac{Q}{\pi R^2 \varepsilon}\left[t + \sum_{n=1}^{3} \frac{J_0(\mu_n r)}{a\mu_n^2 J_0^2(\mu_n R)}\{1 - \exp(-a\mu_n^2 t)\}\right]\right| \Big/ \Delta r$$

where $(i-1)\Delta r = r$

For the maximum, $\exp(-a\mu_n^2 t) = 0$

$$\left(\frac{\Delta h}{\Delta r}\right) = \frac{Q}{\pi R^2 a\varepsilon}\left| \sum_{n=1}^{3} \frac{J_0\{\mu_n(r+\Delta r)\}}{\mu_n^2 J_0^2(\mu_n R)} - \sum_{n=1}^{3} \frac{J_0(\mu_n r)}{\mu_n^2 J_0^2(\mu_n R)}\right| \Big/ \Delta r$$

$$= \frac{1}{\pi R^2}\cdot\frac{Q}{k}\left| \sum_{n=1}^{3} \frac{J_0\{\mu_n(r+\Delta r)\}}{\mu_n^2 J_0^2(\mu_n R)} - \sum_{n=1}^{3} \frac{J_0(\mu_n r)}{\mu_n^2 J_0^2(\mu_n R)}\right| \Big/ \Delta r$$

The maximum gradient will be found out by calculating this formula from r=0 to $R-\Delta r$. As is seen in the formula, it is proportional to Q/k and inversely proportional to the square of cylinder's radius.

(2) Procedure for selecting performance conditions

It is said that to achieve a good state of filling of grout mortar, the gradient of grout flow is required to be 1/2 and desired to be 1/4. The following is a procedure to decide the performance conditions properly.

The factors to be taken into account are
S: area to be grouted per pipe (square meter)
R: radius of S (m)
V_h: rate at which the grout surface comes up (m/hr)
ε: void content of coarse aggregate (ratio)
G_m: allowable maximum gradient of grout flow (ratio)

and the conditions to be decided are
Q: rate of injection per pipe
k: coefficient of permeability

For convenience' sake, the diagrams Fig. 15 and Fig. 16 were made. The calculation procedure is

1) to read Q_ε corresponding to R and V_h from Fig. 15
2) to calculate Q by $Q=\varepsilon Q_\varepsilon$
3) to read Q_k from Fig. 16
4) to calculate k by $k=Q/Q_k$

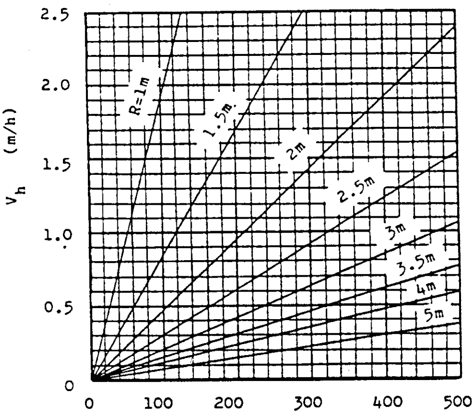

Fig. 15 V_h vs Q_ε.

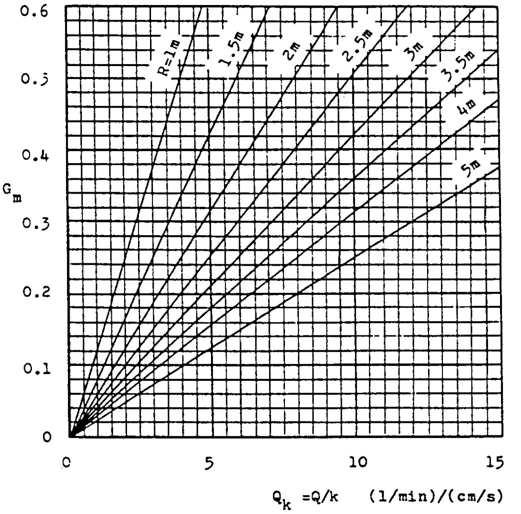

Fig. 16 G_m vs Q_k.

For an example of numerical calculation, assuming
R = 1.5 m
V_h = 0.5m/hr
G_m = 0.25
ε = 0.44

1) from the conditions R=1.5 m and V_h = 0.5 m/hr, Q_ε is read as 59 l/min (Fig.15
2) Q= $\varepsilon Q_\varepsilon$ =0.44x59=26.0 l/min
3) from R=1.5 m and G_m=0.25, Q_k may be read as 3.0 (l/min)/(cm/s) (Fig.16
4) k= Q/Q_k=26.0/3.0=8.67 cm/s

This estimation indicates that the required rate of injection is 26.0 l/min and that the grading of coarse aggregate and the fluidity of grout ought to be selected so that the coefficient of permeability may be larger than 8.67 cm/s.

To the contrary, for estimating the maximum gradient of grout flow under given conditions of grouting Fig.16 may be useful. The rate at which the grout surface comes up will be determined easily by Fig.15.

References

(1) H.KOBA, Y.ARIYOSHI, "On the flow of prepacked concrete mortar through porous coarse aggregate in connection with its grain size", Report of Transportation Technical Research Institute, Ministry of Transportation, Vol.11, No.5, May 1961
(2) Y.AKATSUKA, Report of Port and Harbor Research Institute, Ministry of Transportation, Vol.4, No.6, July 1965
(3) Japan Railway-Construction Public Corporation, Report of prepacked concrete experiments — No.2, 1967
(4) Japan Railway-Construction Public Corporation, Report of experimental investigations in connection with foundations of Honshū-Shikoku bridges, 1968
(5) Y.TANAKA et al, "A field test of large block prepacked concrete containing large size aggregate", Concrete Journal, Vol.9, No.7, July 1971
(6) K.TAKEGAWA, Doctoral thesis, Dec. 1975
(7) N.IWASAKI, "Prepacked Concrete", Sankai-do Co., Ltd., 1981
(8) S.NAGATAKI, A.YONEKURA, Review of 29th JCA Annual General Meetings, 1975