Simulation of rainfall infiltration and seepage flow into an unsaturated river embankment

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1. Introduction

In recent years, many natural disasters have ocurred in the world associated with torrential rainfall. In many cases, slopes and river embankments have been failed due to the rainfall infiltration and the seepage flow. A multiphase coupled elasto-viscoplastic seepage-deformation analysis based on the theory of porous media proposed by Oka et al. (2006) is used to describe the water infiltration and the seepage into an unsaturated river embankment. We have numerically analysed the effect of the saturated water permeability on the development of deformation when a non-uniform rainfall is applied on the top and the left side of a three layered river embankment. The computed results show that the strain localization on the slope surface of the river embanment is associated with the velocity of the seepage flow due to the rainfall infiltration (i.e., seepage induced erosion).

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 saturated soil (Kimoto and Oka 2005) has been extended to one for unsaturated soil using the skeleton stress and the suction effect in the constitutive model (Oka et al. 2006). The material behavior 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:

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

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

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

$$P^F = sP^W + (1-s)P^G, \tag{2}$$

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 the static yield function are defined as follows:

$$f_b = \bar{\eta}^*_{(0)} + M^*_m \ln(\sigma'_m / \sigma'_{mb}) = 0 \tag{4}$$

$$f_y = \bar{\eta}^*_{(0)} + \tilde{M}^* \ln(\sigma'_m / \sigma'^{(s)}_{my}) = 0 \tag{5}$$

where the effect for the unsaturated soil is incorporated for both boundary surfaces and the hardening parameter as:

$$\sigma'_{mb} = \sigma'_{ma} \exp\left(\frac{1+e_0}{\lambda-\kappa}\varepsilon^{vp}_{kk}\right)\left[1 + S_I \exp\left\{-S_d\left(\frac{P^c_i}{P^c} - 1\right)\right\}\right] \tag{6}$$

$$\sigma'^{(s)}_{my} = \frac{\sigma'^{(s)}_{myi}}{\sigma'_{mai}}\sigma'_{ma} \exp\left(\frac{1+e_0}{\lambda-\kappa}\varepsilon^{vp}_{kk}\right)\left[1 + S_I \exp\left\{-S_d\left(\frac{P^c_i}{P^c} - 1\right)\right\}\right] \tag{7}$$

where ε^{vp}_{kk} is the viscoplastic volumetric strain, λ and κ are the compression and the swelling indexes, respectively, and e_0 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 $f_y > 0$.

$$D^{vp}_{ij} = C_{ijkl}\sigma'_m \exp\left\{m'\left(\bar{\eta}^*_{(0)} + \tilde{M}^* \ln \sigma'_m / \sigma'_{mb}\right)\right\}\frac{\partial f_p}{\partial \sigma'_{kl}} \tag{8}$$

$$C_{ijkl} = a\delta_{ij}\delta_{kl} + b\left(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}\right), \quad C_1 = 2b, \quad C_2 = 3a + 2b$$

in which C_1 and C_2 are the viscoplastic parameters.

The relation suction-saturation is given by

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

3. Simulation of the layered unsaturated embankment

A river embankment composed of three homogeneous layers was used for the simulations. Figure 1 presents an sketch of the embankment at the right levee of Seta River, Shiga, along with the boundary conditions and the initial right and the left water levels. The soil is assumed to be unsaturated above the water level. A non-uniform rainfall is applied on the top and slope of the embankment. The rainfall record at the Seta River and the variation of the water level at the right side of the embankment used for the simulations are shown in Figure 2.

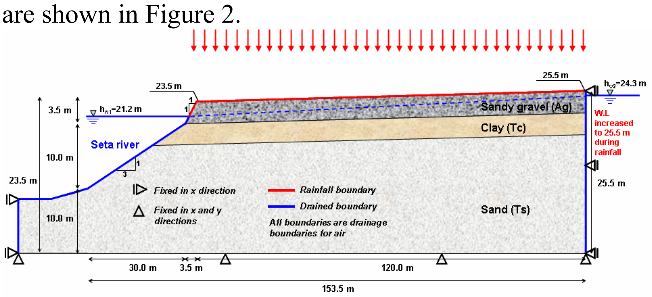

Fig. 1 Cross section of embankment and boundary conditions

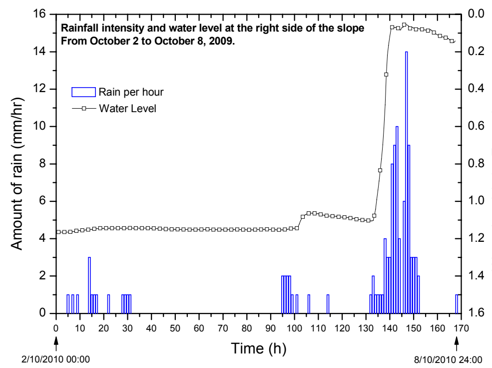

Fig. 2 Rainfall record and variation of water level at the righ side

Key words: Rainfall, seepage, embankment, unsaturated soil, multiphase analysis

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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.

