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Numerical analysis of vacuum consolidation method considering dissolved gasses

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ABSTRACT: In the vacuum consolidation method, horizontal drains and perforated water collecting pipes are installed on the ground surface as a drainage layer after placing a number of vertical drains in the ground to be improved. We then cover them with an airtight sheet and operate a vacuum pump connected to the drainage layer to reduce the pressure of the drainage layer and the vertical drain. At this time, a water head difference occurs between the vertical drain and the ground, so that the pore water in the soft soil layer is drained and the consolidation is promoted. However, in some cases which the vacuum consolidation method was carried out, there are some reports that the pore pressure in the ground under the airtight seat did not reach the vacuum pressure. Analysis of vacuum consolidation by combining models considering dissolved gases revealed that unsaturation of the ground due to vaporization of the dissolved gas caused the response of the pore pressure change to become slow. Furthermore, since the interstitial gas pressure is responsible for a part of the vacuum loaded pressure, the final settlement becomes smaller as the effective stress acting in the ground becomes smaller.

1 INTRODUCTION

In the vacuum consolidation method, horizontal drains and perforated water collecting pipes are installed on the ground surface as a drainage layer after placing a number of vertical drains in the ground to be improved. Then we cover them with an airtight sheet and operate a vacuum pump connected to the drainage layer to reduce the pressure of the drainage layer and the vertical drain. At this time, a water head difference occurs between the vertical drain and the ground, so that the pore water in the soft soil layer is drained and the consolidation is promoted. However, in some cases which the vacuum consolidation method was actually carried out, there are some reports that the pore pressure in the ground under the airtight seat didn't reach the vacuum pressure (Arai et al., 2008). For example, if gas is dissolved in the pore water of the ground, there is a possibility that the ground will be unsaturated by vaporization of the dissolved gas because vacuum pressure is applied in vacuum consolidation method. At this time, the loading pressure is smaller than the vacuum loading pressure in the ground is affected and the compaction is hindered by the decrease of drainage capacity. In this research, we examine the influence of vaporization of dissolved gas on vacuum consolidation by using a program combing mathematical models that can consider dissolved gases.

2 MATHEMATICAL MODELS

2.1 *Governing equation*

Mathematical models used for the analysis are explain in this chapter. The governing equations described soil-water-gas coupled problem are as follows.

Equilibrium equation:

$$div\dot{\boldsymbol{\sigma}} + \dot{\boldsymbol{b}} = 0, \dot{\boldsymbol{\sigma}} = \dot{\boldsymbol{\sigma}}^{T} \tag{1}$$

Principal of effective stress:

$$\dot{\boldsymbol{\sigma}}' = \dot{\boldsymbol{\sigma}}^{net} + \dot{P}_s \boldsymbol{1} \tag{2}$$

Displacement – strain relationship:

$$\dot{\boldsymbol{\varepsilon}} = -\frac{1}{2}(\nabla \otimes \dot{\boldsymbol{u}} + \nabla \otimes \dot{\boldsymbol{u}}^{T}) \tag{3}$$

Constitutive equation:

$$\dot{\boldsymbol{\sigma}}' = \boldsymbol{D} : \dot{\boldsymbol{\varepsilon}} - \boldsymbol{C}^{S_e} \dot{S}_e \tag{4}$$

Darcy's law (pore water):

$$\tilde{\boldsymbol{v}}_w = -\boldsymbol{k}_{uw} \cdot \nabla h = -K_{rw} \boldsymbol{k}_w \cdot \nabla h \tag{5}$$

Darcy's law (pore gas):

$$\tilde{\boldsymbol{v}}_g = -\boldsymbol{k}_{ug} \cdot \nabla h = -K_{rg} \boldsymbol{k}_g \cdot \nabla h_g \tag{6}$$

Water retention characteristic curve:

$$\frac{S_r - S_{r0}}{S_{rf} - S_{r0}} = \frac{1}{1 + \exp(A + B \log_e S)} \tag{7}$$

Continuity condition (solid - liquid):

$$n\dot{S}_r - S_r \dot{\varepsilon}_v + div\tilde{\boldsymbol{v}}_w = 0 \tag{8}$$

