Long- and short-term pore water pressure variations in sandy river dike interpreted with 1- and 2-phase seepage flow analysis

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ABSTRACT

The hydraulic states in dike are affected by external factors such as rainfall and river water level, and have direct relevance to the safety and stability of the structure. Unsteady unsaturated seepage flow analysis based on Richards equation for water mass balance is widely used to predict hydraulic states in dikes. However, previous trials suggest that this approach tends to reproduce much higher phreatic surface than observed in field during and after heavy rainfall. One factor explaining this problem is the potential effect of entrapped air in dike. In this study, a sandy river dike along Babame River in Akita, Japan, was chosen as a study site. Along with basic site investigation and long-term pore water pressure monitoring with tensiometers, 1- and 2-phase seepage flow analysis was performed to understand the role of air impedance in light of field monitoring results. 2-phase seepage flow analysis outputs more subdued pore water pressure responses than 1-phase analysis during and after extremely heavy rainfall (more than 100mm/day). For lesser rainfalls, however, the difference between the two analytical approaches was negligible.

Keywords: river dike, seepage, infiltration, coupled seepage flow analysis

1 INTRODUCTION

The safety and stability of river dikes are closely related to their hydraulic states. The mounting evidence of failures caused by heavy rainfall and flood-induced seepage in recent years (e.g. JGS Hokkaido Branch Geodisaster Survey Unit, 2017) is a strong motivation for endeavour to understand and predict the pore water pressure variations in dikes during heavy rainfalls, possibly followed by a quick river water level rise. In case of sandy river dike, because of high permeability of its body, a particularly quick phreatic surface rise and destabilization are anticipated.

A commonly adopted approach to predict hydraulic states in dikes, embankments and slopes is unsteady unsaturated seepage flow analysis based on Richards equation. This method is encoded in Japanese dike engineering guideline, a de fact standard. In Richards equation, however, only water mass balance is considered, with an implicit assumption that pore air pressure dissipates without incurring any impedance to water flow. Previous trials by the authors (e.g. Nishimura, 2015) suggest that this approach tends to reproduce much higher phreatic surface rises (i.e. rapid pore water pressure rises) during and after heavy rainfall. As the air impedance becomes important only when the air phase is enclosed by advancing wetting

fronts, it cannot be accounted for simply by inputting an equivalent, reduced hydraulic conductivity.

This study aims to explore the potential importance of considering the air phase behaviour in predicting the river dike wetting through field observation and numerical analysis. Although infiltration of rainfall is a complex problem with other potential influencing factors such as vegetation (e.g. Ng and Zhan, 2007) and surface crusting (e.g. Morin and Benyamini, 1977), this study focuses on the air impedance effects only. Long-term pore water pressure measurement with electric tensiometers was conducted in a sandy river dike, along with basic site characterization. The dike section was modeled and analysed with 1-phase (water only) and 2-phase (water-air coupled) seepage flow theory to clarify the effect of entrapped air and capture more accurate hydraulic state changes. As the monitoring period is yet limited to less than three months, an imaginary scenario in which the observed rainfall was doubled was also considered to discuss the potential consequence of an extreme rainfall.

2 SITE DESCRIPTION AND MONITORING

2.1 Studied dike

A sandy river dike along Babame River, Akita Prefecture, Japan, was chosen as a study site. Figs. 1

and 2 show the site location and cross-section of the site, respectively. Although there is a very thin gravel layer at a depth of 1m from the crest, it is estimated that this dike is composed of mostly homogeneous sandy soil. The front toe of the dike is always under river water, and the back slope toe is also in contact with canal running in parallel to the dike (see Fig. 3). This configuration makes clear the hydraulic boundary conditions in front and back slope sides. The canal water level is approximately lower by 1m than the river water level for most of the time, and hence there should be steady seepage flow from the river to the canal. The relative height and gradient of the dike is 2.8m and 1:2, respectively, and the surface of dike is covered with short vegetation, as shown in Fig. 3.

The dike body and the foundations layers were characterized by boring from the crest, and the stratification was estimated as shown in Fig. 2. This stratification was confirmed at multiple other locations within this section by portable dynamic cone sounding and hand excavation. Given the hydraulic boundary

Fig. 1. Study site location: Hachirogata Town, Akita, Japan.

Fig. 2. Cross-section of studied dike.

