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A three-field coupled model for seepage failure

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Abstract

A new model for seepage failure has been established in this study . Seepage field, particle concentration field, stress field and interactions among them are simultaneously taken into consideration in this fluid-soil coupling system. A hybrid numerical algorithm incorporating FEM and FVM is proposed and implemented to solve the physical equations. The numerical model is validated by successful simulation of the flow pump test experiments. Finally, soil erosion and differential settlement of a typical levee due to seepage failure in a double-layer levee foundation are simulated andanalyzed.

Keywords: seepage failure, three-field coupled system, partitioned analysis approach, soil erosion

1. Introduction

Seepage failure is one of the major causes of levee accidents in the flood season. Its dynamic process is influenced by complex interactions of seepage field, particle concentration filed and stress field. Figure 1 shows various interactions among fields: (a) Removal of soil particles leads to the growth of soil permeability and speeding up of seepage flow, which in turn causes more particle loss from the foundation than before, over and over again. (b) Increment of seepage flow results in the rise of seepage force and redistribution of stress field, which in turn brings about the augment of porosity, permeability and seepage flow, over and over again. (c) Removal of soil particles reduces the elastic modulus and enhances stress and deformation, which in turn results in more particles removing from the foundation than before. Previous models only focused on seepage field and particle concentration field [1,2]. Thus far, there is still very few model available to deal with stress field simultaneously. The objective of

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this research is to establish a new three-field coupled model to simulate this complex problem and analyze its influence on levee security.

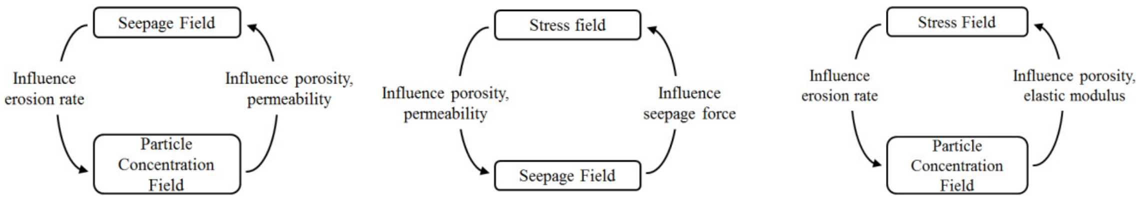


Fig. 1. Interactions among seepage field, particle concentration filed and stress field

2. Three-field coupled model

2.1. Model simplification

Influence of stress field on porosity is estimated in Table 1. The results show the order of its magnitude is about 10^{-3}, which is considerably smaller than fine particle content of soil (about 10^{-1}). It means that the influence of stress field on permeability is negligibly smaller than the influence of soil erosion on permeability. Meanwhile, the influence of stress field on particle concentration field can also be overlooked for the same reason.

Table 1. Influence of stress field on porosity.

	Parameters	Magnitude
Estimated value	Diameter of backward erosion pipe (m)	10^0 (maximum)
	Gravitational acceleration (m/s^2)	10^0
	Density of saturated sand (kg/m^3)	10^3
	Density of water (kg/m^3)	10^3
	Compression modulus of sand (MPa)	10^1
Calculated value	Superimposed load of sand (MPa)	10^{-2}
	Superimposed stress of sand (MPa)	10^{-2}
	Variation of strain	10^{-3}
	Variation of porosity	10^{-3}

2.2. Model description

The governing equation for seepage flow was proposed by Richards. It is written as follows:

$$C(h)\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}\left[k_x(h)\frac{\partial H}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_y(h)\frac{\partial H}{\partial y}\right]+\frac{\partial}{\partial z}\left[k_z(h)\frac{\partial H}{\partial z}\right], \quad (1)$$

in which $H = h + z$ is the total hydraulic head, h is the pressure head, $C = \partial\theta/\partial h$ is the volumetric water retention capacity, θ is the volumetric water content, and k_x, k_y, k_z denote permeability vector in the x-direction, y-direction and z-direction, respectively. The van Genuchten's model and Mualem's model are used for θ and k_x, k_y, k_z.