Continuity condition (solid - gas):

$$\begin{aligned} &-(1 - S_r + A_{dg} S_r)\dot{\varepsilon}_v - (1 - A_{dg})n\dot{S}_r \\ &+ \left(\frac{n(1 - S_r) + A_{dg} n S_r}{P_g}\right)\dot{P}_g + (1 + A_{dg}) div\tilde{\boldsymbol{v}}_g = 0 \end{aligned} \tag{9}$$

where $\boldsymbol{u}$ = displacement vector; $\dot{\boldsymbol{u}}$ = velocity vector; $\boldsymbol{b}$ = body force vector per unit mass; $\boldsymbol{\sigma}$ = total stress tensor; $\boldsymbol{\sigma}'$ = effective mean stress tensor; $\boldsymbol{\sigma}^{net}$ = net stress tensor; P_s = suction stress; $\boldsymbol{1}$ = Kronecker's delta; $\boldsymbol{\varepsilon}$ = strain tensor; $\boldsymbol{D}$ = elasto-plastic stiffness tenor; $\boldsymbol{C}^{S_e}$ = coefficient tensor; S_e = effective saturation; $\tilde{\boldsymbol{v}}_w$ = flow velocity of pore water; $\boldsymbol{k}_{uw}$ = unsaturated conductivity tensor for pore water; K_{rw} = specific water permeability coefficient; $\boldsymbol{k}_w$ = saturated conductivity tensor for pore water; h = total water head; $\tilde{\boldsymbol{v}}_g$ = flow velocity of pore gas; $\boldsymbol{k}_{ug}$ = unsaturated conductivity tensor for gas; K_{rg} = specific gas permeability coefficient; $\boldsymbol{k}_g$ = saturated conductivity tensor for gas; h_g = total gas head; S_r = degree of saturation; S_{rf} = degree of saturation at $s=0$; S_{r0} = residual degree of saturation; S = suction; n = porosity; ε_v = volumetric strain; A_{dg} = coefficient for dissolved gas. Note that the rate form of the equilibrium equation, principal of effective stress and displacement-strain relationship is used because the constitutive equation, Darcy's law and continuity equations are described in rate form. As the water retention characteristic model, the model that can express the hysteresis proposed by Kawai et al. (2007) is employed and Logistic curve proposed by Sugii and Uno (1995). The Se-hardening model that can express the hardening due to the decrease of the degree of saturation proposed by Ono et al. (2007) is used as the constitutive model in this research. The state change of dissolved gas is incorporated in the mathematical model as the phase change model between liquid phase and gas phase by applying Henry's law additional to the state equation.

3 CONDITIONS OF NUMERICAL ANALYSIS

The mesh used in the numerical analysis is shown in Figure 1. A negative pressure of -101.3 kPa as a vacuum pressure was instantaneously applied to the upper end for a certain period of time. The other boundary is a undrainage condition, and the gas boundary is set as a non-exhaust condition over the entire surface. The numerical analysis are performed under the plane strain condition. The material parameters and initial conditions are summarized in Table 1. The material parameters are set with reference to numerical simulation of ground on which vacuum consolidation is carried out performed by Hirata et al. (2010), and it corresponds to a material composed of clayey soil and peat. Water retention characteristic curve, as well, is assumed as one of a typical clayey soil and is depicted in Figure 2.

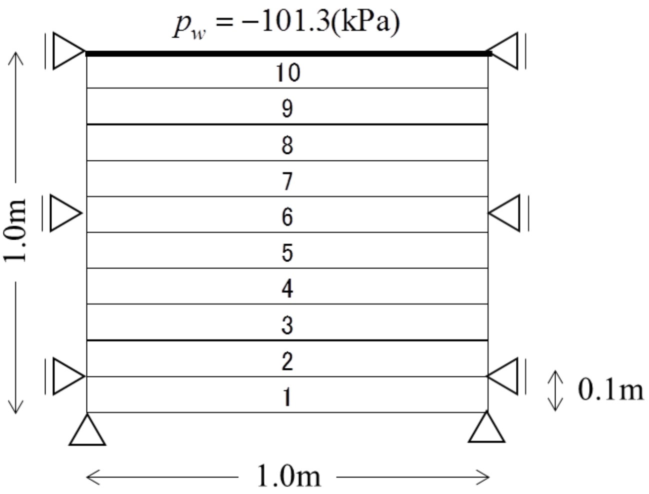

Figure 1. Analysis mesh diagram

Table 1. Material parameters and initial conditions.

