

A consideration of river embankment slip failure caused by seepage-induced foundation ground weakening

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ABSTRACT

In the present paper, we report on a series of seepage model tests that were carried out to investigate the mechanisms of seepage-induced slip failure in river embankments constructed on multi-layered permeable foundation ground. The results obtained from two-dimensional seepage model testing showed that seepage-related weakening of upper foundations constructed on highly permeable ground can result in embankment slip failure. Specifically, we found that a decline in the effective stress acting on slope toes eventually results in slope slip failure that passes through the foundation ground. Additionally, three-dimensional seepage model tests conducted with a long longitudinal section show that sand boils and slip failures are not localized phenomena that occur at local weak points.

Keywords: river embankment; seepage failure; slip failure; effective stress; multiple layer foundation

1 INTRODUCTION

In recent years, levee failures have frequently occurred in Japan due to heavy rainfall. Some of those incidents were the result of bank breakage or serious seepage-induced embankment slip failure without overtopping. As a representative case, the 2012 bank breakage of the Yabe River in northern Kyushu due to torrential rains is believed to have been caused by the occurrence of piping beneath the embankment. Furthermore, in the case of the large-scale embankment slip failures that occurred on the dike bank brinks of the Koyoshi and Kakehashi Rivers in 2013, ground investigations conducted at the damaged sites revealed that most of the embankment failures occurred above sections of highly permeable foundation ground.

This indicates that a proper understanding of the permeability states of the foundation ground beneath river embankments is a very important part of resolving the reasons behind seepage-induced embankment failures. In particular, the soil materials of the foundation ground beneath such embankments, as well as their combinations, are key issues requiring consideration. However, the actual mechanisms of seepage failures occurring in river embankments constructed on highly permeable foundation ground have not yet been clarified.

2 FAILURE PATTERN CLASSIFICATION

In previous research, we conducted a series of two-dimensional (2D) seepage model tests to study the

mechanisms of river embankment seepage failures on highly permeable foundation ground. In particular, the effects of highly permeable foundation ground on the deformation and progressive failure of model slopes were discussed (e.g. Kodaka et al., 2015, 2016, 2017).

The results of numerous model tests indicate that river embankment seepage failures occurring on multiple layers of permeable foundation ground can be classified into three patterns, as shown in Fig. 1. Failure Pattern I is the so-called piping failure, which can only be observed in the case of low permeable embankments constructed on top of high permeable foundation ground. In such cases, a water channel, commonly referred to as a “pipe” develops in the permeable sand layer just beneath the low permeable embankment from the land side toe to the river side of an embankment. When the water pipe finally passes through the river embankment, internal collapse within the river embankment can occur.

Failure Pattern II refers to progressive slip failure from the land side toe of a slope that is caused by foundation ground weakening. In such cases, the shear strength as well as the effective stress around the slope toe in the upper foundation, decreases due to the concentration of seepage flow from the lower portion of the highly permeable foundation ground. The foundation weakening is induced by the decreasing shear strength as well as the effective stress.

Alternatively, in cases where the upper permeable layer is thick or has a large shear strength, the seepage flow in the lower portion of the highly permeable layer

