A STUDY ON NUMERICAL SIMULATION DURING CHEMICAL GROUTING

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The chemical grouting has the advantages that equipments are small and the direction of boring has flexibility. Therefore, in Japan, it is frequently used for a soil-improvement method in the railway construction site where workspace or working hours is limited. However, it has the possibility to cause a ground displacement around the site. Because there is no method that estimates it quantitatively, the design based on old cases is still used mainly and focuses on safety overly.

In this Study, the simplified numerical analysis for ground behavior due to the osmotic pressure during injection is proposed.

1. INTRODUCTION

Chemical grouting is the soil-improvement method that injects grouting material into a void of soil to increase soil strength and prevent a water leak. In Japan, it has been frequently used in the railway construction site where workspace or working hours is limited (Fig. 1). In this case, it is necessary to inject grouting material so as not to cause a displacement of the railway track more than a maximums permissible value. However, there is no method that estimates it quantitatively. The design that based on old cases is still used mainly and focuses on safety overly.

In this study, the simplified numerical analysis for the ground behavior due to the osmotic pressure during injection is proposed. The procedure of this numerical analysis is as follows (Fig. 2).

1. The excess pore pressure during injection is calculated by both "Magg's method" or "convection-diffusion analysis".
2. The excess pore pressure is converted into the osmotic pressure.
3. The numerical analysis for ground behavior is carried out by using this osmotic pressure.

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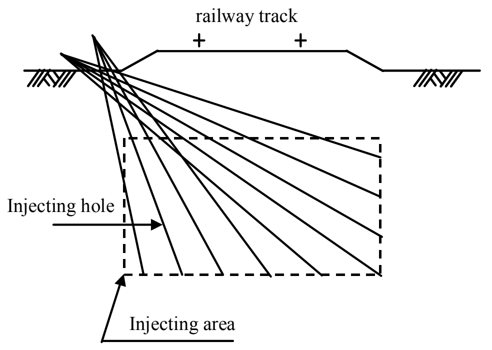

Figure 1. Example of grouting layout under railway track.[1]

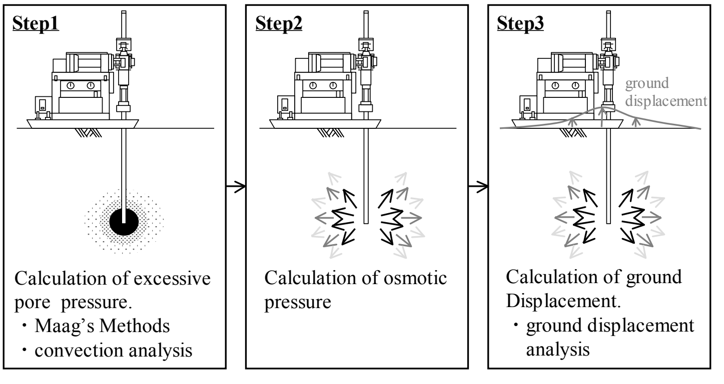

Figure 2. The numerical analysis that evaluates ground behavior during injecton.

In this paper, this numerical analysis is applied to a general case and the applicability of the osmotic pressure calculated by both "Magg's method" and "convection-diffusion analysis" is shown.

2. EXCESS PORE PRESSURE

2.1. *Magg's method*[1]

Magg's method is the simple method from which a excess pore pressure can be calculated. It is based on following assumptions.

1. The flow of grouting material is laminar flow and it follows Darcy's law.
2. The unit weight of grouting material is same as the unit weight of water.
3. The viscosity of grouting material doesn't change until the "gel time".
4. The excess pore pressure balances with hydrostatic pressure at infinity ("A" in Fig. 3).
5. Ground conditions are constant and the grouting material flows to radially.
6. The grouting area is below groundwater table and the underground water geostationary.

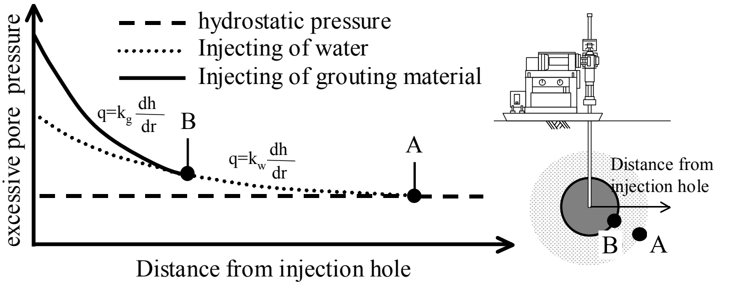

Figure 3. Relationship between distance from injection hole and excessive pore pressure.

