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INFLUENCE OF SEEPAGE FLOW HISTORIES ON DETERIORATION WITHIN EMBENKMENTS

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ABSTRACT: Embankment structures are important to protect against flooding damage. Suffusion, in which fine particles within the soil are transported and washed away following the seepage flow, intensifies the instability of embankment structures. Therefore, it is possible that some embankment structures that repeatedly experienced flooding and rainfall penetration have been deteriorated. However, there is little research investigating the relation between seepage flow histories and deterioration within the embankments. In this study, small-scale modeling tests duplicating a river levee were conducted under different seepage flow histories: (*i*) short term-critical ground water level, (*ii*) continuous-high ground water level and (*iii*) repeated-high ground water level. The work in this paper investigates changes in "drainage flow rate", "height of ground water level" and "particle size distribution" during the seepage tests, and evaluates the effects of seepage flow histories on them. Soils gradually showed lower permeability under the first seepage experience in each cases. In the case of relatively longer flooding duration, the drainage flow rate is gradually increased. Fine particles were eroded, regardless of the seepage flow histories; "the number of fluctuations" and "height" of ground water level could particularly be a trigger of suffusion.

Keywords: Seepage, Embankment, Suffusion, Particle size distribution

1. INTRODUCTION

Soils are often used for the construction of embankment structures, such as levees and earth dams, and they protect neighborhoods from flooding.

In recent years in Japan, increased daily precipitation tends to accompany global warming, which frequently causes flooding events and an embankment failure. For example, a river levee along the Yabe River failed following heavy rains in Northern Kyusyu, in 2012. A piping development was assumed as a cause of the failure [1-3]. In 2015, a river levee along the Kinu River failed due to overtopping and seepage of water during heavy rain [4]. Furthermore, in 2017, many embankment structures were failed due to flooding, such as a river levee along the Oda River.

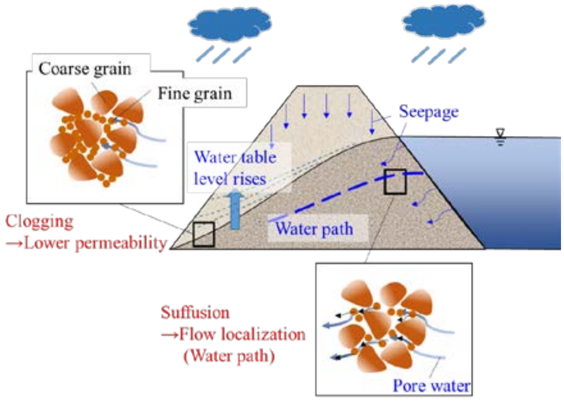


Fig. 1 Deterioration problems of concern for a river levee under seepage

Most embankments are constructed from the various natural soil materials extracted from the local area, and they are repeatedly elevated using additional material. Therefore, the embankment is assumed to have uncertain homogeneity in terms of such as particle properties, density, permeability and strength. Suffusion is one of the causes of internal erosion, in which fine particles within the soils are transported and washed away following the seepage flow [5]. Figure 1 illustrates the deterioration problems of concern for a river levee under seepage. Once fine particles wash away, the area could become a water path for localized flow. Moreover, clogging due to transported fine particles increases the possibility of water level rises. High ground water levels raised during flooding events due to conditions such as continuous rain or torrential rain intensify the occurrence of suffusion, whereby the deterioration of embankment may lead to devastating failure. Hence, it is thought that there are many working embankment structures which have been progressively deteriorating and have been having a potential for failure.

Various laboratory experiments and analytical studies have previously been performed regarding internal erosion, and they have revealed the causes of soils instability, such as particle properties, hydraulic conditions and stress conditions [6]. However, there is very little research investigating the relation between seepage flow history and deterioration within the embankments due to suffusion.

In this research, small-scale modeling tests duplicating a river levee were conducted under different seepage flow histories. For the test conditions, different seepage histories were applied to investigate their influences on the deterioration of soils within the embankment. As an evaluation of deterioration, the work in this paper focuses on changes in “drainage flow rate”, “height of ground water level” and “particle size distribution” during the seepage flow tests.

