PENETRATION BEHAVIOR OF CHEMICAL GROUTING CONSIDERING GROUND UNCERTAINTY

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ABSTRACT: The chemical grouting is one type of ground-improvement methods. It injects liquid consolidation material into the gaps of a soft sandy ground. It is mainly used for improving a stable ground, such as by preventing liquefaction and increasing the strength of the ground. Chemical grouting has been successfully applied at many construction sites; however, the behavior of the chemical solution being injected into the ground is unclear. Furthermore, because the ground involves uncertainty, it is difficult to determine the penetration range of the chemicals (grouting materials). In this study, the authors carry out a seepage flow analysis of a chemical solution for a ground requiring improvement due to uncertainty. They then compare the difference in the behavior of the chemical solution between the case in which the ground is assumed to be heterogeneous and that in which it is assumed to be homogeneous.

Keywords: Chemical grouting material, Ground improvement, Ground uncertainty, Seepage flow analysis

1. INTRODUCTION

1.1 Background

The chemical grouting method (see Fig. 1), which is one type of ground-improvement method, involves the injection of a liquid cling material (hereinafter referred to as grouting material) into the gaps of a soft sand plate to prevent the liquefaction of the sand base and to increase the strength of a stable ground. It is one of the consolidation methods used to improve a ground [1], [2]. The chemical grouting material permeates the gaps between the soil particles and eventually solidifies and assumes a gel state. The gel plays the role of an adhesive and, as a result, the ground is strengthened and the water barrier in the ground is improved. Since the chemical grouting method uses compact equipment, that can be carried around comparatively easily, and it can be completed in a short amount of time, it has been successfully applied for temporary construction (auxiliary construction method in underground construction) at many construction sites. In recent years, along with improvements in grouting technology, typified by the double-tube double packer construction method, and progress made in the development of grouting material, the application of chemical grouting has been expanding [3], [4], [5]. For example, as the performance of the grouting material has improved, there has been an increasing demand for its use in various fields not only as a temporary solution, as was the original purpose in the past, but also as a permanent solution, such as in countermeasures to

liquefaction [5], [6]. However, if the grouting material is to be used as a more permanent solution, it must have long-term durability. In addition, remarkable progress has been made in grouting technology itself, and along with the double-pipe double packer construction method, it is now possible to excavate a ground just under an existing structure by curve boring and to perform grouting without interrupting the function of the structure. Thus, it is expected that the chemical liquid grouting method will soon be used for a wide range of purposes, including liquefaction countermeasure work and deep underground development work. As an example, Haneda Airport underwent improvement work while the function of the airport was maintained. As a countermeasure for the liquefaction of the runway, the chemical liquid grouting method, using a grouting tube which can bend freely, was applied. On the other hand, although the performance of the chemical grouting method has been proven [1], [2], [3], [4], the mechanism by which the chemical
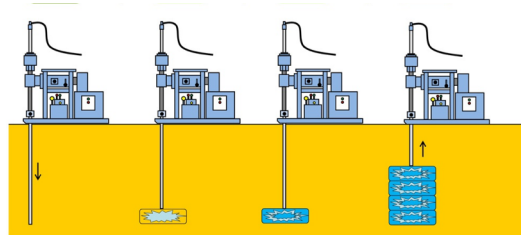