The equation is as follows. In this study, the penetration radius of grouting material is assumed to be time dependent variable.

$$\begin{cases} p(r,t) = \frac{\gamma \cdot q}{4\pi k_w} \cdot \left\{ \left(\frac{\mu_g}{\mu_w}\right) \frac{1}{\gamma} + \left(1 - \frac{\mu_g}{\mu_w}\right) \frac{1}{R(t)} \right\} + \gamma \cdot h_w & (\gamma \le R(t)) \\ p(r,t) = \frac{\gamma \cdot q}{4\pi k_w} \cdot \frac{1}{\gamma} + \gamma \cdot h_w & (\gamma > R(t)) \end{cases} \tag{1}$$

$p(r,t)$: pore pressure at radius r and time t (kPa), γ: unit weight of water (kN/m^3), h_w: ground water level form injecting hole (m), q: injection rate (m^3/sec), k_w: water permeability (m/sec), μ_w: viscosity of water (Pa · s), μ_g: viscosity of grouting material (Pa · s), $R(t)$: penetration radius of grouting material from injecting hole at time t(m).

$R(t)$ is as follows ("B" in Fig. 3).

$$R(t) = \sqrt[3]{\gamma + \frac{300 \cdot q \cdot t}{4\pi \cdot n_e}} \tag{2}$$

n_e: void ratio, r_a: radius of injecting hole (m).

This method has the advantage that a simple calculation can be done to figure out an excess pore pressure. But theoretically, this method cannot be used because of the assumptions 4)~6), when there are a structure and ground water table near the strainer of grout tube or continuous injection is handled.

2.2. Convection-diffusion analysis

When the excess pore pressure is calculated by the finite element method, the seepage flow analysis which based on Eq. (3) should be used. Besides, in the Multi-phase flow with a different viscosity, it is necessary to correct the permeability progressively according to penetration area of the grouting material.

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_i}\right) - q = \frac{\partial}{\partial t}(S_w \cdot n_e) \tag{3}$$

In this study, the penetration area is calculated as density by convection-diffusion analysis. It is assume that the permeability is calculated according to density (Eq. (4)).

K_{ij}: water permeability, h: hydraulic head, S_w: degree of saturation, n_e: void ratio

$$K = \left(\frac{\mu_g}{\mu_w} C(t) + (1 - C(t)) \right) \cdot K_w \tag{4}$$

K: permeability, $C(t)$: density as time t (the maximum value of density is 1.0)

The procedure of this analysis is as follows:

1. The flow velocity field is calculated by the seepage flow analysis.
2. The density distribution is calculated by the convection-diffusion analysis by using this flow velocity field.
3. The permeability is corrected according to this density distribution and Eq. (4).
4. 1)∼3) is repeated until the end of the injection.

When multilayered ground or a continuous injecting stage are handled, this method can be used. However, it take time to calculate excess pore pressure.

2.3. *Application to general case*

2.3.1. *Calculation conditions*

Figure 4 and Table 1 show the construction conditions. The depth of the grouting area is from 1 to 3 m and the grouting material is injected by 5 steps. The axisymmetric element mesh (Fig. 5) is used to express radial flow. In the seepage flow analysis, the free drainage condition applied at the upper boundary and the side boundary and the horizontal constant flow is applied at the position of strainer. In the convection-diffusion analysis, the density boundary $(C = 1)$ is applied at the position of strainer.

The ground conditions are constant. These properties of the soil and the grouting material are shown in Table 2.

The permeability is applicability limits for permeation grouting using the liquid grouting material which is composed of Water Glass and doesn't contain particles (it is mainly used in Japan) and the injection rate is the maximum value of it set in general. Therefore, it

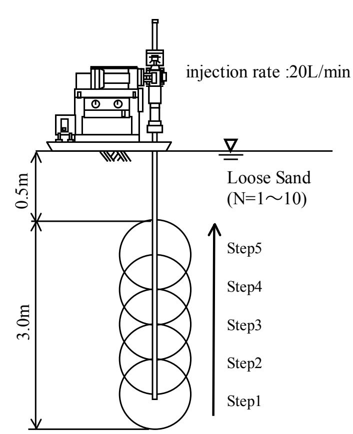

Figure 4. Construction conditions.

