Prevention effects of slope-covering method against seepage failure of river embankment

Taizo Kobayashi i), Hiroki Uwa ii), Takahiro Miyamoto ii), and Kazuyuki Hayashi iii)

i) Associate Professor, Department of Architecture and Civil Engineering, University of Fukui, 3-9-1, Bunkyo, Fukui 910-8507, Japan
ii) Master Student, Graduate School of Engineering, University of Fukui, 3-9-1, Bunkyo, Fukui 910-8507, Japan
iii) Associate Professor, Department of Civil Engineering, National Institute of Technology, Wakayama College, 77, Noshima, Nada, Gobo, Wakayama 644-0023, Japan

ABSTRACT

This paper presents a study on slope-covering method, which is frequently used in Japan as a reinforcement measure against seepage failure of river embankments. Covering the face of the riverside slope with impervious materials (impervious soil, concrete, impervious sheet, or other artificial materials) prevents the river water from penetrating into the embankment. In this study, a series of model experiments and numerical seepage analyses were performed to clarify the prevention effect of this method. From the results, it is clear that covering the slope is effective not only in delaying the rising speed of local hydraulic gradient at the slope toe, but also in reducing the hydraulic gradient. The numerical analyses showed that this method is more effective when used on steeper slopes. However, the reinforcing effect is drastically reduced when the water level exceeds the area of the slope covered.

Keywords: river embankment, seepage failure, seepage analysis

1 INTRODUCTION

Japan is one of the countries most affected by natural disasters. The country has been experiencing typhoons and torrential rains with unexpected severity, and there appears to be no end to flood disasters due to river embankment failures. It is well known that the failure of river embankments is due mainly to scour and erosion by overtopping flow; however, there are many cases of failure caused by seepage flow that occurred in the embankment body. Figure 1 shows concrete-faced embankments damaged by Typhoon Talas when it hit Japan in September 2011. All the surfaces of the embankments had been covered by concrete; therefore, it is unlikely that scour and/or erosion by overtopping flow could have triggered the failure of the interior embankment bodies. This indicates that the river embankments were damaged by seepage flow. It was reported that several embankments were damaged by the typhoon, even though they were reinforced as shown in this figure. River embankments in Japan will become increasingly vulnerable not only to disaster hazards, but also to the deterioration of the embankments due to aging. The construction and maintenance of river embankments should be undertaken more cautiously than ever before.

In this study, we focused on seepage failure, and performed a model experiment and seepage analysis to gather knowledge that can contribute to appropriate design and selection of the reinforcement method.

Fig. 1. Concrete-faced river embankments (in Wakayama Prefecture) damaged by Typhoon Talas when it hit Japan in September 2011.

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2 REINFORCEMENT METHODS AGAINST SEEPAGE FAILURES

In Japan, river embankments have been basically designed in accordance with the Structural Standard for River Administration Facilities\(^1\) (originally enacted in 1976), which stipulates the cross-sectional geometry of the embankment. In 1997, the Technical Criteria for River Works\(^2\) was revised, and the safety verification-based design method was introduced. The safety verification presently covers performances against erosion, seepage, and seismic loading. For seepage failure, the performances are verified with respect to slip failure of the embankment slopes and piping failure of the foundation. If the result does not meet the requirements, the embankment must be reinforced. Table 1 summarizes the standard reinforcement methods against seepage failure. The reinforcement methods for improving the embankment body include cross section widening method, slope-covering method, and drain method. For reinforcing the foundation, the sheet wall method, blanket method, and dewatering method are frequently used in Japan. As each method has a different target and principle, it is important to take the conditions of the soil and water level into consideration before selecting the best-suited method.

