Simulation of unsaturated layered soil column subjected to rainfall infiltration

Kyoto University Student member ○ E. Garcia
Kyoto University Fellow F. Oka
Kyoto University Member S. Kimoto
Kyoto University Member Y. Higo

1. Introduction

Water infiltration into unsaturated soils has received significant attention in the recent time; this is mainly because many of the geotechnical and hydraulic problems are related to heavy rain-induced slope failure and expansive soil. Additionally, it is very common to find in the nature different instability problems related with layered soils. In this paper results obtained by experimental layered column tests are simulated by means of a multiphase coupled elasto-viscoplastic finite element analysis proposed by Oka et al. (2006). Results of the simulations are presented as pore-water pressure profiles in order to compared with the experimental results (Yang et al. 2006). It is seen that the multiphase coupled model proposed can capture very well many of the characteristics of the transient vertical infiltration into leyered soils.

2. Elasto-viscoplastic constitutive model considering suction effect for unsaturated soil

An elasto-viscoplastic model based on the overstress-type of viscoplastic theory with soil structure degradation for unsaturated soil (Kimoto and Oka 2005) has been extended to unsaturated soil using the skeleton stress and the suction effect in the constitutive model (Oka et al. 2006). The behavior of the material is described within the framework of a macroscopic continuum mechanical approach through the use of the theory of porous media. In the model, total stress tensor is defined as:

$$\sum_{\alpha}\sigma_{ij}^{\alpha}=\sigma_{ij}\ (\alpha=S,W,G).\quad \text{S=Soil, W=Water, G=Gas.}$$

$$\sigma_{ij}^{S}=\sigma'_{ij}+n^{S}P^{F}\delta_{ij},\quad \sigma_{ij}^{W}=n^{W}P^{W}\delta_{ij},\quad \sigma_{ij}^{G}=n^{G}P^{G}\delta_{ij} \tag{1}$$

where P^F is the average pressure of the fluid surrounding the soil skeleton, and it is given by

$$P^{F}=s_{r}P^{W}+(1-s_{r})P^{G} \tag{2}$$

And the skeleton stress is given by

$$\sigma'_{ij}=\sigma_{ij}-P^{F}\delta_{ij} \tag{3}$$

In this model, the overconsolidation boundary surface and static yield functions are defined as follows:

$$f_{b}=\overline{\eta}_{(0)}^{*}+M_{m}^{*}\ln(\sigma'_{m}/\sigma'_{mb})=0 \tag{4}$$

$$f_{y}=\overline{\eta}_{(0)}^{*}+\widetilde{M}^{*}\ln(\sigma'_{m}/\sigma'^{(s)}_{my})=0 \tag{5}$$

where the effect for the unsaturated soil is incorporated for both boundaries as:

$$\sigma'_{mb}=\sigma'_{ma}\exp\left(\frac{1+e}{\lambda-\kappa}\varepsilon_{kk}^{vp}\right)\left[1+S_{I}\exp\left\{-S_{d}\left(\frac{P_{i}^{c}}{P^{c}}-1\right)\right\}\right] \tag{6}$$

$$\sigma'^{(s)}_{my}=\frac{\sigma'^{(s)}_{myi}}{\sigma'_{mai}}\sigma'_{ma}\exp\left(\frac{1+e}{\lambda-\kappa}\varepsilon_{kk}^{vp}\right)\left[1+S_{I}\exp\left\{-S_{d}\left(\frac{P_{i}^{c}}{P^{c}}-1\right)\right\}\right] \tag{7}$$

where ε_{kk}^{vp} is viscoplastic volumetric strain, λ and κ are the compression and the swelling index, respectively, and e is the initial void ratio. $P^{C}{}_{i}$ is the initial suction value, P^C is the present suction value, S_I denotes the material parameter that denotes the strength ratio to the saturated soil when suction is $P^{C}{}_{i}$. S_d is the parameter which controls the rate of increasing or decreasing strength. σ'_{ma} is a strain softening parameter to describe the degradation of the material caused by structural changes.