Table 1. Construction conditions.

Injecting rate q (L/min)	20.0
Diameter of a lod r_a (m)	0.10
Lengs of a strainer l (m)	0.10
Penetration distance R (t)(m)	0.50
Injecting step	Step up
Step interval d (m)	0.5

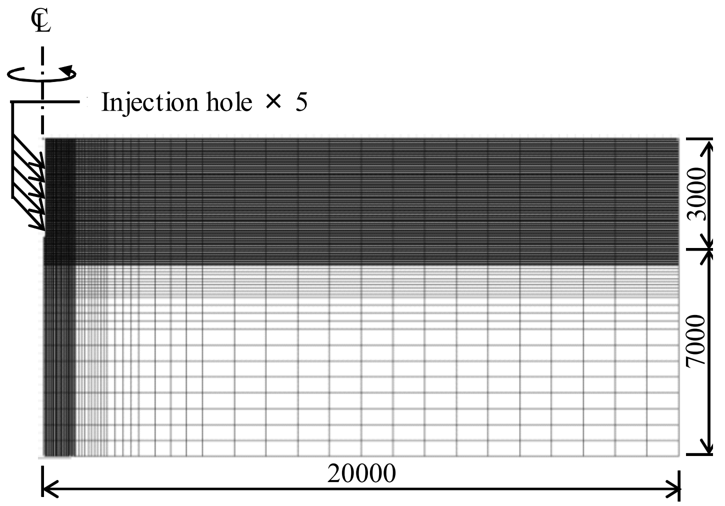

Figure 5. Axisymmetric element mesh.

is thought that these conditions lead the result of the maximum and wide-ranging excess pore pressure distribution in actual grouting. The the viscosity of water is shown in Table 3. The dynamic viscosity of liquid grouting material is shown in Fig. 6. Because of the concentration of Water Glass in the general liquid grouting material is 25% in Japan, the dynamic viscosity of the grouting material is about 2.5 $\times 10^{-3}$ Pa · s at 15 degrees Celsius. As a result, the value that the dynamic viscosity of the water is divided by the dynamic viscosity of the grouting material is about 0.5.

Table 2. The soil and the grouting material property.

soil	Unit weight of water γ_w (kN/m^3)	10.0
	Permeability k_w (m/sec)	1.0×10^{-5}
	Void ratio e	0.92
	Specific storage S_c (1/m)	1.80×10^{-4}
grouting material	Rate of viscosity μ_w/μ_g	0.50

Table 3. The viscosity of the water.

Temperature (Centigrade)	Dynamic viscocity ($\times 10^{-3}$ Pa $\cdot$ s)
10	1.308
15	1.139
20	1.002
25	0.89

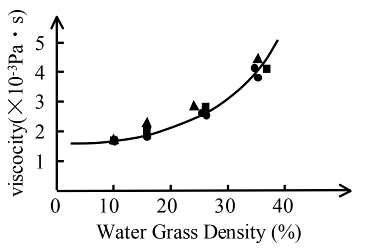

Figure 6. The dynamic viscosity of the grouting material.

2.3.2. *Results*

The injection pressures are shown in Fig. 7. This injection pressures that is calculated by both Magg's method and the convection-diffusion analysis reach a close value. The injection pressure rises rapidly at first and it changes into the gradual increase about 1 minute later. The ultimate injection pressure became about 1.0 MPa. The time required for the injection is 12.53 minutes.

The excess pore pressure distributions are shown in Fig. 8 and Fig. 10. In the seepage flow analysis, because flow velocity is small, the excess pore pressure distribution become radically though the horizontal constant flow is applied at the position of strainer. These excess pore pressures that are calculated by both Magg's method and convection-diffusion analysis draw a close path. The excess pore pressure decrease rapidly as going away from the injection hole and disperses at about 1.0 m. Moreover, as the result of the convection-diffusion analysis. It is understood that the excess pore pressure which was generated at the former injection stage disperses at the next injection stage.