2. EXPERIMENTAL STUDY

2.1 Experimental Material

The experimental material, which incorporated fine and coarse grain fractions, was prepared by mixing No.4 and No.8 silica sands. The combined particle size distribution curves are shown in Figure 2. Kenny and Lau [7] proposed the criterion that classifies the stability of soils against internal erosion. The criterion can be defined by two parameters, H and F, which are obtained from particle size distribution curve, as illustrated in Figure 3. According to the criterion, the experimental material has $(H/F)_{min}$ of 0.55 (<1.0), which can be interpreted as having a potential for instability due to internal erosion, as shown in Figure 4. The material properties are also presented in Table 1.

Constant head permeability tests were conducted for 3 days in advance. Figure 5 shows the fluctuation of the coefficient of permeability k during the permeability test. For comparison, the result of a stable soil mixture with a $(H/F)_{min}$ of 1.84 (>1.3) is also shown in the figure. It is worth mentioning that decreasing of the coefficient of permeability can be observed.

2.2 Model Preparation

Figure 6 illustrates details of the model configuration. The embankment model was constructed by compaction. A 0.075mm mesh filter was fixed in a perforated metal plate to allow the washing away of fine particles. The plate was then installed into the test box. Water was added to the test material to a moisture content of w=10%, and unsaturated soil material was prepared. Five layers of the material were gently compacted into the test box at a relative density of D_r=80%. After compaction, the excess materials were then excavated using pallet knives, and the embankment model was sculpted. The embankment model had the following geometry: height of 185mm, crest width of 60mm, base width of 330mm, and a slope of 1:2. Three manometers were equipped to the bottom of the base materials through the test box. Figure 7 shows an overview of the test equipment. An observation camera used to capture the pictures for digital image correlation (DIC) analysis was set in front of the model.

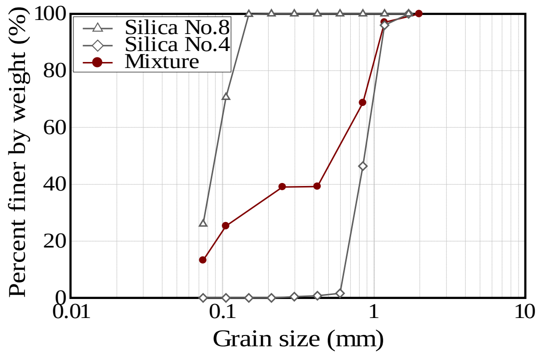


Fig. 2 Particle size distribution curve

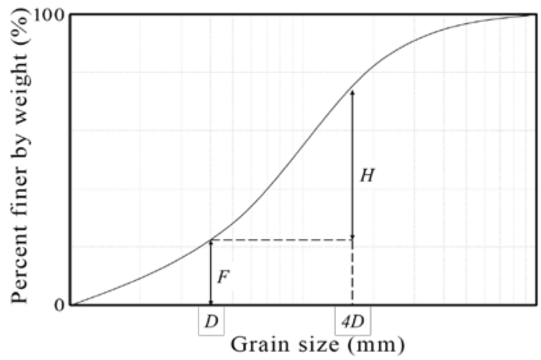


Fig. 3 Definition of parameters H and F

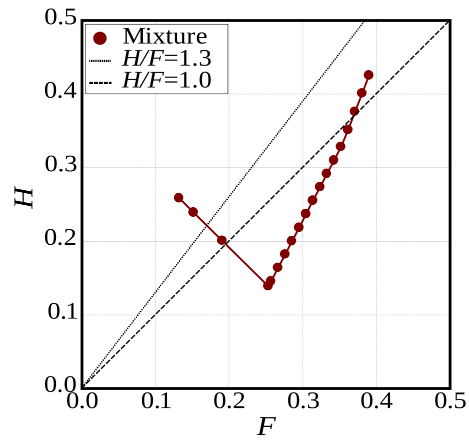


Fig. 4 H/F relation

Table. 1 Material properties

Specific gravity of soil particles G_s	Fines content F_c (%)	Mean diameter D_{50} (mm)	Uniformity coefficient U_c	$(H/F)_{min}$
2.67	13.2	0.58	16.7	0.55