Index property	
Compression index λ	0.614
Swelling index κ	0.17
Initial void ratio e_i	1.0
Grain density G_s	2.7
S_e-hardening model parameters α, n_s	5.0, 1.2
Initial degree of saturation S_{ri}	1.0
EC model parameter n_E	1.5
Bulk modulus of pore water K_w (kN/m^2)	4.0E+05
Conductivity for pore water k_w (m/s)	4.0E-07
Conductivity for pore gas k_g (m/s)	4.0E-05
Amount of substance M_d (g/mol)	28.8
Gas constant R (J/K/mol)	8.31
Temperature T (K)	288.15
Henry's law parameter k_h (g/kPa)	0.173
Unit weight of pore water γ_w (kN/m^3)	9.8

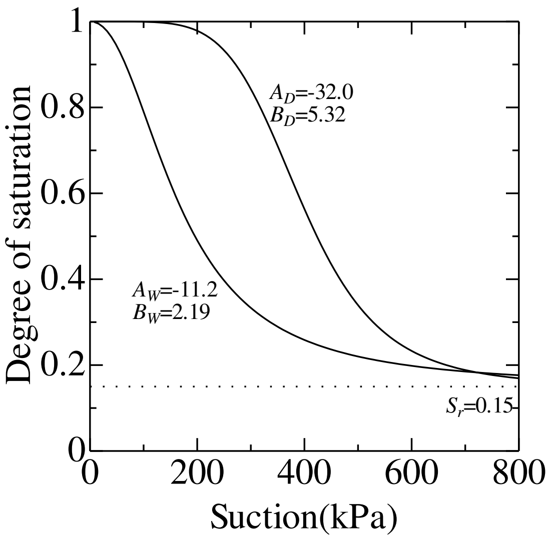

Figure 2. Water retention characteristic curve.

In this research, two cases of numerical analysis were carried out. In both cases, soil-water-gas coupled but in case 1, the dissolved gas in the pore water is not considered and in case 2, the dissolved gas in the pore water is considered. Since there is no data on dissolved gas, we assumed the air as dissolved gas that is relatively difficult to dissolve and vaporize.

4 NUMERICAL RESULTS

The degree of saturation distribution in the ground after 180 days of applying vacuum pressure is given in Figure 3 and Figure 4 shows the numerical result of Suction-Degree of saturation relationship at the depth of 0.5m. In Figure 3, in case 1, the degree of saturation does not change even if vacuum pressure is applied, but in case 2, it can be seen that unsaturation occurs. This is because suction is increased due to applying a negative pressure, and it becomes larger than the air entry value. The saturation distribution in the ground shows a tendency that it becomes lower as the surface of ground.

Figure 5 shows the change with time in pore gas pressure at the depth of 0.5m. In the case 1, pore gas pressure is constant at 0.0kPa, whereas in the case 2, the negative pore gas pressure is occurred due to the desaturation by phase change of the dissolved gas in pore water. It resulted in carrying a part of the vacuum pressure. Since suction is defined as the difference between gas pressure and water pressure, it is observed that suction and vacuum pressure are not equal due to generation of the gas pressure. Change with time in pore water pressure / settlement is presented in Figure 6. From the figure, it can be seen that it takes time until the pore water pressure reaches the vacuum pressure because the ground becomes unsaturated. This resulted in the delay of convergence of the settlement. For these reasons, when vacuum pressure loads the ground and the desaturation is occurred, it takes more time for the consolidation compared to the case that the ground remains to be saturated. Moreover, there is also a difference in final settlement. Figure 7 summaries *e*-ln*p'* relationship. This shows the effective mean stress acting finally is the same, but the void ratio is not the same in the end. In this research, we use a model that takes into consideration the increase in stiffness accompanied by desaturation. The stiffness increases with unsaturated in case 2, so that the change in void ratio becomes small and affects the settlement.