Fig. 1 Overview of chemical grouting method

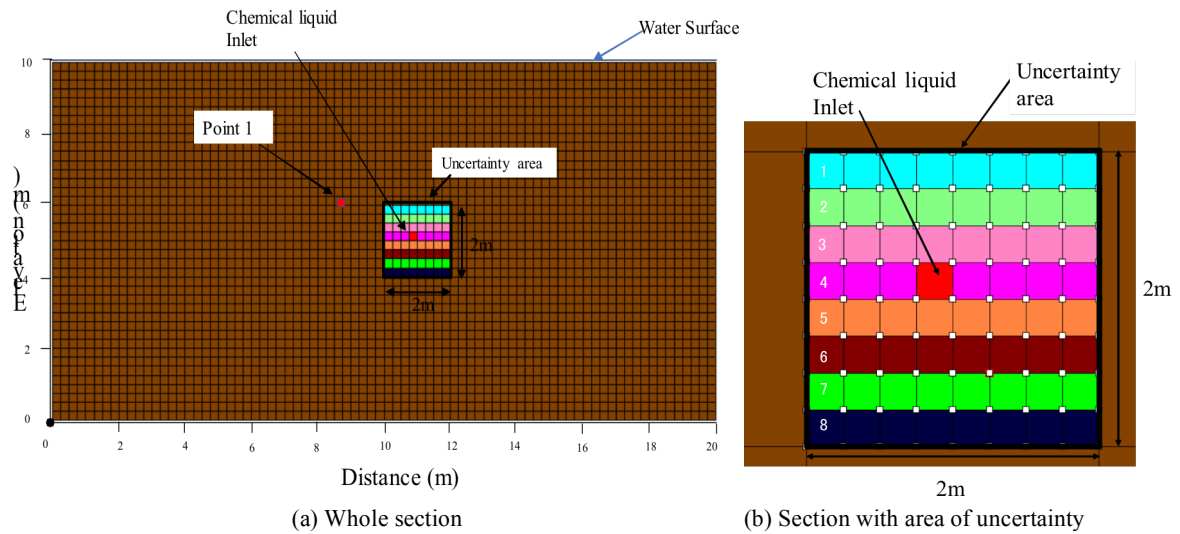(a) Whole section (b) Section with area of uncertainty

Fig. 2 Analysis section

solution penetrates the soil is unclear. A problem also appears at the design stage. This is because, in deciding which material should be used, it is inevitable that engineers must rely on only a small amount of ground survey data on the ground properties of the overall site. The numerical values showing the properties of the ground are not uniform values even in the plane direction, and they also vary in the depth direction. However, as a practical problem, design specifications using these average values as representative values contain contradictions which cannot be eliminated.

1.2 Purpose

In conventional research, authors have conducted their analyses on a homogeneous ground which does not represent the actual ground. In this research, therefore, the authors create a ground with uncertainty to evaluate the influence of the contradiction in average design values as representative values in real problems. In addition, the authors set the cross-section so that the average value of the entire ground with uncertainty is equal to the ground without uncertainty.

2. METHOD OF REPRODUCING UNCERTAINTY
2.1 Summary

A method to reproduce the uncertainty in the ground, to give uncertainty to the cross-section, to give uncertainty to the boundary condition, etc. was conceived. The problems encountered when creating a ground with uncertainty are listed below.
(1) Correlating the homogeneous ground and the ground with uncertainty
(2) Processing the results
(3) Simulating the actual ground as a ground with uncertainty

(4) Simplifying the analysis

The way to solve these four problems is thought to be through the use of the permeability coefficient parameter. The permeability coefficient should be investigated at the time the chemical liquid is injected; it is easy to change this parameter for the cross-section in the analysis. The actual ground consists of strata of different permeability coefficients, and the average permeability coefficient in the vertical direction is different from that in the horizontal direction. In this study, the authors reproduce the uncertainty in the ground by focusing on the permeability coefficients in the vertical and horizontal directions. The average permeability coefficients are expressed by Equations (1) and (2).

$$K_h = \frac{1}{H}(k_1 H_1 + \cdots k_n H_n) \qquad (1)$$

$$K_v = \frac{H}{\frac{H_1}{k_1} + \cdots + \frac{H_n}{k_n}} \qquad (2)$$

where K_h is the average permeability coefficient in the horizontal direction, K_v is the average permeability coefficient in the vertical direction, H is the overall height, k_n is the permeability coefficient of the n layer, and H_n is the height of the n layer.

In this research, to simplify the analysis, the authors set up an area of uncertainty in a homogeneous ground. Also, the permeability coefficient in the vertical direction and the permeability coefficient in the horizontal direction are made equal as per Equations (1) and (2). From this, it can be seen that the ground contains uncertainty although, as a whole, it is a homogeneous ground.

2.2 Analysis Section

The section of the ground analyzed in this study is shown in Fig. 2(a).