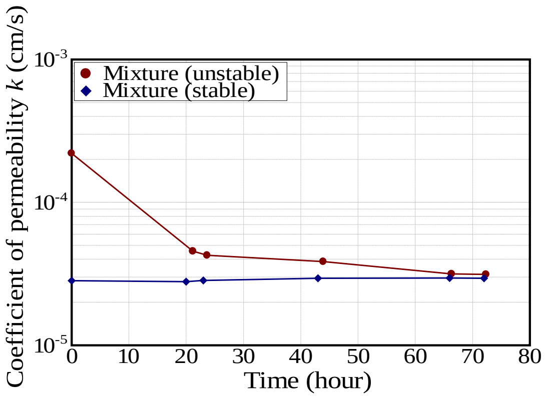


Fig. 5 Fluctuation of coefficient of permeability

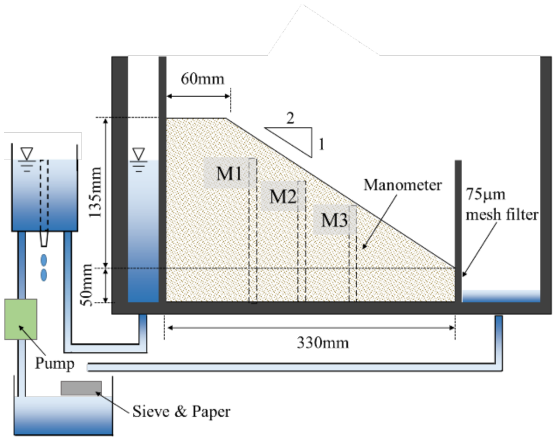


Fig. 6 Model configuration

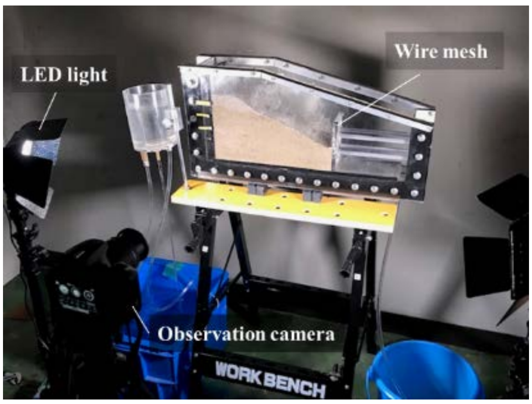


Fig. 7 Overview of test equipment

2.3 Test Procedures

The seepage tests were conducted by suppling water from the back of the embankment, as shown in Figure 6. Water circulation using a pump enabled a constant water level at the upper tank and the back of the embankment.

In this study, three seepage histories were set as the test conditions, as shown in Figure 8. Case 1 is the condition which simulates short term-critical ground water level (90% of the embankment height) caused by concentrated heavy rain. Case 2 simulates continuous-high ground water level (70% of the embankment height), such as seen in the rainy season. Case 3 simulates repeated-high ground water level rises (70% of the embankment height). In each cases, a ground water level at 50% of the embankment height is assumed as the usual groundwater, and seepage for 24 hours was previously carried out.

Leaking water from the toe of the embankment model was collected, and the flow rates were calculated. The water level within the embankment was investigated by measuring the manometer’s water level.

After the seepage tests, the soil materials at different locations were sampled, and sieve analysis was then conducted.

	Top water level: percentage of embankment height (Duration)			
Case 1	50% (24h) →	90% (6h) →	50% (24h)	
Case 2	50% (24h) →	70% (120h)		
Case 3	50% (24h) →	70% (24h) →	50% (48h) →	70% (48h)

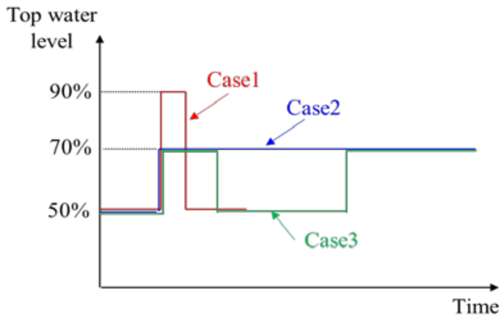
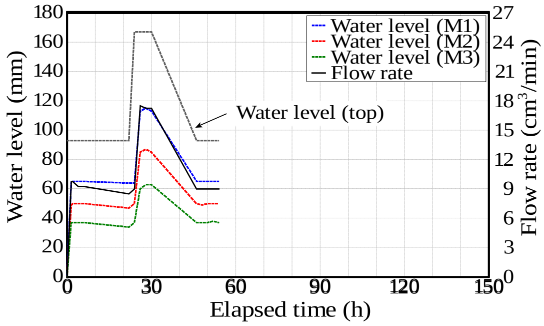


