Study on Modeling the Coupled Hydro-mechanical Processes by Combining DDA and FEM

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1. INTRODUCTION

Coupled hydro-mechanical process in porous media represents the interaction between solid particles movement and fluid flow during external and internal loading. It attracts attention in geotechnical engineering field since it causes many disasters such as boiling. To characterize the coupled hydro-mechanical problems, many methods[1] based on continuum mechanics theory have been proposed. However, they are insufficient to describe the behavior of soil because soil is an assembly of many independent particles. This study presents a numerical method combining Discontinuous Deformation Analysis (DDA) method and Finite Element Method (FEM) to model the interaction between solid particles movement and fluid flow from microscopic viewpoint. Fig-1 shows the concept of the model in this methodology.

2. ANALYTIC METHOD

In this study, since the blocks considered in DDA are disc-shaped and rigid, the unknown variables only include the displacements in x, y directions and the rotation, which is denoted with $D = (u_0, v_0, r_0)^T$. Thus, the displacement matrix at an arbitrary point in the block is described as Eq-1.

$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} 1 & 0 & -(y-y_0) \\ 0 & 1 & x-x_0 \end{pmatrix} \times \begin{Bmatrix} u_0 \\ v_0 \\ r_0 \end{Bmatrix} = [T_i] \times [D_i] \qquad \text{Eq-1}$$

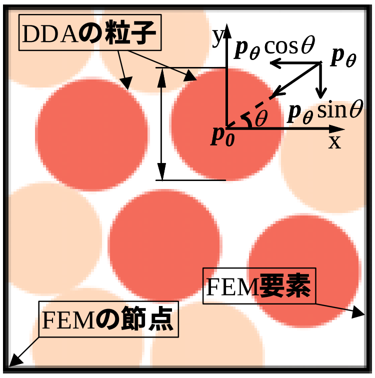

Fig-1 Conception of the Coupled Hydro-mechanical Model

Using the pressure P_θ acting on the block's surface vertically, which is obtained from FEM, and the particle's radius R (Fig-1), potential energy due to water pressure can be described as Eq-2. Based on the minimization theory of the total potential energy[2], the formulation of the new term due to water pressure is supplemented for dealing with the coupled hydro-mechanical problems.

$$\Pi_W = \int (u \quad v) \begin{pmatrix} P_\theta \cos\theta \\ P_\theta \sin\theta \end{pmatrix} dl = [D_i]^T \int [T_i]^T \begin{pmatrix} P_\theta \cos\theta \\ P_\theta \sin\theta \end{pmatrix} R d\theta \qquad \text{Eq-2}$$

On the other hand, fluid flow is approached from the macroscopic viewpoint. The governing equation is derived from the conservation law of fluid mass as Eq-3, where t is time, n porosity, h hydraulic head, and k_x, k_y are the permeability in x and y direction, respectively. In the results of the computations by DDA, permeability and porosity are included.

$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) - \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) = 0 \qquad \text{Eq-3}$$

Inputting the water pressure distribution, calculated by FEM under the initial conditions to DDA, blocks' displacements can be calculated. According to the results of DDA computations, the permeability of FEM mesh are updated due to the change of porosity by using the *Kozeny-Carman* equation[3] (Eq-4). Here a, c are constant factors representing the particle's shape. With this iterative solution system, hydro-mechanical process is coupled.

$$k_x = k_y = \frac{n^3}{ca^2(1-n)^2} \qquad \text{Eq-4}$$

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3. APPLICATION AND RESULTS

For validating the effect of the newly added water pressure terms, the stress distribution of a basic one-dimensional example (shown in Fig-2) is calculated. Two cases of dry condition and saturated hydrostatic condition are considered. The particles' diameters are entirely 0.01*m*, and located in the most dense situation (the porosity n 0.119). The comparison between the straight line showing the exact solution and the results of the computation gives an agreement with the theoretical calculation, and shows that the new terms are adapted for the hydrostatic conditions.