The grouting of a sandy ground, 10 m × 20 m, is supposed to be carried out with a chemical liquid in the cross-section of a ground with uncertainty. It is assumed that the water surface is set at elevation = 10 m and that the region of analysis is saturated. The chemical grouting inlet is set to be 0.25 m × 0.25 m; this is close to the size of the grouting port used for actual chemical liquid grouting. The size of the mesh in the analysis is unified at 0.25 mm × 0.25 m. The area of uncertainty was set at 2 m × 2 m near the chemical liquid inlet. On the other hand, the cross-section of the homogeneous ground has a cross-section with no area of uncertainty.

2.3 Area of uncertainty

The area of uncertainty is shown in Fig. 2(b).

The section with uncertainty was set to have eight layers with different permeability coefficients. Here, four models for the permeability coefficients are prepared (see Table 1), and the permeability coefficient is set for each of the eight layers by spreading out these four models randomly.

The average permeability coefficients of the vertical and horizontal directions are consistent with the average permeability coefficients in Table 1. The average permeability coefficients were set, as seen in the table, except for the area where uncertainty is considered. Thus, it is possible to make a comparison with the homogeneous ground. In other words, it is thought that it is possible to approach the cross-section of a real problem by averaging 8 points in the region of uncertainty and treating it as a representative site, or by sampling it outside the region as a representative value.

3. SEEPAGE FLOW ANALYSIS OF CHEMICAL SOLUTION

3.1 Analysis Method

For the analysis in this study, "Dtrans-3D-EL" was used. It is a finite element code expressing the movement of water and solute in groundwater and is based on the penetration of the saturated/unsaturated states and advective dispersion [7], [8], [9].

The fundamental equation of the seepage flow analysis is shown in Equation (3).

$$\{\beta S_S + C_S(\theta)\}\frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x_i}\left[K_{ij}^S\{K_r(\theta)\}\frac{\partial \varphi}{\partial x_i} + K_{ij}^S\right] - Q_C$$
(3)

where β is 1 in the saturated region and 0 in the unsaturated region, S_s is the specific storage

Table 1 Permeability coefficient model

k_n (cm /sec)				Average Permeability coefficient
①	②	③	④	
3.10E-03	1.00E-03	8.80E-04	9.80E-05	6.35E-04

Table 2 Permeability coefficient of uncertainty area

Area	Permeability coefficient(cm/sec)			
	Vertical direction permeability coefficient setting section		Horizontal direction permeability coefficient setting section	
	Vertical direction	Horizontal direction	Vertical direction	Horizontal direction
1	3.10E-03	6.35E-04	6.35E-04	3.10E-03
2	8.80E-04	6.35E-04	6.35E-04	8.80E-04
3	9.80E-05	6.35E-04	6.35E-04	9.80E-05
4	8.80E-04	6.35E-04	6.35E-04	8.80E-04
5	9.80E-05	6.35E-04	6.35E-04	9.80E-05
6	1.00E-03	6.35E-04	6.35E-04	1.00E-03
7	1.00E-03	6.35E-04	6.35E-04	1.00E-03
8	3.10E-03	6.35E-04	6.35E-04	3.10E-03

Table 3 Analysis parameters

Permeability coefficient(cm/sec)		Effective porosity (%)	Specific storage coefficient (1/m)
Vertical direction	Horizontal direction		
6.35E-04	6.35E-04	30	1.00E-04

coefficient, C_S is the specific water content, φ is the pressure head, K_{ij}^S is the saturated permeability tensor, $K_r(\theta)$ is the specific permeability coefficient, and Q_C is the outflow and suction term.

The Galerkin method is used as the discretization method; however, the term for time is discretized by the alternation difference method.

3.2 Analysis Conditions

The seepage flow of the chemical solution was reflected in the permeability coefficient. To obtain the permeability coefficient, the viscosity of the chemical liquid is considered, as shown in Equation (4).

$$k = C\frac{e^3}{1+e}D_s^2\frac{\gamma_w}{\mu}$$
(4)

where K is the permeability coefficient, C is the correction coefficient, e is the porosity, D_s^2 is the particle size, γ_w is the unit volume weight, and μ is the viscosity coefficient

Focusing on the viscosity coefficient shown in Equation (4), the authors reproduce it by dividing the permeability coefficient by the viscosity coefficient.