Fig. 8 Seepage test condition

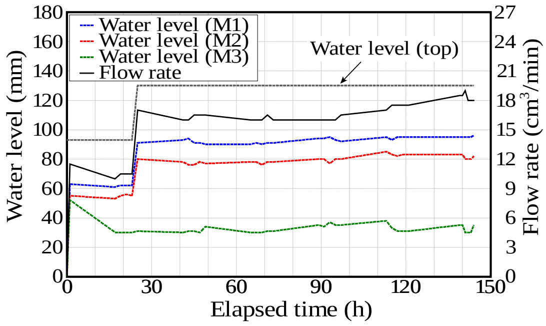
3. TEST RESULTS

(1) Ground Water Table and Flow Rate

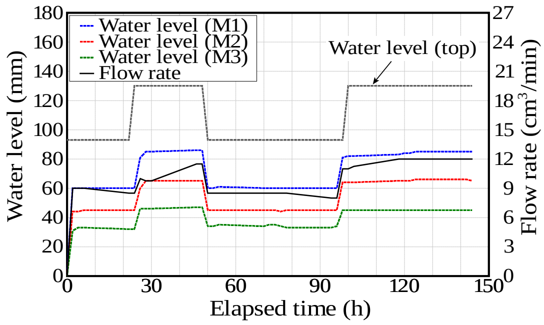
Figure 9 shows the results of the ground water level for each manometers and drainage flow rate during the seepage tests. As seen in the figure, the result of the first 24 hours duration, when the top water level was 50% of the embankment height, shows a gradual decrease of drainage flow rate in each tests. A decreasing a magnitude of the coefficient of permeability was confirmed from the constant permeability test, as mentioned before. According to these results, the permeability of the soils tends to decrease in the first seepage experience. The embankment model was



(a) Case 1

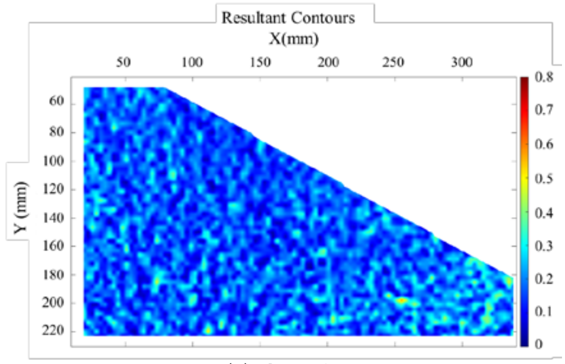


(b) Case 2

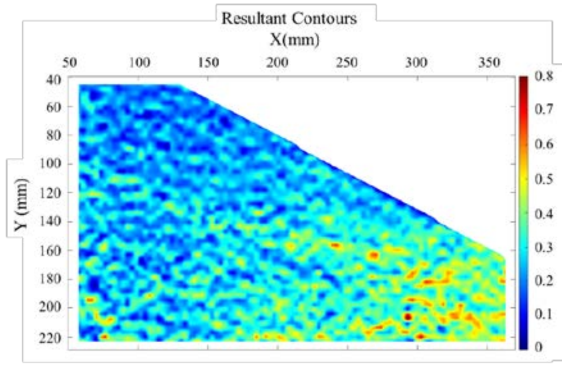


(c) Case 3

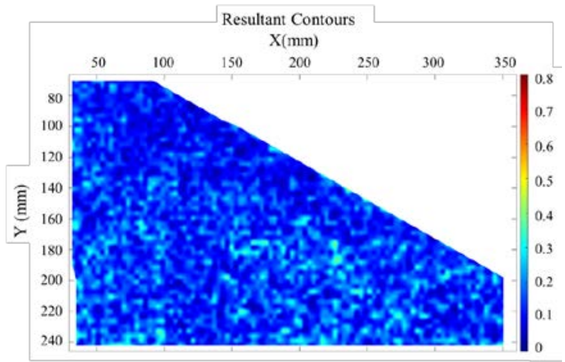
Fig. 9 Time histories of ground water level and drainage flow rate



