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Evaluation of piping stability under dynamic conditions

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ABSTRACT: When flood water level of river is higher than the ground level outside the levee in a rainy season, storm water in protected low land is discharged to river using pumps. In this case, the culvert (sluice) connected to a pumping station passes through the levee body. In an old levee, piping occurs around the culvert frequently causing an accident of sweeping away of the levee or flooding of the surroundings. In this study, the effect of the cavity beneath the discharge pipe and pump vibration on piping during flood was reviewed through a numerical analysis and a model test. The result of the study has confirmed that increase in the length of cavity and vibration level noticeably decreases the water level at which piping occurs. The closer the cavity was to the upper stream and the more the vibration level increased, the more the risk of piping increased.

1 INTRODUCTION

As the flood water level of the river is higher than the ground level outside the levee in a rainy season, storm water in protected low land is discharged to river using a pump. In this case, the culvert (sluice) connected to a pumping station passes through the levee body. In an old levee, piping occurs around the culvert sometimes causing sweeping away of the levee or flooding of the surroundings. Up to now, many cases of similar levee collapses in old levees have been reported (KICT (2005), Kim et al. (2011)). Figure 1 shows a piping example which has occurred in the levee and beneath the culvert.

Such an accident is understood to have been complexly caused by the two problems, generation of a cavity beneath the culvert and vibration of pumps. The cavity beneath a culvert generated by the relative displacement resulting from pile foundation and vibration of pump and current reduces the infiltration flow path in the protected land (outside the river) during a flood. In the meantime, as pumps are operated mainly in a flood water level condition, the problem has been raised that the vibration of pumping station may also threaten the stability of levee.

When such conditions are put together, the scenario of levee collapse can be presumed to be as follows: First, infiltration takes place toward a river side land through a cavity beneath a drainage structure in a flood condition. At this time, when large pumps (Figure 2) of the pumping station is operated for removal of rainwater, pump vibration in combination with the discharged current has a considerable dynamic effect on the culvert and the levee body and, as a result, the pore water pressure increases. Decrease in infiltration flow path and increase in pore water pressure noticeably reduces the resistance of the levee against piping resulting in collapse caused by piping.

Due to such accidents, the necessity for the measures to safely design and maintain a levee was raised.

Figure 1. Cavity beneath the Culvert.

Figure 2. Pumps in Pumping Station.
In this study, the effect of cavity beneath culvert and pump vibration on the potential for piping during a flood was investigated.

2  THEORETICAL BACKGROUND

In general, cavity beneath culvert is presumed to be generated by the relative displacement resulting from the difference in the rigidities of the pile foundation and the supporting ground and the effect of the vibration generated by the drainage pumps operated. Many cases have been reported where a ground subsidence has occurred due to ground vibration (Gazetas and Seling, 1985). As in here piping is reviewed in relation to a cavity which has been already generated; cavity generation mechanism is not covered in this paper. The generation of cavity has an effect on piping by reducing the flow path of seepage water which passes through a levee during a flood.

The vibration of the drainage pump during discharge of rainwater will increase the pore water pressure, which is also expected to increase the risk for occurrence of piping. Accordingly, if a cavity is generated beneath a drainage sluice due to vibration, the characteristics of piping occurrence in a dynamic condition is required to be investigated.

In order to understand the effect of cavity, the shape of the seepage line has been investigated through a numerical simulation. Figure 3 shows the result of the numerical analysis.

If a cavity exists beneath the culvert, it can be seen that the length of the seepage line is formed to be very short. It implies that piping may occur between the upper stream slope and the cavity. In such a case, review of piping should reflect the effects of the reduced infiltration route due to the cavity and of the excessive pore water pressure generated by vibration.

In general, piping can be evaluated using a critical hydraulic gradient. When \( \Delta h \) is the flood water level and \( L \) is the seepage line length, hydraulic gradient \( (i) \) is defined as follows:

\[
i = \frac{\Delta h}{L} \quad (1)
\]

Using this equation, the effects of the reduction in flow path due to generation of the cavity and of the excessive pore water pressure caused by vibration can be reflected. First, cavity has an effect on the infiltration distance \( (L) \) and the increase in the pore water pressure caused by vibration has an effect on the head difference \( \Delta h \). When the infiltration distance and head difference on which the effects of these factors are reflected are \( L' \) and \( \Delta h' \) respectively, the hydraulic gradient can be expressed as follows:

\[
i = \frac{\Delta h'}{L'} \quad (2)
\]

\( L' \) and \( \Delta h' \) are influenced by head difference during flood, length of cavity and vibration level. Accordingly, each variable can be expressed as follows:

\[
L' = f(\Delta h, L_C)
\quad (3)
\]

\[
\Delta h' = f(\Delta u, L_C)
\quad (4)
\]

Here, \( L' \) is the length of the modified seepage line, \( \Delta h \) is the flood water level, \( L_C \) is the length of the cavity beneath the culvert, \( \Delta u \) is the excessive pore water pressure, and \( g \) is the vibration level (vibration acceleration).
In this study, the piping stability for which the effects of cavity and vibration were considered was investigated through a small scale model test for which the above variables were considered.