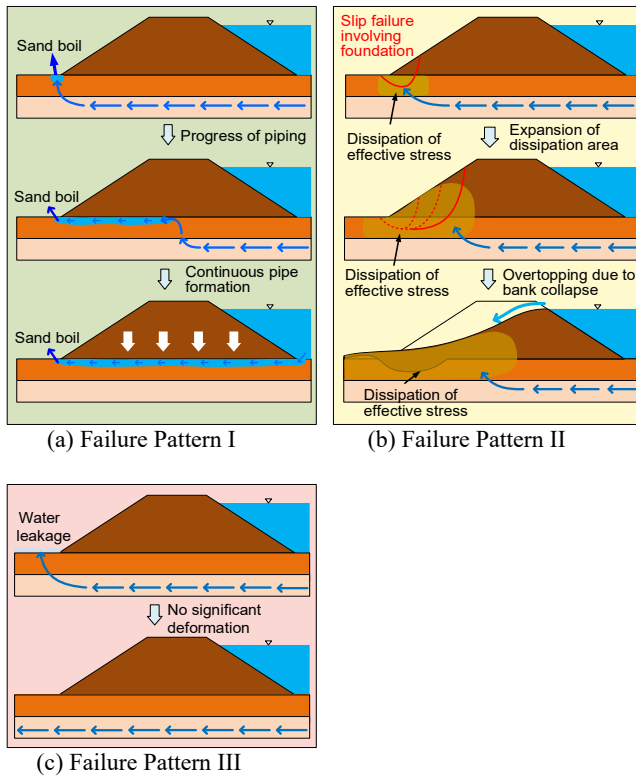


Fig. 1. Three pattern classifications for river embankment seepage failures on multilayered permeable foundation ground.

does not affect the embankment. Thus, any river embankment deformation that occurs will depend solely on the embankment seepage phenomenon. We refer to such failure cases as examples of Failure Pattern III.

In this paper, we focus on Failure Pattern II since it is understood that, except for cases of overtopping, river embankment slip failures cause the most serious damage. Specifically, two- and three-dimensional (2D-3D) seepage model tests were carried out to investigate the mechanisms of seepage-induced river embankment slip failure existing on multi-layered permeable foundation ground.

3 MODEL TEST CONDITIONS

Figure 2 shows a schematic view of our 2D seepage model test. Here, it can be seen that the experimental container, which was made of clear acrylic boards, was separated from right to left into three spaces for the water supply, embankment model, and drain. Since the 2D model test focuses on phenomena that can be observed in the embankment cross-section, the depth of the experimental container was just 120 mm and the longitudinal section of the embankment was not considered. In contrast, since our 3D seepage model test was also conducted to observe phenomena occurring in the longitudinal section of embankments during the seepage process, the longitudinal direction depth of the container was 1200 mm, ten times that for the 2D test, as shown in Fig. 3.

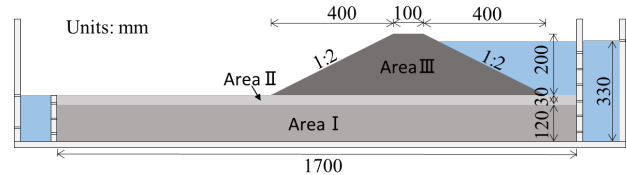


Fig. 2. Schematic view of 2D seepage model test.

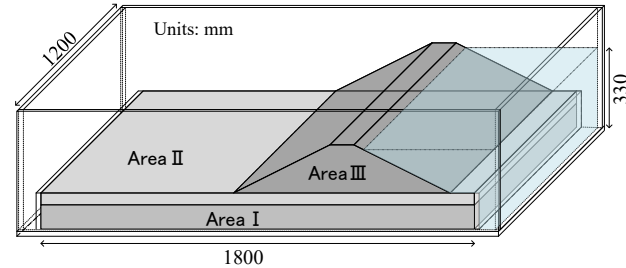


Fig. 3. Schematic view of 3D seepage model test.

Table 1. Soil materials for each area used in the model test.

Area	Void ratio	Coefficient of permeability (m/s)
I	0.95	2.67×10^{-3}
II	1.06	3.98×10^{-5}
III		9.96×10^{-5}

Area I simulates the lower foundation ground and was constructed from coarse highly permeable No. 3 Mikawa silica sand. Area II simulates the upper foundation ground and was constructed from fine No. 8 Mikawa silica sand, and has lower permeability compared with Area I. Area III simulates the embankment model slope and was created by mixing Mikawa silica sand Nos. 6, 7, and 8. The coefficient of permeability for this medium coarse sand mixture and the void ratio for each area are listed in Table 1.