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 10 Displacement contours for first 24h

compacted in the same manner, nevertheless, the decreasing trends of flow rate are different for each cases. Figure 10 shows the displacement contours for first 24 hours. Matlab and GeoPIV [8] were used to compute the DIC analysis. For Case 2, larger displacement can be seen compared with other cases. This result especially exhibits compaction of the embankment at the toe. It is likely that clogging caused by the compression at the toe induced the decreasing permeability. It is assumed that differences in deformation are caused by non-uniformity in the model construction. However, this clearly implies that non-uniformity during construction of an embankment structure greatly affects permeability and deformation behavior.

The results of Case 2 and Case 3 show that the manometer water levels respond in an accordance with flooding; whereas, the drainage flow rate gradually increases after flooding. After the second flooding event for Case 2, the gradient of increasing drainage flow rate is flatter, compared with the first flooding. For Case 1, it is assumed that a delay of increasing flow rate cannot be seen because the flooding duration is relatively shorter than those of the other two cases. Devastating failure was not observed in any of the cases.

The expended energy E_{flow}, which is the time integration of the instantaneous power dissipated by the water seepage for the test duration, is represented as follows [9];

$$E_{flow}(t) = \sum_{0}^{t} Q\gamma_w \Delta h \Delta t \tag{1}$$

where, Q (m^3/s) is the flow rate of water; γ_w (kN/m^2)

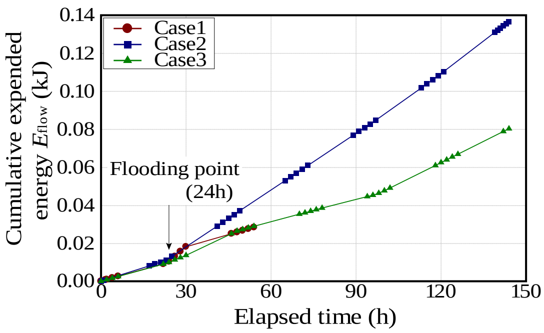


Fig. 11 Time histories of cumulative expended energy

is the unit weight of water; Δh is the difference of water level between the upstream section and the downstream section; and Δt is the time for a certain duration. In this study, Δh is defined as the difference between the top water level and the water level of the toe h_{toe}. h_{toe} can be calculated by Eq.(2);

$$h_{toe} = \sqrt{l^2 + h_{top}{}^2} - l \qquad (2)$$

where, h_{top} is the top water level and l is the base width. Figure 11 represents the time histories of cumulative expended energy during the seepage tests. As shown by the result of the first 24 hours duration, the expended energy of each test is almost the same. The cumulative expended energy at the terminate point of Case 1 agrees with the magnitude of Case 3 at that time. Larger cumulative expended energy at the terminate point can be seen in Case 2 compared with the other cases.

(2) Particle Size Distribution

The tested materials were extracted at different locations in the embankment model, as illustrated in Figure 12. Figure 13 shows the particle size distribution curves after the seepage tests. It can be observed that finer particles were washed away in each case. A decreasing rate of 0.075mm percentage by weight after the test is summarized in table 2. Assuming that the decreasing rate corresponds to the magnitude of suffusion, in Case 1 and Case 3, it is confirmed that greater fine particles are washed away compared with Case 2. A correlation between the location where the materials were extracted and the decreasing rate was not observed.