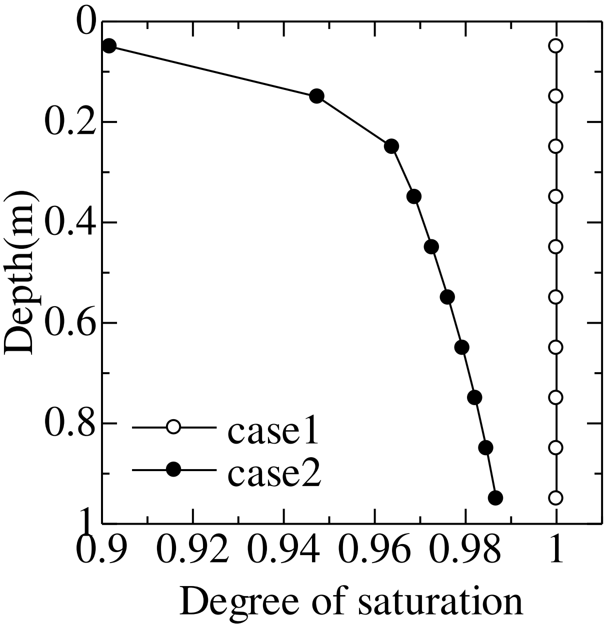

Figure 3. The degree of saturation distribution in the ground after 180 days of applying vacuum pressure.

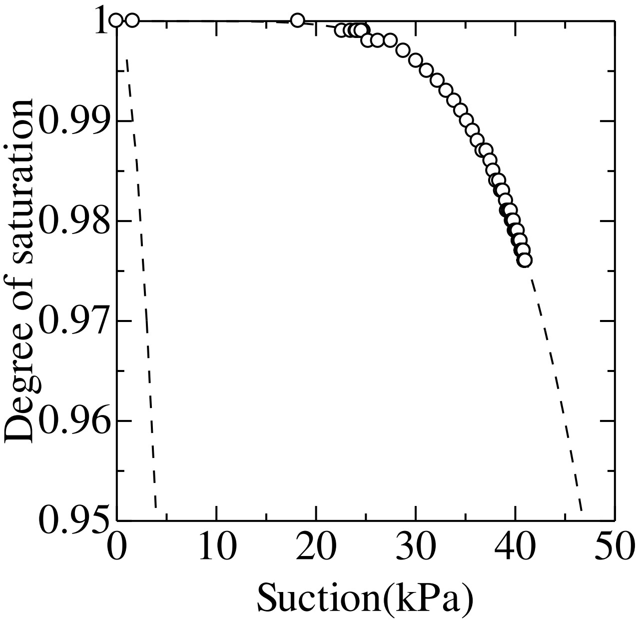

Figure 4. Suction – Degree of saturation relationship.

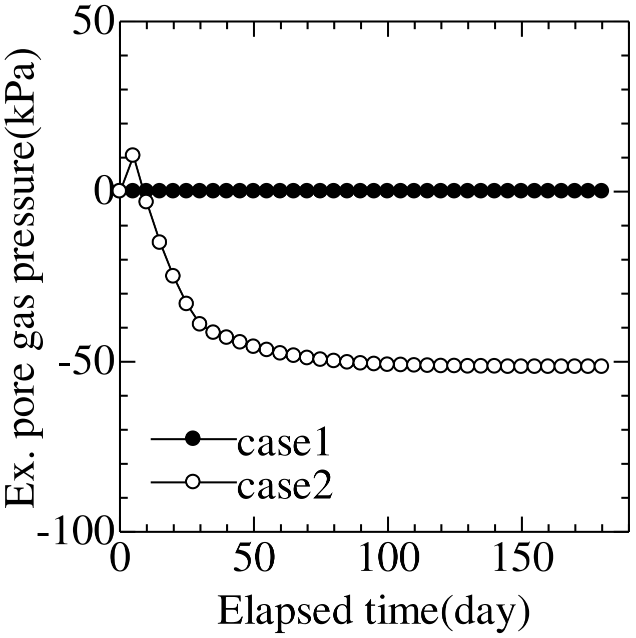

Figure 5. Change with time in pore gas pressure at depth 0.5 m.