The governing equation for erosion process proposed by Vardoulakis et al. was derived from the mass-balance equation. It is used to calculate particle concentration field.

$$\frac{\partial(cn)}{\partial t} = \frac{\dot{m}}{\rho_s} - \left(\frac{\partial c v_x}{\partial x} + \frac{\partial c v_y}{\partial y} + \frac{\partial c v_z}{\partial z} \right), \tag{2}$$

in which c is the fluidized particle concentration contained in the pore water, $\dot{m}$ corresponds to the rate of net mass eroded and fluidized at any time and point, ρ_s is the density of fluidized particles, v_x, v_y, v_z denotes the seepage velocity in x, y and z-direction, respectively.

Equilibrium equations and elastic constitutive model of the skeletal grains are employed for stress field. Empirical formulas are employed to represent interaction among fields. Khilar and Fogler's study with Vardoulakis et al.'s equation for suffusion, Terzaghi's equation with Wan and Fell's study for backward erosion, Kozeny and Carman's equation for permeability are employed in this model.

3. Numerical method

3.1. Numerical model

Partitioned analysis approach [3] is employed to analyze this three-field coupled system numerically as shown in Figure 2. In this paper, seepage field and stress field are solved by the FEM while particle concentration field is solved by the FVM. Interactive effects among fields are accounted for by transmission and synchronization of coupled state variables. Seepage field and stress field are simultaneously solved using the commercial software Abaqus. Particle concentration field and data transmission are conducted by programming user subroutines in Abaqus, which is the second-development platform of Abaqus.

3.2. Validation

Experimental data of flow pump test conducted are used for the model validation. The erosion rate measured by Reddi et al. [4] is used to verify the validity of the present three-field coupled model for seepage failure. In this experiment, mixtures composed of Ottawa sand and kaolinite were compacted in a cylindrical mold and saturated by distilled water. Seepage flow generated by computer-controlled flow pump caused erosion in the interior of the sample. Turbidity of the effluent was measured and then converted into kaolinite particle concentration. The simulation matches the experimental data well as shown in Figure 3. The observation data and prediction results exhibit good agreement.

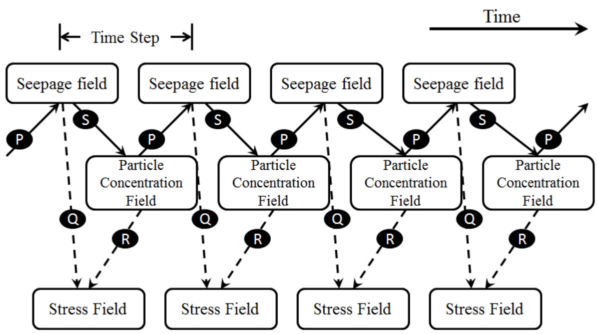


Fig. 2. Diagram of partitioned analysis approach for fluid-soil dynamical system

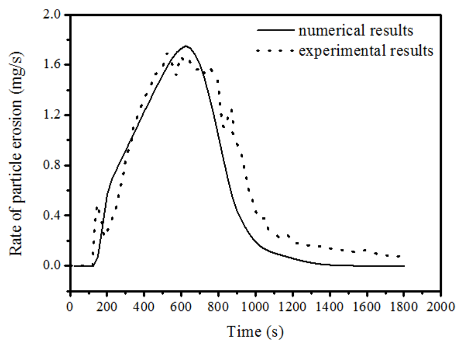


Fig. 3. Relationship between erosion rate of kaolinite and elapsed time after Reddi et al. (2000)

4. A case study

Double-layer levee foundation is most prone to collapse by seepage failure. Its upper layer consists of clay and its lower layer consists of sand with impervious material under the foundation. With the help of this new model, a seepage failure case of double-layer levee foundation, which is very common in the Yangtze River Basin, is analyzed numerically.