3 MODEL TEST

3.1 Test setup

A soil tank for piping a model test was developed. A circular levee with a slope gradient of 1:2 a freeboard of 2 m, and a levee crown of 6 m was used as the models. In order to secure similarity between prototype and a model, the scale factor of stress was set to 1/n, and the transmissibility was set to 1. The hydraulic gradient is as follows when the accumulation factor is applied:

\[ i = \frac{1}{n} \frac{\Delta p}{l} \]

\[ \eta_i = \frac{n_p}{n_p n_x n_i} \]  

where \( \eta_p \) is 1/n as it is the accumulation factor for the external load and, as both \( n_{pf} \) and \( n_{g} \) are 1, \( \eta_i = \frac{n_p}{n_i} \). As both \( n_{pf} \) and \( n_i \) are 1/n, \( \eta_i \) is 1. Accordingly, when the same levee bodies and the same fluids are used, the test conditions are satisfied.

The test setup produced applying the scale factor of 40 was 1,530 mm long, 500 mm high, 500 mm wide and 20 mm thick. Figure 4 shows the schematic diagram of the piping model test. A vibration and pore water pressure measurement system was added to the model test setup in order to measure the vibration level and change in the pore water pressure.

3.2 Physical properties of model ground

In this test, Joomunjin standard sand which is sandy soil was used as the test material. The void ratio of this specimen at a relative density of 40% is 0.812. The critical hydraulic gradient at which piping occurs was \( i_{cr} = 0.88 \) when obtained using the above basic physical properties of the soil. Accordingly, if the safety factor drops below 1 as the hydraulic gradient grows bigger than 0.88, the critical hydraulic gradient, it can be presumed that piping will occur.

3.3 Vibration generation and measurement system

In order to apply the pump vibration to the model, a vibration motor and a measuring instrument were installed as shown in Figure 4. Figure 5 shows the pictures of a vibration generating device and a vibration measuring system. The pump vibration was simulated using a controller and an asymmetric motor for adjustment of the vibration level. In order to reflect 0.15 g which is the intensity of the site vibration, 3 levels of vibration were applied as shown in Figure 6.

3.4 Test case selection and test method

For cavity lengths of 60 cm, 70 cm and 80 cm, tests in a static condition and dynamic condition were conducted respectively. The static tests were conducted to comparatively analyze them with the results of dynamic tests, and the water level of the riverside land was increased by 1 cm at a time after the groundwater level was stabilized. Each water level was maintained for 30 minutes. If boiling was found while the water level was increased and maintained, it was determined that piping had occurred. The water level at this time was considered the water level at which piping occurs. Though the method of the dynamic test was the same as that of the static test, the piping water level was observed applying a vibration load. The vibration level and the pore water pressure were measured at this time. The groundwater level initially set was 20 cm from the bottom of the soil box, and the flood water level was 35 cm. The test cases were put in order in Table 1. Figure 7 shows the model test setup prepared finally. The levee body of the model was formed using a sand falling technique. The slope was formed in saturated condition after the ground was formed.
Table 1. Test cases.

<table>
<thead>
<tr>
<th>Length of cavity (cm)</th>
<th>Static test</th>
<th>Dynamic test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level 1</td>
<td>Level 2</td>
</tr>
<tr>
<td>60</td>
<td>60Lv0</td>
<td>60Lv1</td>
</tr>
<tr>
<td>70</td>
<td>70Lv0</td>
<td>70Lv1</td>
</tr>
<tr>
<td>80</td>
<td>80Lv0</td>
<td>80Lv1</td>
</tr>
</tbody>
</table>

Figure 7. Piping Model Test Setup.

Figure 8. Failure of Riverside Land.

4 RESULT ANALYSIS

4.1 Test result

Figure 8 shows the wedge failure of the riverside land (inside the river) and the boiling in the protected low land (outside the river) due to piping. In the case of the static tests, outflow from the protected low land through the levee body was observed in a small scale, and weak boiling occurred. In the case of dynamic tests, as the vibration level was up, piping rapidly progressed. The wedge failure on the slope of the riverside land showed that the scale of the failure developed bigger following the rise of the vibration level as a phenomenon of propagation of piping toward the upper stream. The wedge failure of the riverside land occurred at the start point of the upper stream seepage line.

The seepage line which differs depending on the change in the cavity length was estimated using the Casagrande method (1937). The infiltration length was obtained through the line integral of the estimated seepage line. In order to obtain the excessive pore water pressure caused by vibration, other effects than the vibration level was equally set, and pore water pressure was calculated for each test case in the condition of the mean water level of 7 cm.

\[
\Delta u \equiv u' - u_i
\]  

(7)

Here, \(\Delta u\) is the excessive pore water pressure \((\Delta h' = \Delta u/\gamma_w)\), \(u_i\) is the pore water pressure when there is no vibration, and \(\gamma_w\) is the pore water pressure where there is vibration. Figure 9 shows the excessive pore water pressure depending on the vibration level. The higher the vibration level rose, the more the excessive pore water pressure exponentially increased.

Figure 10 is the flood water level which piping occurs depending on the cavity length. The water level when boiling was found was determined to be the water level at which piping occurs. It can be seen that the flood water level at which piping occurs decreases as the cavity length increases and the vibration level rises. The results indicate that vibration and cavity greatly increased the risk of piping. When the cavity length was 80 cm and the vibration level was 3, piping occurred at the water level lower by about 58% than that when there was no vibration.

5 CONCLUSION

In this study, the piping stability of levee is investigated when a cavity is generated beneath the drainage structure and there is an effect of vibration. The result has
shown that, the closer the cavity is to the upper stream of the levee body and the higher the vibration level rises, the lower the water level at which piping occurs. In the test conducted in this study, the water level at which piping occurs in a dynamic condition was lower than that in static condition by maximum about 58%.

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