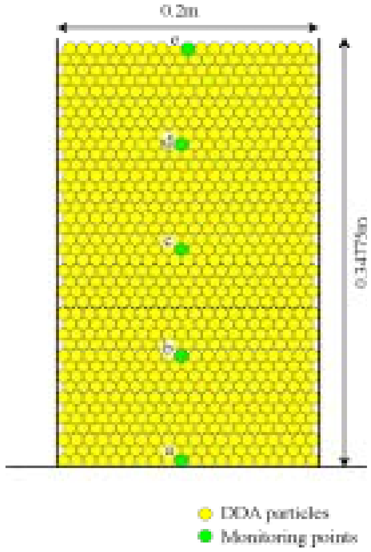


Fig-2 Model for Validation

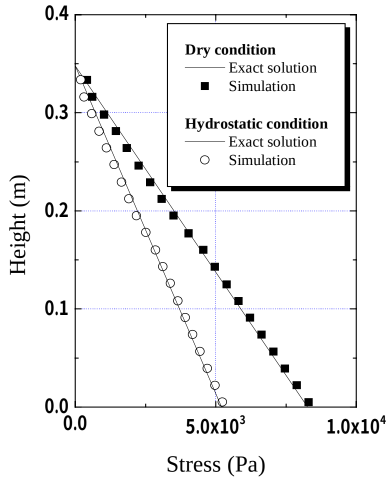
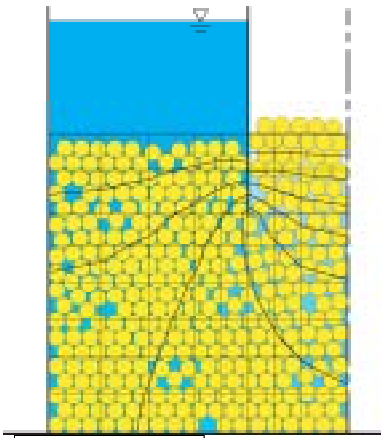


Fig-3 Stress Distribution in *y*-direction

As a two-dimensional example, half of cofferdam that is symmetric was modeled (shown in Fig-3). The newly proposed method was applied to compute the boiling phenomenon. Using the blocks of uniform size (diameter d = 0.5*m*), in this simplified example, one-way computation in the coupled process was conducted. Fig-4 shows the large deformation due to the boiling phenomenon after adding the seepage force, in which separation of blocks on the right side is obvious. In Fig-5, it can be seen that blocks nearer to the end of the sheetpile have bigger change in stress value during the action of seepage force, and boiling phenomenon occurs when the value falls down to 0.0.


Fi ... mena of the Model

By changing the embedded depth of sheetpile, computations were conducted for several times. The conclusion was drawn that boiling phenomena happens to the cofferdam with shorter sheetpile more easily, which is in agreement with the practical situation in the previous study. Therefore, to some degree this model can be adapted to treat the practical problems.

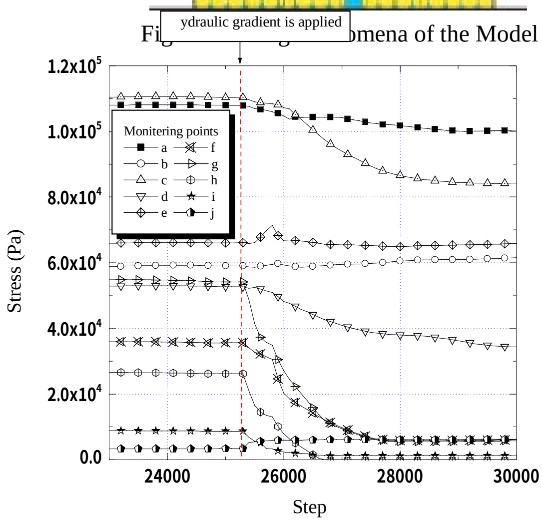


Fig-6 Change of the Effective Stress

4. CONCLUSION

In this study, a new numerical model is proposed to solve coupled particles movement and fluid flow processes in porous media using DDA-FEM approach. With the examples, the method expressed the behavior of saturated soil foundation well to some extent. Since this method is adapted to the discontinuous porous media, the correct valuation on the deformation phenomenon can be considered. As the future's study, in addition to accomplish the whole couple routine of the model, more consideration is needed for the size of blocks, the treatment of pores and the formulation of water pressure.

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