4. DISSCATION

It was expected that one of the reason why the flow rate gradually increases after flooding is due to the formation water paths following the transportation and washing away of fines. Especially in cases where the ground water level

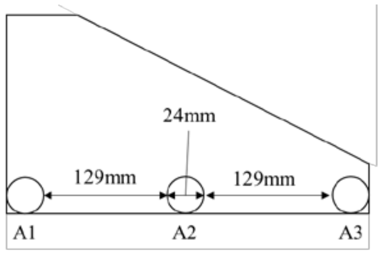
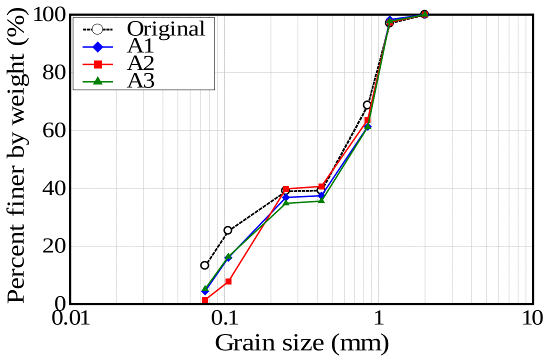
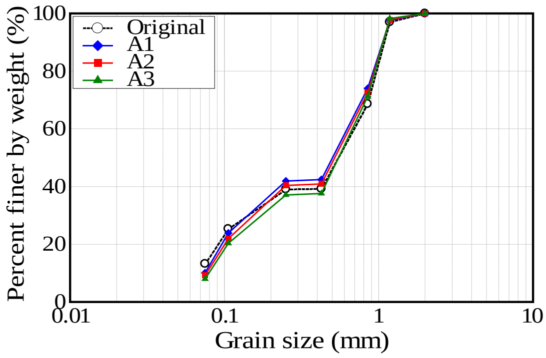


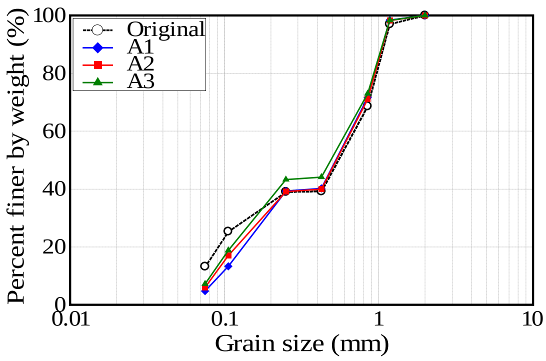
Fig. 12 Sampled location



(a) Case 1



(b) Case 2



(c) Case 3

Fig. 13 Particle size distribution after test

repeatedly changes, such as in Case 3, structural changes are possible due to the fluctuation of pore water pressure within the soil, whereby the permeable area regularly changes. As a result, Table. 2 Decreasing rate of 0.075mm particles

	A1	A2	A3
Case 1	57%	90%	67%
Case 2	39%	30%	23%
Case 3	79%	72%	81%

suffusion is significantly observed in Case 3. In addition, in cases where the ground water level rapidly rises, such as Case 1, it was expected that the pore water pressure would vary rapidly, and hence the possibility of suffusion would increase.

According to the one-dimensional seepage flow tests of the elemental specimens, the mass of fine particles that wash away, generally increases in accordance with the magnitude of expended energy [9, 10]. As observed in Fig.11 and Table.2, the results in this study do not follow such trends. This is probably because the compression of the embankment model occurred with the first seepage, and the non-permeable area was maintained after flooding. Additionally, wherever there is less fluctuation of ground water levels, such as in Case 2, the flow of water becomes locally concentrated in the same area, whereby less fine particle loss can be observed against greater drainage flow rate.

It was expected that “the number of fluctuations” and “height” of ground water level could certainly be a trigger of suffusion. However, the event of fine particles washing away has less effects on the deformation of the embankment.

5. CONCLUSION

In this paper, small-scale modeling tests duplicating a river levee were carried out under different seepage flow histories. The test material for constructing the embankment model was prepared based on the Kenny’s criterion. The following conclusions were drawn;

1) Whenever soils experience the first seepage, permeability tends to decrease. It is interpreted that the soil structure easily changes and that some areas could become clogged due to fine particle transportation following seepage flow.

2) In the case of relatively longer flooding duration, it is assumed that a water path could gradually form, and water is locally transported, whereby the flow rate gradually increases.

3) Loss of finer particles could be observed in each case, and the magnitude of the suffusion was evaluated by a decreasing rate of 0.075mm particles. The relation between the cumulative expended energy during the seepage tests and the loss of fine particles could not be confirmed.

The results indicate that “the number of fluctuations” and “height” of ground water level could certainly be a trigger of suffusion.

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