Instability on dike with scour due to surface flow and seepage

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ABSTRACT

The damage to a dike caused by high water levels from a localized torrential downpour over a long period is presumed to be related to dike saturation from the seepage water from the dike surface and the blow off of pore air following a movement in the seepage line in the dike. The water flow generates a large-scale scour around the structure, and as a result, the stability of the structure is decreased. We discuss the ways in which multi-scaling problems and multi-phase interactions between soil, water, and gas affect these structures in three types of fundamental scour experiments. This study attempted to elucidate the scouring mechanism by experimenting using a movable bed channel device. During the water flow acting on the ground, a vertically upward hydraulic gradient along with excess pore water pressure was generated in the saturated ground, and a liquefaction-like phenomenon was generated by an increase the excess pore water pressure in the ground. Consequently, scouring was facilitated. The pore air in the unsaturated ground formed an air bubble due to seepage flow, and it spouted in the ground surface. The importance of the scour phenomenon of the dynamic interaction of soil particles, pore water, and pore air was discovered.

Keywords: seepage, scour, erosion, liquefaction, pore pressure

1 INTRODUCTION

In past studies on scouring, many researchers considered the application of a tractive force for the prediction of topographical changes due to water flow (e.g., Partheniades, 1965). In tractive force evaluations, the scouring phenomenon is evaluated from a microscopic viewpoint, which takes into consideration the equilibrium condition between the shear force generated by the fluid force passing through the ground surface layer and the effective weight of soil particles in the outermost layer of the ground. However, we believed that the scouring phenomenon of structures could not be evaluated using only tractive force when the scale of the generated scouring is taken into account. As a recent study pointed out, fluid force does not only affect the ground surface layer but also causes stress changes in the ground (e.g., Imase et al., 2011). Therefore, it is important to focus on mesoscopic and macroscopic perspectives as well as the microscopic.

We attempted to elucidate the scouring mechanism by performing three fundamental and typical model tests of movable bed channel devices, focusing on stress changes in the ground. Experiment 1 included a scouring experiment due to a horizontal flow. Experiment 2 was a scouring experiment due to an overflow. Experiment 3 was a scouring experiment of the seepage force that generated in the upper base layer (mound-like) with different permeability.

2 OUTLINE OF THE EXPERIMENTS

The experiment channel was 2.0m in length, 0.3m in width, and 0.3m in height. In the tank, sedimentary soil (0.5m long, 0.3m wide, and 0.1m high) was installed as the ground, the starting point of which was 1.0m from the upstream end. For the fluid force, a circulation flow was generated using a submersible pump to unify the external force, taking into consideration Froude’s similarity law. During the experiments, the cross-sectional velocity distribution of the fluid was measured using a pitot tube, and the pore water pressure in the ground was measured using pore water pressure sensors. The experiments were recorded by using a high-speed camera (200–400 fps) and a video camera (29.97 fps) to observe scouring and corrosion.

Fig. 1. Schematic diagram of a movable bed channel device.
3 SCOUR DUE TO HORIZONTAL FLOW: EXPERIMENT 1

3.1 Experimental conditions

Figure 2 shows the schematic diagram of the ground tank and an install position of the pore water pressure sensors. The geomaterial in this experiment used Toyoura sand ($D_{50}=0.17\text{mm}$). The effects of differences in relative density $D_r$ (40, 60 and 70%) and ground saturation $S_r$ (0, 17.7 and 100%) were examined. In this paper, we discuss both saturation and unsaturated ground.

Fig. 2. Schematic diagram of the ground tank and an install position of the pore water pressure sensors (Experiment 1).

3.2 Experimental results and discussions

First, we calculated the non-dimensional tractive force $r^*$. The non-dimensional critical tractive force $r_{c*}$ was calculated based on the particle size of the sand using a formula proposed by Iwagaki (1956). We can see that soil particles began to move compared to non-dimensional critical tractive force and the non-dimensional tractive force. As a result, $r^*=1.03 > r_{c*}=0.30$, and scouring was observed.

Figure 3 shows the scouring phenomenon in the saturated ground obtained using relative densities 40% and 70%. The scour started due to open channel flow and made a dune at ground surface. The scouring velocity toward the downstream was visually confirmed to be faster in the ground with loosely deposited sand ($D_r=40\%$) than with densely deposited sand ($D_r=70\%$). We found scour velocity differed according to the relative density of the ground.

Fig. 3. Scour behaviors: (a) $D_r=40\%$ and (b) $D_r=70\%$.

Figure 4 shows the temporal change in the pore water pressure due to an open channel flow. In particular, the excess pore water pressure was generated from the ground surface layer near the bottom of the earth tank on loose deposited ground ($D_r=40\%$). Therefore, the generation of the excess pore water pressure was considered to be one of the causes of the scour phenomenon.

Fig. 4. Change in the distribution of excess pore water pressure: (a) $Dr=40\%$ and (b) $Dr=70\%$.

Figure 5 shows the blowout of the air bubble in the dry ground due to the horizontal flow. Pore air was replaced with seepage water and blown out from the ground. Consequently, scouring was facilitated in the ground. Moreover, a crack was generated by pore air particles trapped in the ground.

Fig. 5. Scour behaviors in the unsaturated (dry) ground: blowout of the bubble was generated in the ground surface, and the crack was generated by trapping pore air in the ground.