First, a 100 mm water level was applied and maintained for 90 minutes in order to saturate the foundation ground. Next, the water level was increased rapidly to 330 mm and kept at that level by overflow from the water supply section. The water level of the drain section was maintained at 150 mm, which was the same height as the simulated ground surface. Thus, the total hydraulic head at the left end of the model ground can be considered to be the same as that of the horizontal ground.

4 TEST RESULTS

4.1 2D seepage model test

Figure 4 shows the embankment model slope seepage failure process as observed in our 2D seepage model test. The left-side column shows the overall progress of the failure process to the overflow point that results from the crown collapse of the embankment model slope. The right-side column shows the progressive slip failure process for the slope in detail. At each time step, two photos (side view and top view) are shown.

At around 30 seconds after the start of the test,

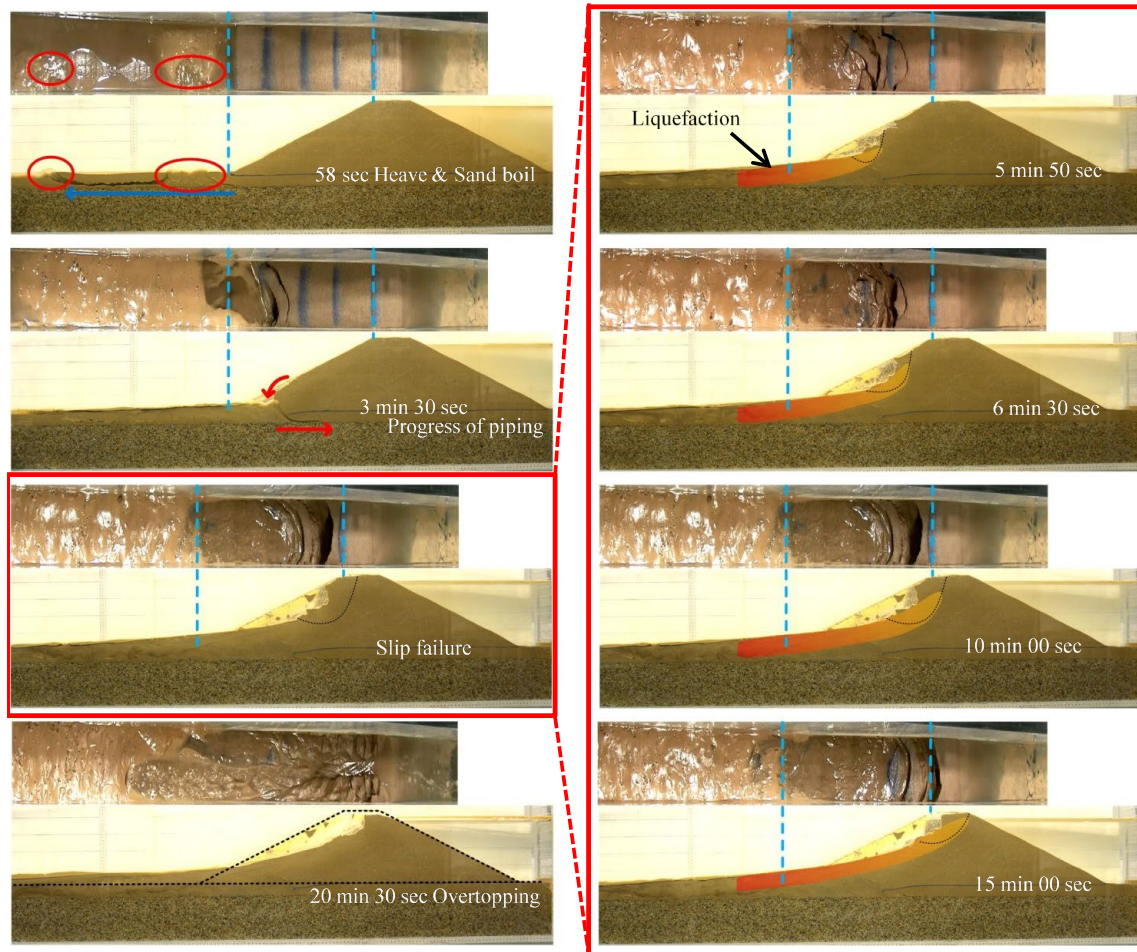


Fig. 4. Observation of progressive failure by two-dimensional seepage model test.