Fig. 3. Photograph of back slope side of the studied dike.

conditions, the layers below the ‘Sand with gravel 1’ layer are always underwater and not to play any significant role in the infiltration analysis.

2.2 Pore water pressure measurements

The pore water pressure was monitored at multiple points in the back slope of the dike with home-grown tensiometers, as indicated in Fig. 4. Each of the tensiometers has been monitoring the pore water pressure once per hour since 18 Aug 2018 (the monitoring exercise started in 2017 but was rebooted since). To check the reliability of the measurements, in particular the accuracy of the offsetting, duplicate tensiometers were installed at three locations, as indicated in Fig.4. Fig. 5 is a schematic diagram and photograph of the tensiometer. With relatively low air entry value ceramics (100 kPa), the response time is very short. Although the pressure sensors (SMC PSE573-01; -100 to +100 kPa range) were buried underground, it was still subject to the effect of temperature changes. Thermometers were therefore also installed to correct for the temperature effect. The river and canal water levels were recorded by self-recording water level gauges.

Fig. 4. Tensiometer location, shown with burial depths.

Fig. 5. Developed electric tensiometer.

3 NON-COUPLED (1-PHASE) AND COUPLED (2-PHASE) SEEPAGE FLOW ANALYSIS

3.1 Governing equations

Recent advanced modeling of unsaturated ground involves complex multi-physical coupling such as

soil-water-air (e.g. Oka et al., 2010; Xiong et al., 2014), water-air-vapor-temperature (e.g. Wilson et al., 1994; An et al., 2017), or more comprehensively, soil-water-air-vapor-temperature coupling (e.g. Gens, 2010). Despite these developments, a simpler model considering only air and water mass balance is better suited to focus on the air impedance effect on water infiltration, when the dike deformation is negligible, because the results are free from many assumptions. The authors' experience (e.g. Nishimura et al., 2016) suggests that the evapotranspiration and temperature effects are negligible in water mass balance for dikes with high-permeability soils. This study therefore adopts two simple formulations; non-coupled 1-phase (water mass balance only) seepage (e.g. Nguyen et al., 2014) and air-water coupled 2-phase seepage (e.g. Fredlund and Rahardjo, 1993). The governing equation for non-coupled 1-phase seepage flow is expressed as;

$$\frac{\partial}{\partial x} \left[\frac{k_{wr}}{\eta_w} k_{0x} \left(\frac{\partial u_w}{\partial x} + \rho_w g_x \right) \right] + \frac{\partial}{\partial y} \left[\frac{k_{wr}}{\eta_w} k_{0y} \left(\frac{\partial u_w}{\partial y} + \rho_w g_y \right) \right] - c \frac{\partial u_w}{\partial t} = 0 \quad (1)$$

where k_{0x} and k_{0y} are the intrinsic permeability of the soil in the x and y directions, k_{wr} , η_w , ρ_w are the relative permeability, the viscosity ($=0.001$ Pa·sec was adopted), and the density of water, respectively, and g_x and g_y are the gravity acceleration in the x and y directions. The unknown u_w is the water pressure. The coefficient c is the specific moisture capacity, as defined by $\partial \theta_w / \partial u_w$, where θ_w is the volumetric water content.

The governing equations for 2-phase seepage flow, combined with Boyle's law, are expressed as;

$$\frac{\partial}{\partial x} \left[\frac{k_{wr}}{\eta_w} k_{0x} \left(\frac{\partial u_w}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[\frac{k_{wr}}{\eta_w} k_{0y} \left(\frac{\partial u_w}{\partial y} + \rho_w g \right) \right] - c \frac{\partial (u_w - u_a)}{\partial t} = 0 \quad (2)$$

$$\frac{\partial}{\partial x} \left[\frac{1}{\beta_a} \frac{k_{ar}}{\eta_a} k_{0x} \frac{\partial u_a}{\partial x} \right] + \frac{\partial}{\partial y} \left[\frac{1}{\beta_a} \frac{k_{ar}}{\eta_a} k_{0y} \frac{\partial u_a}{\partial y} \right] + \frac{c}{\beta_a} \frac{\partial u_w}{\partial t} - \left[\frac{\Phi(1 - S_w)}{p_{atm}} + \frac{c}{\beta_a} \right] \frac{\partial u_a}{\partial t} = 0 \quad (3)$$

$$c = \frac{\partial \theta_w}{\partial (u_w - u_a)} \quad \beta_a = \frac{p_{atm}}{u_a + p_{atm}} \quad (4)$$

where k_{ar} and η_a are the relative permeability and the viscosity of air ($=0.1$ Pa·sec was adopted), respectively, and Φ and S_w are the porosity and the degree of water saturation, respectively. The additional unknown, u_a , is the air pressure in gauge scale (i.e. with the atmospheric pressure, p_{atm} , as reference). These non-coupled (Eq. 1) and coupled (Eqs. 2 and 3) equations were solved by finite element method in this study.