4 SCOUR DUE TO OVERFLOW AT WEIR: EXPERIMENT 2

4.1 Experimental conditions

Figure 6 shows the schematic diagram of the ground tank and an install position of the pore water pressure sensors. A weir $h_{weir}=80\text{mm}$ in height was installed at the uppermost side of the ground, and a water sealing plate was set at the lowermost side of the channel to control the water level in the downstream. The geo-material in this experiment was Toyoura sand and gravel ($D_{50}=4.73\text{mm}$), which we called Gravel-B. The geomaterial condition changed relative density $D_r$ (40% and 70%). In this paper, the initial water-level difference expressed as $\Delta h$ and $\Delta h$ was the setting 0, 20, 40, 60, and 80mm.

Fig. 6. Schematic diagram of the ground tank and an install position of the pore water pressure sensors (Experiment 2).
4.2 Experimental results and discussions

Figure 7 shows the scour phenomenon at \( \Delta h = 20 \text{mm} \). The scouring speed and scouring profile were not different compared to loose density and dense density in Toyoura sand. However, the scouring phenomenon in the ground differed according to particle size of the ground.

Figure 8 shows the temporal change in the pore water pressure at CH5. The pore water pressure was increased by the same volume in all sensors when gravel was used. However, the excess pore water pressure was generated with the progress of the scouring when Toyoura sand was used. Therefore, we calculated the vertical overburden pressure (\( \sigma = \gamma_w h_{wd} + \gamma_u h_u \); refer to Figure 9 for symbols of depths), and the effective overburden pressure (\( \sigma' \)) was obtained by subtracting the pore water pressure (\( u \)) from the overburden pressure and considering the effect of the stress change on the scour phenomenon. As a result, the effective overburden pressure (\( \sigma' \)) became zero (\( t = 49 \text{s} \)) before the pore water pressure sensor was exposed (\( t = 68 \text{s} \)) and a liquefaction-like phenomenon occurred.

![Fig. 7. Scour phenomenon in the ground behind a weir due to overflow at \( \Delta h = 20 \text{mm} \): (a) Toyoura sand (\( D_r = 40\% \)), (b) Toyoura sand (\( D_r = 70\% \)), and (c), Gravel-B.](image)

![Fig. 8. Change in pore water pressure.](image)

5 SCOUR DUE TO SEEPAGE FORCE IN PERMEABLE BASE LAYER: EXPERIMENT 3

5.1 Experimental conditions

Figure 10 shows a schematic diagram of the experimental device and measurement points of the pore water pressure in the ground in Experiment 3. Toyoura sand was used in the seabed ground and a relative density of \( D_r = 40\% \) was adopted for all the experiments. For the upper base layer, its materials with different permeability coefficients \( k \) were used (Case 1, no structure: \( k = \infty \); Case 2, Gravel-A: \( k = 2.846 \times 10^{-1} \text{m/s} \); Case 3, Gravel-B: \( k = 5.378 \times 10^{-2} \text{m/s} \); Case 4, Impermeable structure: \( k = 0 \text{m/s} \)). Pressure difference was produced using the water level difference \( \Delta h \) between the upper and lower sides of the breakwater. To observe the ground changes due only to flow, the rigid-like structure (caisson) was completely fixed onto both sides of the channel. In this experiment, soil structures with different permeabilities were employed to investigate the interaction between different seepage flow rates. For the upper base layer (mound), a mesh-shaped formwork was fixed.

5.2 Experimental results and discussions

Figure 11 shows the scouring behaviors. In Case 1, the scour occurred from the corner of the front edge of the rigid structure (caisson). Even after the water level difference became constant (\( t = 17 \text{s} \)), scouring gradually developed toward the inner region of the breakwater. In Case 2, the scour was similar to Case 1. A fan-shaped expansion of scouring was then observed as water level difference \( \Delta h \) increased. A similar tendency was also observed in Case 3. In Case 4, the bearing ground began to deform near the tip of the base layer at the outer region of the harbor as water level difference \( \Delta h \) increased. After \( t = 60 \text{s} \), the boiling occurred at the slope toe of the upper base layer in the inner harbor side.
We examined the effects of the tractive force that acted on the surface layer of the seabed ground and the seepage force in the ground. These forces are generated by the seepage flow in the upper base layer (mound) due to the water level difference. Here, tractive force was expressed using friction velocity \( u^* \) and the action of the seepage force is expressed using the macroscopic hydraulic gradient \( i = \frac{\Delta h}{L'} \). Seepage distance \( L' \) was obtained by subtracting scoured distance \( \Delta L \) from the initial seepage distance \( L \).

Figure 12 shows the relationship between tractive force and seepage force on the scour. Mark "×" shows point that the soil particle began to move. In Cases 2 to Case 4, scouring occurred before friction velocity \( u^* \) reached critical friction velocity \( u_c^* \). Therefore, the hydraulic gradient slightly increased as the permeability of the base layer of the structure decreased, thereby increasing seepage force.

6 CONCLUSIONS

The vertically upward hydraulic gradient along with excess pore water pressure was generated in the saturated ground during a water flow. In addition, a liquefaction-like phenomenon (fluidization) due to flow tractive force and seepage was generated in the surface ground and/or the interface between different permeability. The scour was also expanded when the pore air was blown out of the unsaturated ground or dry ground due to rapid seepage into ground and the capture of air by the seepage water front line.

These results showed the dynamic multi-phase interaction and the instability of the sand structure due to the interaction between seepage force and tractive force were important on soil scouring.

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