heaving generated by the water channel at the boundary between Areas I and II can be observed on the land side ground surface. Next, boiling occurs at two places, causing the water beneath the upper foundation layer to spout. After the boiling subsides, a water channel develops from the left to the right side, i.e., under the embankment. The water channel moves to the right side in a series of repeated generation and disappearance steps.

The red colored zone seen in the right side column in the photographs can be considered to be liquefied ground whose effective stress is almost zero. The yellow colored zone is previous stage of the red zone. The dotted line in the yellow zone indicates the slip line observed during the process of an actual test. The progressive slip failure can be observed in the right-side column. As water moves through the pipe, the red zone gradually expands to reach the inner side of the embankment.

Even though the water pipe disappears completely at a point near the underside of the crown, the effective stress around the upper foundation layer and the embankment bottom declines due to seepage flow through the lower portion of the highly permeable foundation layer. The permeability gap between Areas I and II raises the hydraulic gradient and lowers the

effective stress in the upper layers, including the embankment. The small slip failure that occurs at the slope toe is the trigger of the progressive slip failure that eventually results in complete embankment failure.

From the results of our 2D seepage model test, it was clarified that multi-layered foundation ground combined with a permeability gap and a low permeable upper layer has a strong potential to result in progressive river embankment slip failure.

4.2 3D seepage model test

Figure 5 shows our 3D test, which was carried out to observe the phenomena appearing in the longitudinal direction of a river embankment prior to failure. The test conditions were the same as in the 2D test except for the increased longitudinal direction depth.

At the beginning of the test, heaving was observed over a wide area of the land-side ground surface, after which multiple sand boils were generated simultaneously at points some distance from the slope toe. These sand boil generation points rapidly began approaching the toe. After reaching the toe, a small slip failure is first observed over a wide area in the longitudinal direction of the slope.

As the slip failure progresses, slope failure seems to be localized at three points, as shown in the