3.2 Unsaturated hydraulic models

The equations described above contain variable coefficients characterizing the seepage process in unsaturated ground. The coefficient c is the slope of the soil-water characteristic curve (SWCC) in the unsaturated domain, and equivalent to the specific storage s_s in the saturated domain. An SWCC and s_s are therefore necessary together with the relative permeability functions, k_{wr} and k_{ar} . This study adopted the van Genuchten (VG) model (van Genuchten, 1980) for SWCCs and van Genuchten-Mualem model for relative permeabilities;

$$c = (\Phi - \theta_r) \alpha m n \{ \alpha (u_a - u_w) \}^{n-1} \times [1 + \{ \alpha (u_a - u_w) \}^n]^{-m-1} \quad (5)$$

$$k_{wr} = \sqrt{S_e} \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (6)$$

$$k_{ar} = (1 - S_e)^\gamma \left(1 - S_e^{\frac{1}{m}} \right)^{2m} \quad (7)$$

where θ_r is the residual volumetric content, α and n are fitting parameters, $m = 1 - 1/n$, and S_e is the effective degree of saturation, $(\theta_w - \theta_r) / (\Phi - \theta_r)$. For 1-phase flow, $u_a = 0$ is considered in Eq. 5. The exponent γ is a constant, and set 0.5 in this study. The SWCC parameters were determined by the laboratory test (the suction method) using undisturbed soil samples. Fig. 6 shows the result for samples from the layers Bk ('Sand') and Asc ('Sand with silt'). Table 1 shows VG parameter values obtained by fitting to these test results. The other layers never came above the water level during the observation period, and the unsaturated behaviour did not need to be considered. A lower-bound value for k_{ar} of 0.001 was set to prevent numerical instability in saturated states.

Fig. 6. Soil-water characteristics curves and VG model fitting for samples from Bk and Asc layers.

Table 1. VG parameters for Bk and Asc layers.

Sample layer	α (1/kPa)	n	m	Φ	θ_r
Bk	0.54	2.45	0.59	0.34	0.10
Asc	0.27	2.20	0.55	0.40	0.31

3.3 Finite element model and boundary conditions

Fig. 7 shows the adopted finite element mesh of the studied dike with input parameters and applied boundary conditions. Saturated permeabilities of Bk and Asc layers were determined by laboratory permeability test. Saturated permeabilities of As-g1 and Ac layers were determined by field permeability tests using the borehole and gradation-based estimation, respectively. The saturated permeability k_{sat} values are shown in Fig. 8 in Darcy's law format (i.e. in m/sec), approximately 10^7 times the values of k_0 in (m^2). Isotropy of permeability was assumed for all the layers ($k_{0x} = k_{0y}$). The specific storage s_s value of each layer was set as a general value, as its influence is limited in the current study.

The ground surface above the river and canal water levels was set a flux-controlled boundary where flux corresponding to the precipitation is input. Whenever the pore water pressure at this boundary rises to zero, zero-pressure control was automatically imposed, so as not to force further infiltration. The surface boundaries below the water levels were pressure-controlled according to the water depth. Along the base of the model, the pressure was controlled such that the water levels of the river and canal were linearly interpolated, considering the high permeability of 'Sand with gravel 2' layer. For the air phase, the ground surface above the river and canal water level was set as zero (atmospheric)- pressure boundary, while zero-flux was imposed along the underwater boundaries.

The analysis was run for a period from 18 Aug to 1 Nov 2018, for which complete field record is available. The analysis started from an arbitrary hydrostatic initial condition one month ahead of 18 Aug, to achieve a condition in equilibrium with the boundary conditions by 18 Aug. The Japan Meteorological Agency (JMA) AMeDAS Gojome weather station (Fig. 1) record was used for precipitation input. The river and canal water levels were changed according to the measured values. The time marching was run at 900 sec intervals.