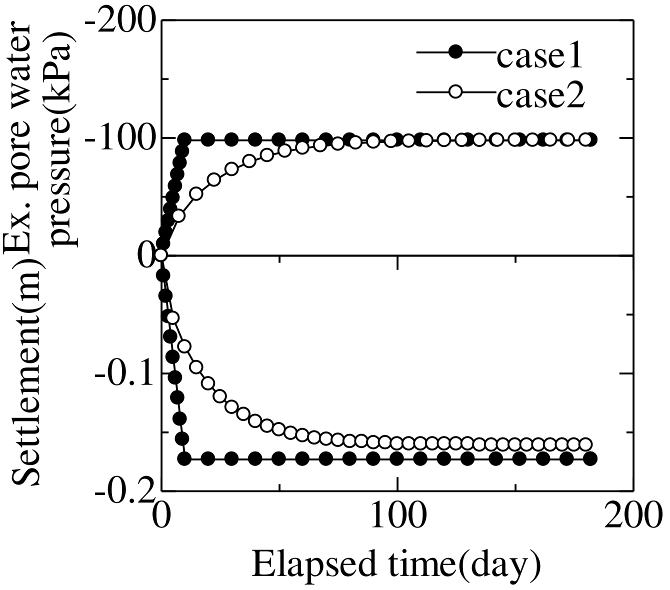

Figure 6. Change with time in pore water pressure / settlement at depth 0.5 m.

5 CONCLUSIONS

As a result of the desaturation of the ground due to the negative pressure, it turns out that the response to the change in the pore water pressure in the ground is slow and it takes time to research the vacuum pressure. Therefore, when vacuum pressure loads the ground and the desaturation is occurred, it takes more time for the consolidation compared to the case that the ground remains to be saturated. Since there is a report that the settlement calculated was match with the monitored one unless the input vacuum pressure was set to be about 70kPa (Hirata, et. al., 2010), it was supposed that the ground is actually desaturated by the negative pressure. In this site, the vacuum consolidation method and the embankment have been carried out at the same time in order to be earlier the construction term. Since we can prevent the desaturation of the ground just under the drainage layer by simultaneously filling the embankment, it can be said that the method is effective in the mechanical point of view.

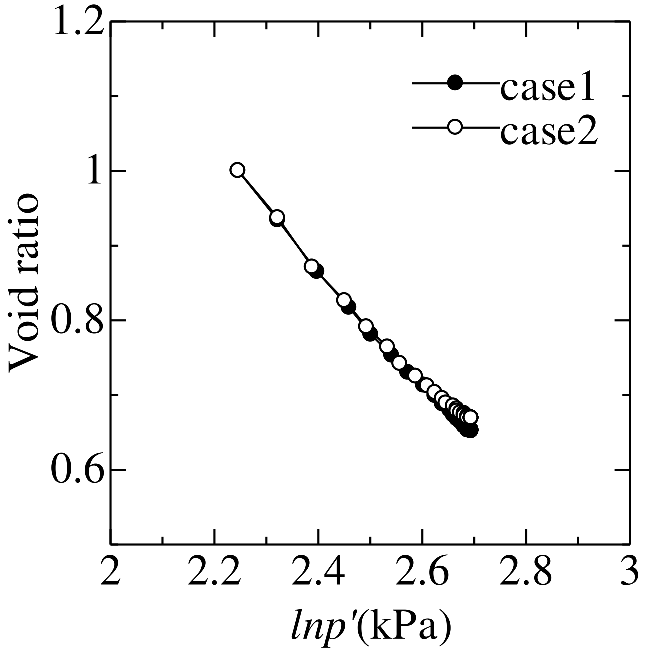

Figure 7.*e – lnp'* relationship.

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