For the analytical model, three cross-sections of a homogeneous ground without uncertainty, a model giving random numbers only in the vertical
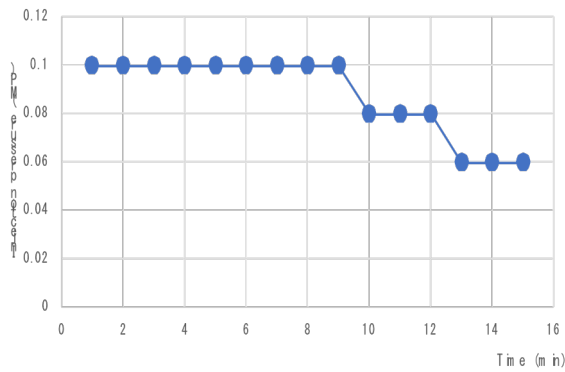
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Fig. 3 Unsteady condition of inlet

direction accompanied with uncertainty, a model giving random numbers only in the horizontal direction with uncertainty were set.

Table 2 shows the permeability coefficients of the area of uncertainty given by random numbers from two sections with uncertainty.

The permeability coefficients of the area of uncertainty, the homogeneous ground, and other permeation analysis parameters are shown in Table 3. The other parameters were determined by referring to past literature.

As the boundary condition, only the grouting port of the chemical solution was set in the transient condition. The reason for setting it to an unsteady condition is the necessary to reproduce the decompression of the chemical liquid grouting (see Fig. 3). The grouting pressure was converted to the pressure head and the parameter was set. Hydrostatic pressure was applied to both ends of the cross-section; it was set to be constant for the whole water head of 10 m. Since the water surface is always set to the elevation = 10 m, because it is a steady condition except at the grouting port, it is treated as being in a saturated state.

3.3 Analysis Results and Evaluation Method

The authors carry out a seepage flow analysis for the chemical solution by a qualitative evaluation and a quantitative evaluation. Firstly, for the qualitative evaluation, Fig. 4 presents contour maps of the whole water head and Fig. 5 presents diagrams of the flow velocity vectors.

The cross-section of the total water head contour map is 10 m × 20 m, and the flow velocity vector diagram is cut out and cut into a section of 6 m × 10 m. Secondly, for the quantitative evaluation, the authors decided to evaluate the total water head at Point 1, as shown in Fig. 6.

3.4 Investigation Based on Results of Seepage Flow Analysis

From the total water head contour maps, it is clear that the penetration is wider in the