4 OBSERVED AND SIMULATED PORE WATER PRESSURE CHANGES IN DIKE

The observed pore water pressure at all the depths is shown in Fig. 8, along with the precipitation and the river and canal water level data. The duplicate measurements are largely consistent with each other, although some offsets are seen, possibly due to drifting at earlier stage of installation. The pore water pressure at different depths is changing in parallel overall, reflecting the high permeability of the dike. Below the mid-height of the dike, where the pore water pressure did not decrease below -5kPa and hence the degree of saturation is high, the vertical distribution of the pore water pressure largely conformed to the hydrostatic gradient all the time. There were two modestly strong rainfall events on 10 Sep and 1 Oct, with a 24-hour rainfall of 87mm and 56mm, respectively. Each event caused a rapid rise in the pore water pressure at all the elevations, with only minor response delays at deeper locations. The river and canal water levels did not show long-term variations, but this is not the case in longer time windows – preliminary observation conducted in 2017, when the site experienced a record-high rainfall, indicated seasonal variations in excess of 0.5m.

The simulated results are shown in Fig.9. For both 1-phase and 2-phase analyses, an imaginary case of twice the measured rainfall was run, in addition to the as-observed input case. When the observed rainfall was input, the 1-phase and 2-phase analyses output almost identical solutions, to the degree that they cannot be distinguished in Fig.9. These results matched the observed pore water pressure variations fairly well (only the results for 1m and 3m depths from the crest are shown). The peaks exhibited on 10 Sep and 1 Oct are largely at the same levels as actually measured. This comparison suggests that for such a high-permeability dike ($k_{sat}=1.3 \times 10^{-5}$ m/sec), the rainfall intensity of 50-100mm/day is not so significant as to warrant 2-phase analysis. However, in the cases where the input rainfall was doubled, there are clear differences in the peak values. The rise of the pore water pressure on 10 Sep was approximately 16kPa in the 1-phase analysis, while it was half that in the 2-phase analysis.

Fig. 7. Finite element mesh of the studied dike and material properties (the other parameters are shown in Table 1).

Fig. 8. Measured pore water pressure, river and canal water levels, and rainfall (JMA AMeDAS Gojome).

Fig. 9. Comparison of observed and simulated pore water pressure at 1m and 3m depth from the crest.

Unfortunately, the studied period did not involve such an intense rainfall event (i.e. daily rainfall in excess of 100-150mm), but the preliminary monitoring in 2017 encountered 132mm/day rainfall on 17 Jul, soon followed by 117mm/day on 23 Jul. Although the reliability of the older tensiometer adopted in 2017 was not sufficient to fully develop discussions, the response was relatively subdued and resembled the 2-phase analysis output here. The current monitoring shall be maintained into 2019 to capture an equally intense

rainfall event with the current renewed instrumentation.

The close-up view of the simulated 10 Sep variation is shown in Fig.10, focusing on the 2m depth from the crest as example. When the observed rainfall was input, the rise of the pore air pressure was not significant. When twice the rainfall was input, however, about 3kPa of pore air rise was computed. There was a little numerical instability as the water and air pressure difference narrows down to zero (i.e. transition from unsaturated to saturated states). Whilst the 3kPa rise in

air pressure may not strike as significant, its influence on the short-term wetting and pore water pressure rise is clear in Fig.9.

Fig. 10. Simulated pore water and air pressured for different rainfall intensity.

5 SUMMARY

This study investigated short- and long-term variations of pore water pressure in a sandy river dike in response to rainfalls. A particular focus was place on infiltration during heavy rainfall, which may be impeded by delayed air pressure release. This aspect was investigated by conducting numerical analysis based on non-coupled 1-phase (water) and coupled 2-phase (air-water) seepage flow theory, and comparing the results to the observed pore water pressure. As the monitoring period was relatively short (less than three months), the most intense rainfall that could encountered was 87mm/day. The pore water pressure response to this level of rainfall was found to be satisfactorily reproduced even by simple 1-phase seepage flow analysis, which output almost identical results as 2-phase analysis. In an imaginary case where the rainfall input was doubled, however, 2-phase analysis output more subdued pore water pressure rise. An air pressure rise before the soil became saturated was more evident in the event of more intense rainfall, and this led to the difference in pore water pressure rise between 1-phase and 2-phase analysis results. The field monitoring, which the authors have been conducting in other multiple sites, shall be continued to further verify the above findings by capturing intense rainfall events in future.

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