Table 1. Standard reinforcement methods (against seepage failure) used in Japan

| Method | Principle / Effect |
|--------|-------------------|
| **Methods for embankment body** | |
| Cross section widening method | - Widening the cross section of the embankment leads to elongation of the seepage path and results in a reduction of hydraulic gradient.<br>- Gentler embankment slope improves safety against slip failure.<br>- The fill material performs the additional function of preventing piping failure of the foundation. |
| Slope-covering method | - Covering the face of the riverside slope with impervious materials (impervious soil, concrete, impervious sheet, or other artificial materials) prevents the river water from penetrating into the bank.<br>- The wetting surface drops to a lower level, and the local hydraulic gradient at the landside slope toe is reduced. |
| Drain method | - Replacing the landside slope toe by permeable materials permits seepage reduction in the bank.<br>- The wetting surface drops to a lower level, and the local hydraulic gradient at the landside slope toe is reduced.<br>- The stability of the slope is also improved by replacing the toe with drain materials having large shear strength. |
| **Methods for foundation** | |
| Sheet wall method | - Installing a sheet pile wall in the riverside foundation controls the seepage flow into the foundation.<br>- The local hydraulic gradient in the landside foundation decreases, and the safety against piping failure is improved. |
| Blanket method | - Installing an impervious blanket onto the bed of a high-water channel leads to elongation of the seepage path in the foundation.<br>- The local hydraulic gradient in the landside foundation decreases, and the safety against piping failure is improved. |
| Dewatering method | - Installing a dewatering system (relief well, dry well, trench, etc.) in the landside foundation reduces the uplift pressure.<br>- The local hydraulic gradient in the landside foundation decreases and the safety against piping failure is improved. |
3 EXPERIMENTAL VALIDATION OF THE EFFECT OF SLOPE-COVERING METHOD

In Japan, slope-covering methods using concrete, blocks, or impervious sheets have been frequently used. The covering material prevents the river water from penetrating into the bank. There appear to be few research studies quantitatively investigating the effect of slope coverage. In this study, a laboratory model experiment was performed to clarify the mechanism of the reinforcing effect of the slope-covering method.

Figure 2 shows the experimental setup used in this study. The model embankment measures 200 mm in height, 150 mm in crown width (top), and 950 mm in the base. The side slope is 1:2 (vertical to horizontal) on both sides, and the thickness of the foundation is 150 mm.

Two types of soils were used for the embankment model – silica No. 6 sand and clay/silica No. 6 sand mixture with a dry weight ratio of 5:1. The dry densities and saturated hydraulic conductivities are $\rho_d = 1.358 \text{ g/cm}^3$ and $k = 2.82 \times 10^{-4} \text{ m/s}$, respectively for the silica No. 6 sand, and $\rho_d = 1.393 \text{ g/cm}^3$ and $k = 3.31 \times 10^{-5} \text{ m/s}$, respectively for the mixture soil.

An acrylic board of 3 mm thickness was used to mimic the impervious material. A series of experiments were conducted under the conditions listed in Table 2.

| Case  | Slope coverage | High water level  |
|-------|----------------|-------------------|
| 1     | No coverage    | 200 mm            |
| 2     | 0 – 160 mm     | 180 mm (overflow of 20 mm) |
| 3     | 0 – 160 mm     | 200 mm (overflow of 40 mm) |
| 4     | 0 – 200 mm     | 200 mm            |

The groundwater table was initially fixed at a height of 168 mm from the bottom of the soil container, and then the riverside water level was raised at a constant speed at 10 mm/s up to the desired level. In the meanwhile, the water in the landside was drained through a drainage outlet, so that the water level was kept constant at the initial level. After the water surface reached designated height, the water level was kept constant.

A short while after the riverside water level started rising, some soil particles at toe of the landside slope began to move out first. The area of soil flow gradually expanded and consequently, the toe of the landside slope collapsed in every case.

Figure 3 shows the time to cause seepage failure. It can be seen in case of the sand-clay mixture that the time to cause the seepage failure increases by covering the riverside slope. On the other hand, no notable difference is seen in the case of silica No. 6 sand. In the case of silica No. 6 sand, it appears that the water that seeped through the embankment passed through the foundation. This indicates that slope-covering method has less reinforcing effect against seepage failure when the foundation is highly permeable. Cases 2 and 3 were those where the river water exceeded the top of the coverage, and the embankment permits water inflow from the top of slope. It can be seen that the effect of slope-covering decreases to some extent when the water level exceeds the covered area.