(a) Permeability coefficient model for vertical direction

(b) Permeability coefficient model for horizontal direction
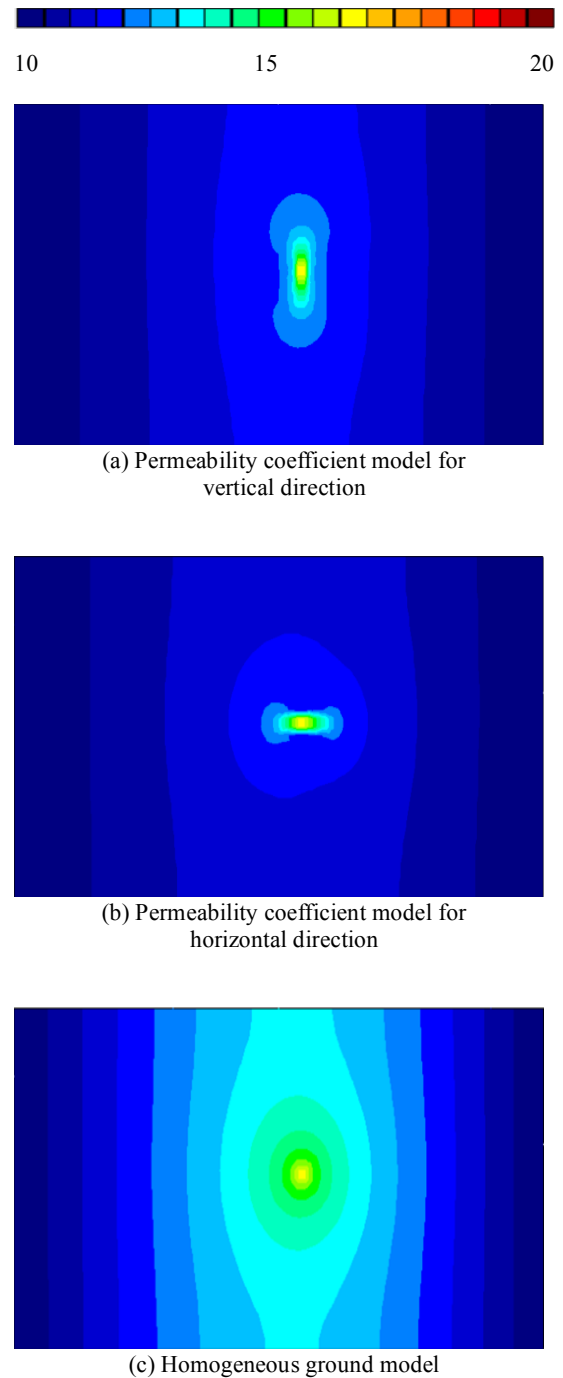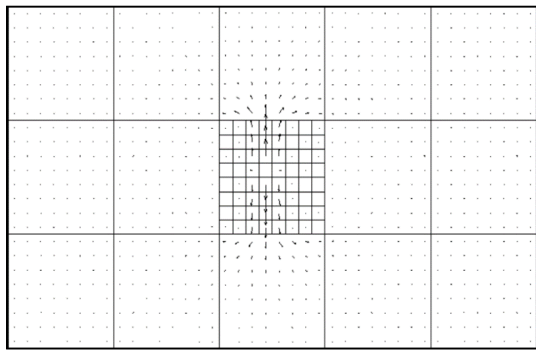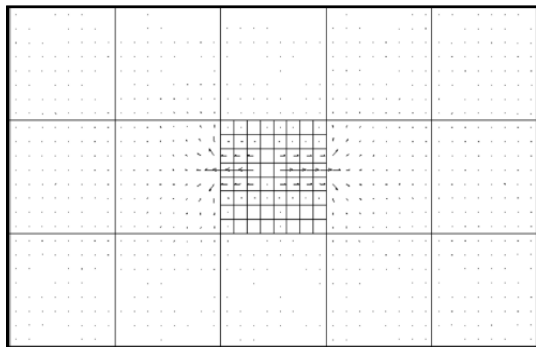

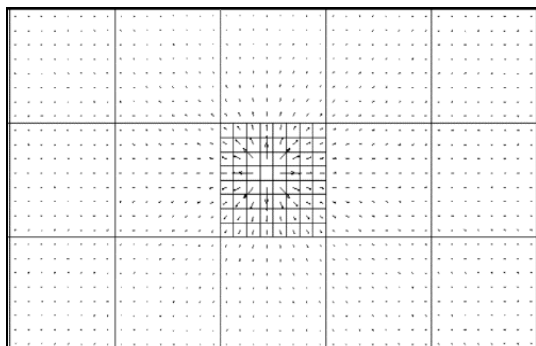(c) Homogeneous ground model

Fig. 4 Total head contour diagrams

homogeneous ground than in the ground with uncertainty. Figure 6 shows the change in total water head at Point 1. However, it can be seen that there is a difference in the total water head of about 1 m between the homogeneous ground and the ground with uncertainty. When the total water head is converted by grouting pressure, it is about 0.01 MP. Although grouting with the chemical liquid consists of invading and consolidating the ground in various forms, the chemical liquid often infiltrates while splitting in the sandy ground (a