The viscoplastic stretching tensor is given by the following equation when $f_y>0$.

$$D_{ij}^{vp}=C_{ijkl}\sigma'_{m}\exp\left\{m'\left(\overline{\eta}_{(0)}^{*}+\widetilde{M}^{*}\ln\frac{\sigma'_{m}}{\sigma'_{mb}}\right)\right\}\frac{\partial f_{p}}{\partial\sigma'_{kl}} \tag{8}$$

$$C_{ijkl}=a\delta_{ij}\delta_{kl}+b(\delta_{ik}\delta_{jl}+\delta_{il}\delta_{jk}),\quad C_{1}=2b,\quad C_{2}=3a+2b$$

In which C_1 and C_2 are the viscoplastic parameters.

The relation between the suction and saturation is given by the expresion

$$s_{re}=\left\{1+(\alpha P^{C})^{n}\right\}^{-m} \tag{9}$$

3. Simulation of the layered soil column

Laboratory test results of vertical infiltration into a layered soil are used in order to compare with the numerical results obtained by a multiphase coupled finite element analysis method. The results were obtained by Yang et al. 2006 by performing column tests of finer over coarser soil subjected to simulated rainfalls under conditions or no-ponding at the surface and constant head at the bottom. Laboratory tests started from a hydrostatic condition where the water level is located at the bottom of the soil column; constant rainfall intensities lower than the permeability of the clayey sand are applied to the top of the column for 24 hours; results of the experiments for two different rainfall intensities (CF-R1:q=1.6x10^{-7}m/s, CF-R2:q=3.3x10^{-7}m/s) are shown in Fig. 1.

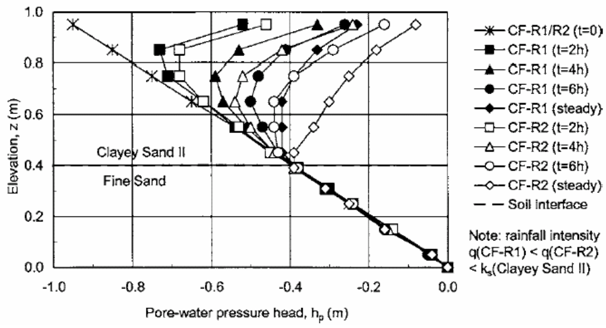

Fig. 1 Pore-pressure head profiles (Yang et al. 2006)

Same boundary conditions as those used in the experiments are used for the simulations. A 20-element column mesh with two soil layers and drained boundary at the top is used as the space discretization. The horizontal dimension of the column is irrelevant because the flow pattern is one-dimensional. The sketch of the soil column is shown in Fig. 2.

Key words: Rainfall, layered soil, unsaturated soil, multiphase analysis
Contact address:〒615-8540 京都市西京区京都大学桂 4　C クラスター　C1 棟　ＴＥＬ075-383-3193

The main parameters for the material properties of the soil particles, water and gas required by the constitutive model as well as those describing the suction-saturation relation that are used in the simulation are listed in Table 1.

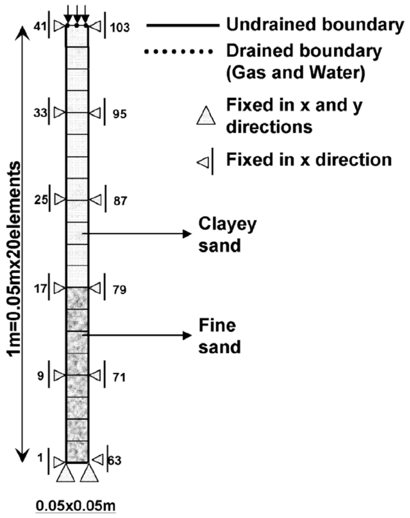

Fig. 2 Finite element mesh for the boundary conditions

Table 1: Material parameters

	Clayey sand	Fine sand
Compression index λ	0.03	
Swelling index κ	0.002	
Initial void ratio e_0	0.762	
Consol. yield stress σ'_{mbi}	205 (kPa)	
Elastic shear modulus G_0	28700 (kPa)	
Viscoplastic parameter m'	23.0	
Viscoplastic parameter C_1	1.0 x 10^{-08} (1/s)	
Viscoplastic parameter C_2	1.0 x 10^{-08} (1/s)	
Stress ratio at failure M^*	0.947	
Structural parameter σ'_{maf}	205 (kPa)	
Structural parameter β	0.0	
Suction parameter S_I	0.2	
Suction parameter S_d	0.25	
Perm. for water at s_r=1.0 k^W_s	8.8 x 10^{-07}(m/s)	2.7 x 10^{-04}(m/s)
Perm. for gas at s_r=0.0 k^G_s	1.00 x 10^{-03} (m/s)	
Maximum saturation s_{rmax}	0.99	
Minimum saturation s_{rmin}	0.0	
van Genuchten parameter α	2.0 (1/kPa)	1.0 (1/kPa)
van Genuchten parameter n'	1.14	5.00