The penetration distance from the injection hole calculated by Maag's method is shown in Fig. 9. It is understood that the penetration rate becomes small as the penetration distance becomes long. The isosurface $(C = 0.5)$ of the density distribution calculated by convection-diffusion analysis is shown in Fig. 11. The isosurface becomes a globe in step 1 and it becomes a portrait because the grouting material of the former step exists since step 2. However, the grouting materials almost stay at the injected position. Finally, the globe became consecutive shape mutually.

Because the excess pore pressure decreases at about 1.0 m, there is no remarkable difference in both methods in this stage in that the excess pore pressure was calculated. Consequently, it is thought that both methods are effective if there is no boundary within about 1 m.

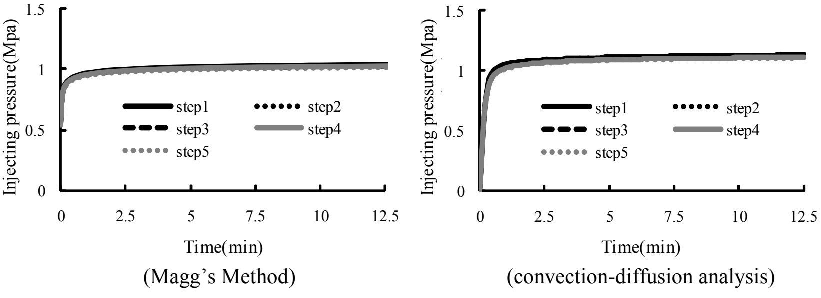

Figure 7. The injection pressure.

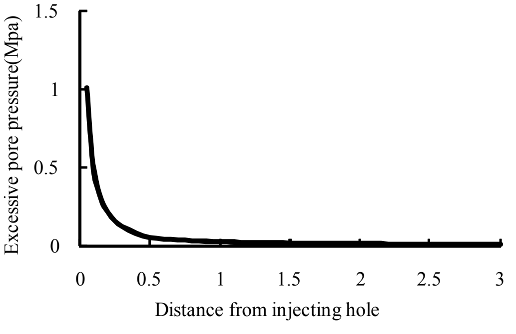

Figure 8. The excessive pore pressure (Magg's Method).

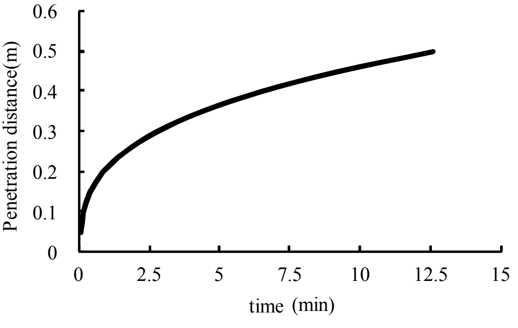

Figure 9. The penetration distance of the grouting material (Magg's Method).

3. GROUND DISPLACEMENT

In clay ground, excess pore pressure acts directly on the ground and generates consolidation. On the other hand, in sand ground, excess pore pressure is instantaneously replaced the seepage flow and osmotic pressure acts on the ground. This osmotic pressure is usually handled as equivalent nodal force in ground displacement analysis.

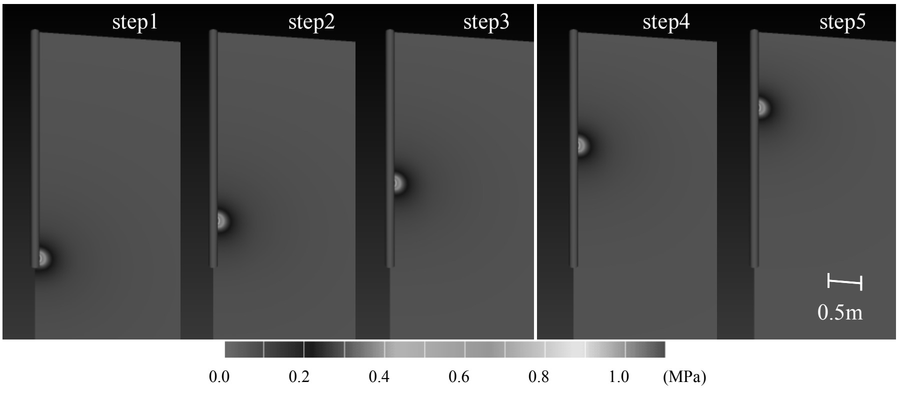

Figure 10. The excessive pore pressure (convection-diffusion analysis).