(a) Permeability coefficient model for vertical direction

(b) Permeability coefficient model
for horizontal direction

(c) Homogeneous ground model

Fig. 5 Flow velocity vector diagrams

phenomenon in which a chemical liquid permeates the ground in a pulse shape). Especially in a sandy ground, the injected solution will penetrate farther from the cleavage plane, so the grouting pressure is large and is related to the penetration of the chemical liquid. In other words, when treating the ground with uncertainty used in this research as a homogeneous ground and injecting the chemical liquid, the split type of infiltration of the chemical liquid becomes difficult and sufficient ground improvement cannot be expected. Even in the flow velocity vector diagrams, it can be confirmed that
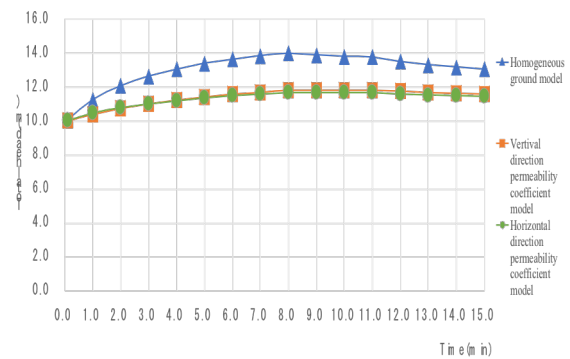

Fig. 6 Total head comparison at Point 1

the chemical liquid permeates the homogeneous ground over a wide range and evenly. However, it can be confirmed that the chemical liquid does not penetrate so much over a wide range into the area with uncertainty; it penetrates along the layer (see Figs. 5 (a) and (b)).

In other words, in this study, since the outermost permeability coefficient is high, ground improvement is necessary. However, as the chemical solution bypasses and penetrates, it can be confirmed from Fig. 5 that it is difficult for the chemical solution to penetrate the ground. While facing the grouting tube upward in the vertical direction, the chemical liquid is injected into the improved ground in steps. As in the case of this study, when regions with uncertainty form a layer, there is concern that the size of the grouting radius will not become uniform and will not sufficiently overlap with the grouting radius from the adjacent hole. Such behavior can be confirmed in Fig. 5. Assuming in Fig. 5 (c) that the design implantation radius is adapted, it cannot be said that penetration of the chemical solution by grouting from an adjacent hole is unattainable with horizontal implantation; therefore, the authors conclude that ground improvement by this method is possible.

4. CONCLUSIONS

In this research, a seepage flow analysis was carried out to evaluate the penetration behavior when chemicals were injected into a ground with uncertainty and into a homogeneous ground.
(1) In the ground with uncertainty, the penetration range was narrow compared to that in the homogeneous ground.
(2) When uncertainty is involved, it can be said that the grouting pressure becomes lower than the specified grouting pressure and that the split type of infiltration of the chemical liquid becomes difficult.

5. REFERENCES

[1] Karol H., Chemical Grouting and Soil Stabilization, Revised And Expanded, CRC Press, 2003.

[2] Moseley M.P. and Kirsch K., Ground Improvement (Second Edition), Spon Press, 2004.

[3] Kazemian S., Huat B.B.K., Prasad A. and Barghchi M., A review of stabilization of soft soils by injection of chemical grouting, Australian Journal of Basic & Applied Sciences, Vol.4, Issue 12, 2010, pp.5862-5868.

[4] Houlsby A.C., Construction and Design of Cement Grouting, John Wiley & Sons, Inc., 1990.

[5] Inazumi S., Shang H.M., Soralump S., Nakagishi Y., Miyatani Y, Mori Y. and Okuno Y., Effect of the molar ratio of liquid glass grouting agents on mechanical characteristics of the solidified soils, International Journal of GEOMATE: Geotechnique, Construction Materials and Environment, Vol.7, No.1, Issues 13, 2014, pp.985-992.

[6] Hayashi K., Zen K. and Yamazaki H., Diffusion and advection phenomenon of soluble type grouting, Journal of Japan Society of Civil Engineers, No.771/III-68, 2004, pp.11-20.

[7] Nishigaki M., Hishiya T., Hashimoto N., Kohno I., The numerical method for saturated-unsaturated fluid density-dependent groundwater flow with mass transport (in Japanese). JSCE Journal of Geotechnical Engineering 501/III-30, 1995, pp.135-144.

[8] Inazumi S., Ohtsu H., Otake Y., Kimura M. and Kamon M., Evaluation of environmental feasibility on steel pipe sheet pile cutoff wall at coastal landfill sites, Journal of Material Cycles and Waste Management, Vol.11, No.1, 2009, pp.55-64.

[9] Kamon M., Inui T., Geotechnical problems and solutions of controlled waste disposal sites (in Japanese), JSCE Journal of Geotechnical Engineering, 701/III-58: 2002, pp.1-15.