Table 1: Material parameters

	Sandy Gravel	Clay	Sand
Compression index λ	0.0894	0.4910	0.0804
Swelling index κ	0.0090	0.0760	0.0090
Initial void ratio e_0	0.344	1.23	0.535
Elastic shear modulus G_0 *(kPa)*	3000	23000	20000
Stress ratio at critical state M_m*	1.27	1.25	1.27
Viscoplastic parameter m'	40.0	27.59	40.0
Viscoplastic parameter C_1 *(1/s)*	$1\text{x}10^{-15}$	$2\text{x}10^{-14}$	$1\text{x}10^{-20}$
Viscoplastic parameter C_2 *(1/s)*	$2\text{x}10^{-15}$	$2\text{x}10^{-13}$	$2\text{x}10^{-20}$
Structural parameter β	5.0	15.0	0.0
Structural parameter $\sigma'_{maf}/\sigma'_{mai}$	0.60	0.579	0.60
Water permeability at s=1 - k_{sv}^W *(m/s)*	**	$1\text{x}10^{-08}$	$1\text{x}10^{-06}$
Gas permeability at s=0 - k_s^G *(m/s)*	$1\text{x}10^{-03}$	$1\text{x}10^{-03}$	$1\text{x}10^{-03}$
Maximum saturation s_{max}	0.97	0.99	0.99
van Genuchten parameter α *(1/kPa)*	0.10	0.13	2.00
van Genuchten parameter n'	4.00	1.65	1.20
Suction parameter S_I	0.20	0.20	0.20
Suction parameter S_d	0.20	5.0	0.20

** Depends on the case
The hor. permeability is 10 times the ver. permeability, $k_{sh}^W=10k_{sv}^W$.

4. Results of the simulations

Two-dimensional numerical analyses of the three layered river embankment under rainfall and seepage condition have been carried out, and the strain localization associated with the seepage flow have been studied. In the top layer, namely, Sandy Gravel layer, four different cases are considered for the permeability k_{sv}^W to show its effect in the seepage flow and deformation due to the rainfall infiltration (Table 2). The slope surface was covered by concrete; then, a low saturated water permeability k_{sv}^W=1x10^{-06} m/s is considered for the slope surface and it is kept constant for the simulation of the four cases.

Table 2: Saturated water permeabilities for the analysis

Case No.	Vertical permeability	
	k_{sv}^W sandy gravel (m/s)	k_{sv}^W slope surface (m/s)
1	1 x 10^{-06}	1 x 10^{-06}
2	3 x 10^{-06}	1 x 10^{-06}
3	6 x 10^{-06}	1 x 10^{-06}
4	1 x 10^{-05}	1 x 10^{-06}

In the analyses, the water level at the river side remained constant while the water level increased at the land side due to the rainfall infiltration applied during 170 h; as a result, a seepage flow was presented toward the slope of the embankment. The distributions of the water velocity and accumulated viscoplastic shear strain for the four different cases are illustrated in Figures 3 and 4, respectively. These figures show that both the seepage velocity and the accumulation of viscoplastic strain increase with the increase of the permeability of the sandy gravel layer. The largest velocities and accumulated deformations were obtained for the largest permeability (k_{sv}^W=1x10^{-05} m/s) and they were located above the water level on the slope of the embankment. Comparison of Figures 3 and 4 shows that the development of deformation is significantly related to the velocity of the seepage flow as well as to the permeability of the soil layers.

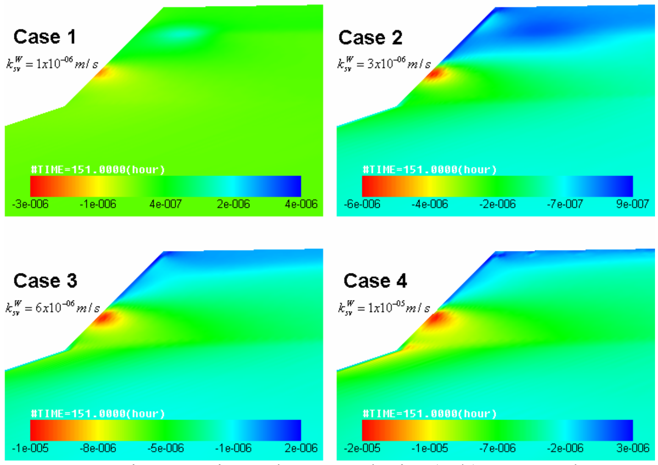

Fig. 3 Horizontal water velocity (m/s) at t=151 h.

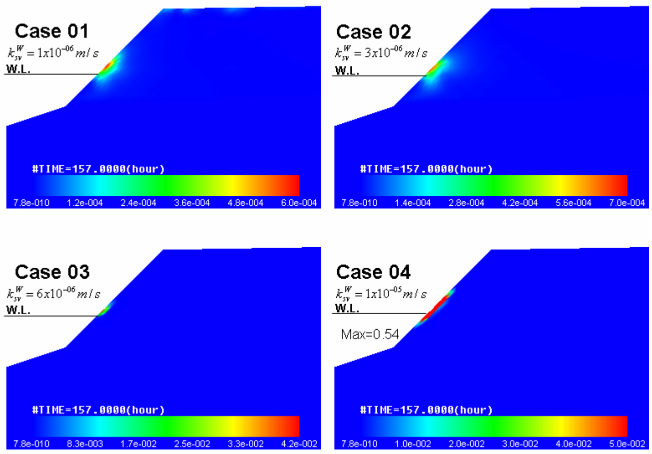

Fig. 4 Viscoplastic shear strain at t=151 h.

5. Conclusions

In the present study, the seepage and the deformation response of a river embankment due to the non-uniform rainfall infiltration has been studied by a coupled seepage-deformation method based on the theory of porous media. This FE method presented here is useful for the study of the unsaturated response of multiple soil layers subjected to complex rainfall records. The results obtained in the simulations show that the deformation of the river embankment depends on the velocity of the water flow and the permeability. The larger the saturated water permeability of the soil, the larger the velocity of the seepage flow and the larger the deformation on the surface of the river embankment.

6. Acknowledgments

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7. References

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