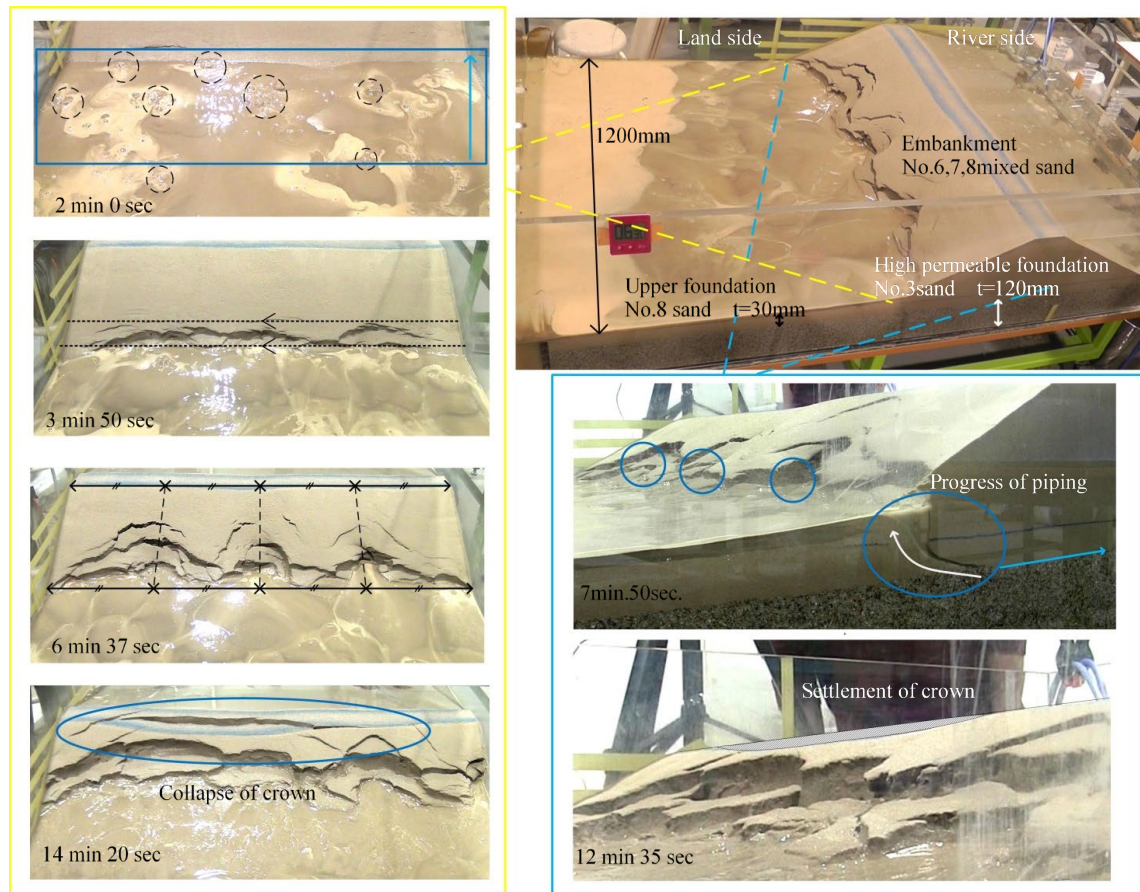


Fig. 5. Observation of progressive failure by three-dimensional seepage model test.

photograph taken at 6 min 37 sec. However, this localization can be considered to depend on small imperfections in the initial conditions of the model ground and embankment, along with boundary conditions such as the depth and embankment height. In other words, the presence of accurate equal intervals in the progress of the slope failure, as observed in this photo, is indicative of uniformity between the model ground and the embankment.

All phenomena observed in the 3D seepage model test, such as the generation and progress of the water pipe (as seen from the side view) as well as the slip failure progress, closely match those for the 2D test. Therefore, it should be noted that sand boils and slip failure are not localized phenomena that occur at local weak points, and that seepage-induced slip failures can occur on any point of a river embankment that is situated on highly permeable foundation ground.

5 CONCLUSION

In this study, 2D and 3D seepage model tests were performed to investigate the failure mechanisms of river embankments constructed on multi-layered permeable foundation ground. Our results show that seepage induced weakening of an upper foundation constructed on highly permeable ground can result in progressive slip failure of the embankment. Specifically, we found that declines in the effective stress acting on

slope toes can eventually result in slope slip failure that progresses through the foundation ground. Additionally, 3D seepage model tests with a long longitudinal section show that sand boils and slip failures are not localized phenomena that occur at local weak points.

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REFERENCES

- Kodaka, T., Lee, K.-T., Cui, Y., Yu, G., Mori, S. and Hayashi, M. (2015). Consideration of the seepage failure of river embankment due to the high permeability of foundation ground, Proc. of the 3rd Symposium on Levee Technology, 42-45. (in Japanese)
- Kodaka, T., Cui, Y., Mori, S., Hayashi, M. and Lee, K.-T. (2016). Seepage failure of river embankment on dead end high-permeable foundation ground, Proc. of the 51th Annual Meeting by Japanese Geotechnical Society, 1085-1086. (in Japanese)
- Kodaka, T., Lee, K.-T., Cui, Y., Mori, T., Mori, S. and Hayashi, M. (2017). A consideration on the slip failure of river embankment caused by weakening foundation ground due to seepage, Proc. of the 5th Symposium on Levee Technology, 55-58. (in Japanese)