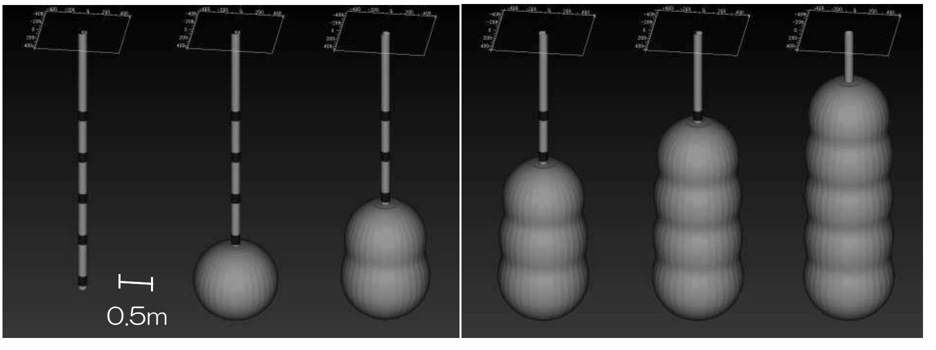

Figure 11. The penetration distance of the grouting material (convection-diffusion analysis).

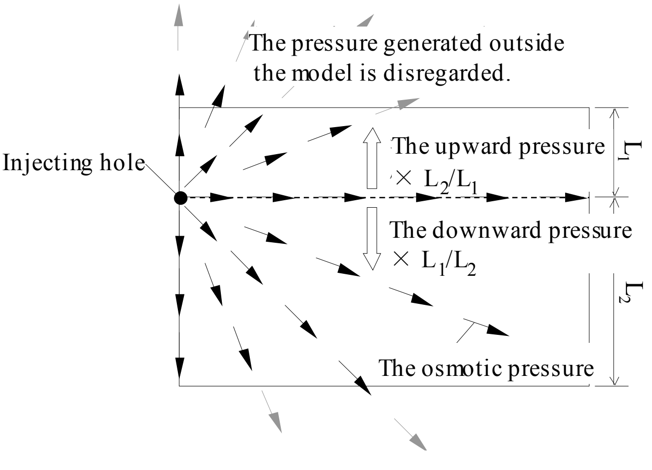

Figure 12. The osmotic pressure (Magg's Methods).

Table 4. The soil property.

Modulus of deformation E (kN/m^2)	40000
Poisson's ratio γ	0.3
Unit weight of soil γ (kN/m^3)	18.0
Degree $\varphi(^\circ)$	30
Cohesion of soil c (kN/m^2)	5.0
Hardening modulus H	10.0

3.1. *The equivalent nodal force*

In the finite element method, the relation between excess pore pressure and osmotic pressure is as follow.

$$\{\gamma \cdot i\} = \begin{Bmatrix} -\frac{\partial p}{\partial x} \\ -\frac{\partial p}{\partial y} \end{Bmatrix} = \begin{Bmatrix} -\sum_{i=1}^{N} \frac{\partial N_i}{\partial x} p_i \\ -\sum_{i=1}^{N} \frac{\partial N_i}{\partial y} p_i \end{Bmatrix} \tag{5}$$

$\gamma \cdot i$: osmotic pore pressure, γ: unit weight, i: hydraulic head gradient, p_i: excess pore pressure, N: shape function.

If this equation is integrated in the element, equivalent nodal forces of each node are calculated.

$$f_x = -\int_\Omega N^T \frac{\partial p}{\partial x} d\Omega \tag{6}$$

$$f_y = -\int_\Omega N^T \frac{\partial p}{\partial y} d\Omega \tag{7}$$

f_x, f_y: equivalent nodal force.

3.2. *Calculation conditions*

The numerical analysis for ground behavior use same axisymmetric element mesh as convection-diffusion analysis (Fig. 5) to handle three-dimensional osmotic pressure.

The soil property is shown in Table 4. The ground is an elastic-plastic body. Mohr-Coulomb theory is applied to yield criterion and flow rule and the plastic behavior is work hardening. The osmotic pressure calculated by convection-diffusion analysis is directly used in the numerical analysis for ground behavior because of using same mesh. On the other hand, all of the osmotic pressure calculated by Magg's method cannot act on node. Because these assumptions of both the ground and the excess pore pressure are different from the axisymmetric element mesh, Magg's method cannot be theoretically applied. But there is a possibility that the influence by the difference of assumption can be disregarded because the excess pore pressure disperses at about 1.0 m. Then, in this study, it is assumed that only pressures within the model are acted and the balance of upward pressures and downward pressures is changed according to the model size (Fig. 12). If such a conversion isn't done, the downward pressure is distinguished.