4 SEEPAGE ANALYSIS

In this study, a 2-D saturated/unsaturated seepage analysis based on finite element method (AC-UNSAF2D) was performed to investigate the seepage mechanism in the slope-covered embankment. Figure 4 shows the calculation results obtained from the model experiment for the condition with the sand-clay mixture. The change in hydraulic head distribution at the bottom of the soil container is shown in Figure 4(a). The solid and dashed lines represent the...
calculation and experimental results, respectively. It is seen that the calculation results were in fairly good agreement with the experimental data. The hydraulic heads steadily decline from the riverside to the landside, and the slopes of the decline become large with time. It is interesting to note that the distribution hardly depends on whether the slope is covered or not. This implies that seepage occurs in the foundation even if the slope is covered with an impervious material.

Figure 4(b) shows the calculation results of the changes in the wetting surface for various cases. It can be seen from the figures that the slope coverage has a significant impact on the wetting surface formation and can lower the level of the wetting surface in the embankments. When the slope is covered with an impervious material, the water in the embankment is supplied from the foundation. It appears that the hydraulic head loss during the detour helps in the control of the wetting surface.

Next, numerical analyses were performed for real-scale models whose height, crown width, and foundation thickness were 6, 4.5, and 4.5 m, respectively. The change in the horizontal hydraulic gradient at the landside slope toe is shown in Fig. 5. This figure shows the influence of hydraulic conductivity of the embankment. It can be seen that the seepage flow finally becomes steady, and the local hydraulic gradient reaches a steady state value after some time has elapsed. It may be noted that the steady state value is not dependent on the hydraulic conductivity; it is significantly dependent on the slope coverage condition. When the embankment permits water inflow from the top of the slope, the reinforcing...
effect against seepage failure is reduced even if the slope is covered with an impervious material. Figure 6 shows the change in local hydraulic gradient for embankments with slopes of 1:1, 1:2, and 1:3 (vertical to horizontal). The height, crown width, and thickness remained unchanged at 6, 4.5, and 4.5 m, respectively. The hydraulic conductivity of the bank and foundation was $3.31 \times 10^{-5}$ m/s (for the sand-clay mixture). This figure shows that the steady state value and the rising speed of the local hydraulic gradient increase with an increase in the slope. Moreover, it can be seen that the reinforcing effect becomes significant as the slope becomes steeper. This figure also indicates that the effect of slope coverage is nearly equivalent to the effect of widening the slope from 1:1 to 1:1.5 and/or from 1:1.5 to 1:2.

5 CONCLUSIONS

In Japan, the design method for river embankments has changed from the specification-based method to the performance-based method. In the performance-based design method, river embankments require safety with respect to erosion, seepage, and seismic loading. If the safety verification result does not meet the requirements, the embankment must be reinforced.

In this study, we focused on seepage failure, which occurs frequently in Japan; the slope-covering method as a reinforcement method against the seepage failure was investigated through model experiments and numerical seepage analyses. The conclusions drawn from this study are summarized as follows.

1) The slope coverage has a significant impact on the seepage flow in the embankment and is effective in lowering the level of the wetting surface.
2) When the slope is covered with an impervious material, the seepage path makes a detour around the slope coverage. The hydraulic head loss during the detour helps in the control of the wetting surface.
3) The slope coverage is effective not only in delaying the rising speed of the local hydraulic gradient at the slope toe, but also in reducing the hydraulic gradient.
4) The reinforcing effect becomes significant as the slope becomes steeper.
5) The slope-covering method has less effect against seepage failure when the foundation is highly permeable.
6) When the water level exceeds the slope coverage, the reinforcing effect is drastically reduced even if the slope is covered with an impervious material.

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