4. Results of the simulations

Figs. 3 and 4 show the calculated pore-water pressure profile obtained in the simulations at similar elevations as shown in the experimental results of Fig. 1. Both figures show the water front advancing with the time from the initial pressure head profile at t=0.0h. When infiltration starts the pore water pressure increases for the clayey sand notably in depths relatively close to the soil surface (suction becomes less negative); this trend gradually progresses downward toward the fine sand layer as the wetting front advances.

When results of the experiment are compared with the results of the simulations, it is seen that the following features observed in the experiments are captured by the numerical model proposed: a) Pore water pressure increases initially at the surface of the clayey sand and gradually increases downward the soil column while the water infiltrates. b) Pore water pressure is higher and infiltration is faster when the intensity of the rainfall is higher (CF-R2). c) Pore water pressures were always negative even after 24h of rainfall infiltration and it did not develop in the fine sand layer. d) Although the infiltration during the simulation was slower compared with the experiments, the final results were very close to the steady state measured.

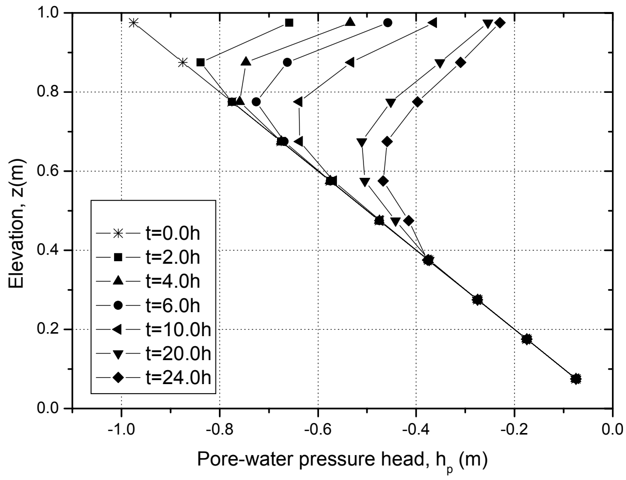

Fig. 3 Pore-water head profile CF-R1 (Simulation)

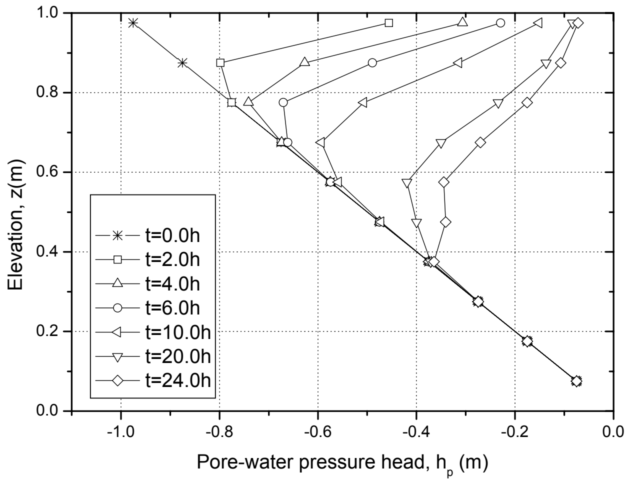

Fig. 4 Pore-water head profile CF-R2 (Simulation)

5. Conclusions

From the results obtained in the simulations, it is possible to say that the multiphase finite element analysis proposed describes very well many of the characteristics observed during the experiments of one dimensional water infiltration into layered unsaturated columns. The model can be useful for the study the unsaturated response of multiple layered soils that are commonly found in the nature and that involve geotechnical problems related to water infiltration such a rainfall and seepage inducing instability.

6. References

1) Kimoto, S. and Oka, F.(2005), Soils and Foundations, 45, 2, pp.29-42.
2) Oka, F., Kodaka, T., Kimoto, S., Kim, Y.-S and Yamasaki, N. (2006). Proc. 2nd US-Japan workshop on Geomechanics, ASCE, pp.124-131.
3) Yang, H., Rahardjo, H. and Leong E.-C. (2006). Journal of Hydrologic Engineering, ASCE, pp. 329-337.