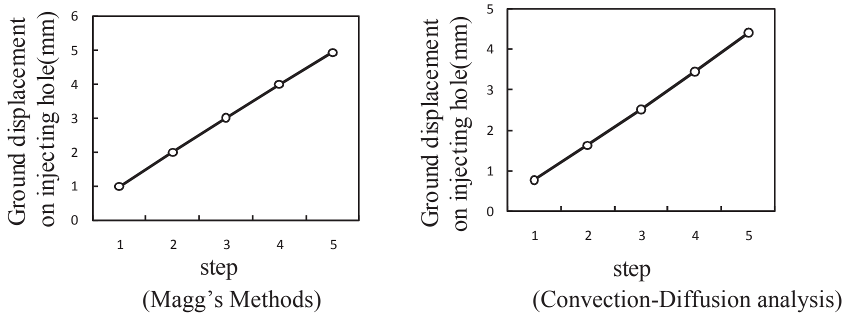

Figure 13. The vertical ground displacement on injecting hole.

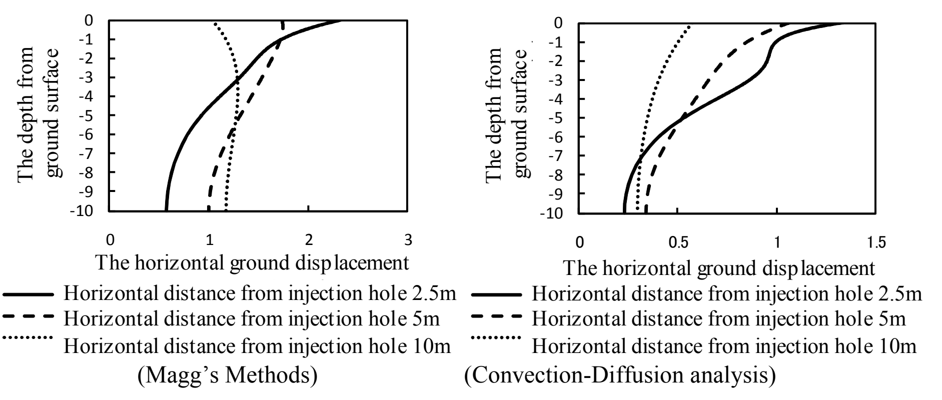

Figure 14. The horizontal ground displacement.

3.3. *Results*

The vertical ground displacement on the injection hole is shown in Fig. 13. Either method show that the ground surface rise up as the injection step advanced. The vertical displacement calculated by Magg's method is larger than it calculated by convection-diffusion analysis. It means that Magg's method will calculate a safety-side value close to the value calculated by convection-diffusion analysis. The horizontal displacement is shown in Fig. 14. The horizontal displacement calculated by Maag's method also is larger than it calculated by convection-diffusion analysis. However, The result calculated by Magg's method shows a tendency different from it calculated by convection-diffusion analysis while going away from the injection hole. The displacement calculated convection-diffusion analysis fluctuates more sharply. It is thought that the difference of Magg's assumption influences this result.

Therefore, when the vertical displacement on injection hole or the horizontal displacement near injection hole is calculated, Magg's method can be applied. However, when a displacement far from the injection hole or the tilt angle is calculated, the convection-diffusion analysis should be executed.

4. CONCLUSION

The conclusions of this study are as follows.

1. These excess pore pressures that are calculated by both Magg's method and convection-diffusion analysis are a close value if there is no boundary within 1 m.
2. As the result of convection-diffusion analysis, the final grouting material shape that is injected by 5 steps can be calculated.
3. The numerical analysis for ground behavior can be carried out with this osmotic pressures that is calculated by both Magg's method and convection-diffusion analysis.
4. The absolute quantity of ground displacement with the osmotic pressure that is calculated by Magg's method is larger than convection-diffusion analysis.
5. When the vertical displacement on injection hole is calculated or the horizontal displacement near injection hole is calculated, Magg's method can be applied. However, when a displacement far from the injection hole or the tilt angle is calculated, the convection-diffusion analysis should be executed.

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