Figure 4 shows the evolution of backward erosion pipe simulated based on this new model. It takes about 240 hours for seepage failure at levee toe to take place when backward erosion starts. The suffusion progresses towards the innerside face of the levee with its breadth to expand gradually. It is estimated that the formation of a continuous pipe needs 420 hours, implying that the place just under the levee is hollowed. At this moment, the security of levee is severely threatened by this phenomenon.

(a) 240 hour (b) 300 hour (c) 360 hour (d) 420 hour

Fig. 4. development of backward erosion pipe

Figure 5 shows differential settlement of the levee due to seepage failure. The levee generally inclines towards the levee toe, for which greater soil loss ratio and weakened soil strength there are responsible. (Fig.6). The resultant force consisting of higher hydraulic pressure and levee weight are applied on the levee foundation and causes differential settlement (Fig. 7).

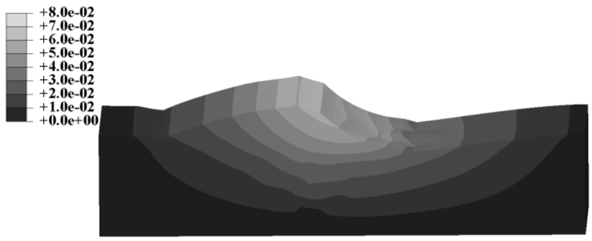
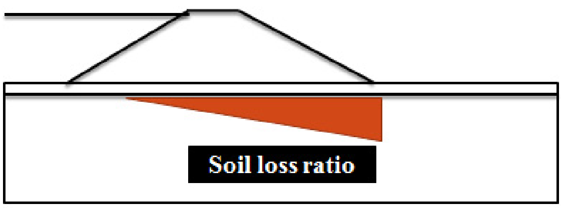


Fig. 5. Deformation of the levee (unit: m)



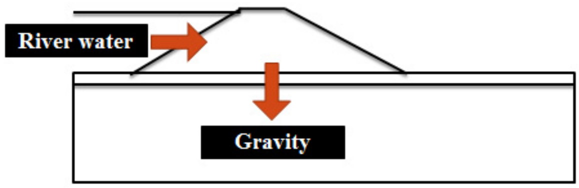


Fig. 6. Schematic of influences of river water and gravity on levee

Fig. 7. Schematic of soil loss ratio of levee foundation

The contours of displacement reveals that the largest horizontal displacement occurs at the innerside of levee top (Fig. 8), and the largest vertical displacement happens at the outside of levee top (Fig. 9).

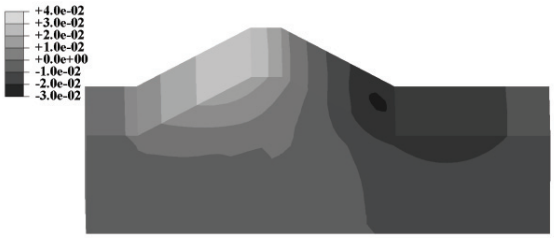


Fig. 8. Contour of x-displacement (unit: m)

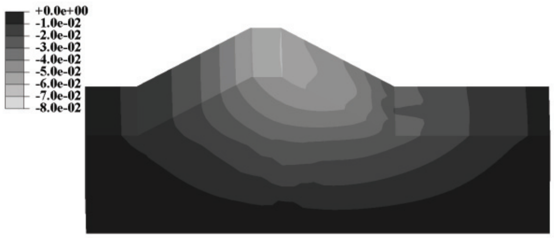


Fig. 9. Contour of z-displacement (unit: m)

5. Conclusions

A three-field coupled model is proposed to study seepage failure. Influence of stress field on seepage field and particle concentration field can be neglected in this study. The model works well and provides soil erosion and differential settlement information owing to seepage failure. The simulated results show that the largest horizontal displacement occurs at the innerside of levee top, and the largest vertical displacement happens at outside of levee top.

Acknowledgements

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