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Model test on the piping resistance of short fibre reinforced soil and its application to river levee

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ABSTRACT: River levees are important flood prevention structures. They are sometimes damaged by a seepage flow due to the rainfall and the flood. The short fibre reinforced soil was developed for the purpose of improving strength and toughness by mixing short fibre into soil. In this research, the permeability tests were conducted to examine the piping resistance of the short fibre reinforced soil. Furthermore, large-scale levee model tests were conducted to investigate the applicability of the short fibre reinforced soil layer to the river levee structure. It was found that short fibre reinforced soil had high piping resistance, and that the short fibre reinforced soil layer increased the stability of levee against seepage of rainfall and flood.

1 INTRODUCTION

River levees are important flood prevention structures. They are sometimes damaged by seepage flow due to the rainfall and the flood. When the seepage velocity exceeds the critical velocity, the piping occurs and the soil in the levee flows out and the levee structure may be weakened. Therefore, the effective countermeasures against the piping destruction of river levees are to be developed urgently.

The short fibre reinforced soil was developed for the purpose of improving strength and toughness by mixing polyester or polypropylene short fibres (length: 10 ~ 100 mm) with soil (See Photo 1.). It has also high erosion resistance.

In this research, the permeability tests were conducted to study the piping resistance of the short fibre reinforced soil. In addition, large-scale levee model tests were conducted to investigate the applicability of the short fibre reinforced soil layer to the river levee structure in order to improve the resistance against seepage flow.

Photo 1. Short fibre reinforced soil

2 THE PERMEABILITY TEST

2.1 *Outline of the permeability test*

A series of permeability tests (Case1 ~ Case 4) was carried out in order to examine the piping resistance of short fibre reinforced soil. The schematic diagram of the permeability test equipment is shown in Figure 1.

The specimen size was 10 cm of diameter and 15 cm of height. Grease was applied between the specimen and the wall of apparatus to prevent the specimen from being floated.

After the specimen was saturated, the water level of the water supply tank was gradually raised to apply the hydraulic gradient to the tested specimen. The water level above the specimen was kept about 5 cm, and the amount of overflow was measured when the overflow rate stabilized. The water head difference (H) was increased and the overflow was measured every 3 cm of H increase in order to obtain the hydraulic conductivity of the tested material until the piping eventually occurred.

The tested specimens were prepared from soil mixed with short fibre. The used soil was an uniform river sand which tends to be subjected to piping. The physical properties of the soil are shown in Table 1. The mixed fibre was made of polyester. A diameter is 45 µm and length is 64mm. The fibre content was varied between 0% and 0.4% of dry weight of the soil. The specimen conditions were shown in Table 2.

Table 1. Physical properties of the tested materials

Engineering soil classification		Sand
Content (%)	Gravel	7.8
	Sand	91.7
	Silt and Clay	0.5
Uniformity coefficient		2.82
Maximum grain size (mm)		4.75
Maximum dry density (g/cm^3)		1.655
Optimum water content (%)		16.4
Specific gravity (g/cm^3)		2.701

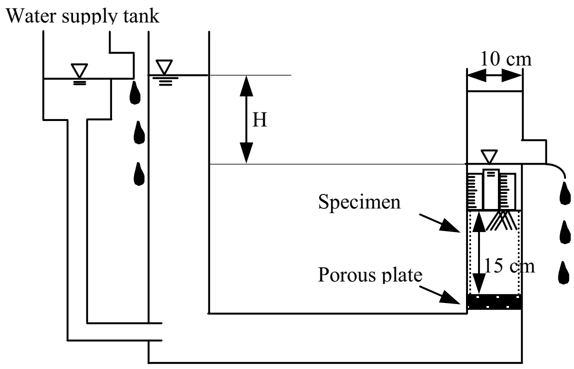


Figure 1. Test equipment

Table 2. Specimen conditions

No.	Fibre content (%)	Water content (%)	Dry density (g/cm^3)	Porosity (%)
1	0	6.65	1.46	45.9
2	0.1	6.58	1.49	44.8
3	0.2	6.62	1.51	44.1
4	0.4	6.55	1.49	44.8

2.2 *Results*

When the water head difference (H) increased and reached certain levels, small bubbles and local sand boiling were observed, the volume of the specimen increased, and finally the specimen failed by the piping.

2.2.1 *Seepage flow velocity and hydraulic gradient*

The relationship between seepage flow velocity (Darcy's flow velocity) and hydraulic gradient is shown in Figure 2. Seepage flow velocity is the volume of overflow divided by the area of specimen. In all cases, the relation between seepage flow velocity and hydraulic gradient was primarily proportional. However, the volume of the specimen as well as the seepage flow velocity rapidly increased before the piping failure.

2.2.2 *Coefficients of permeability of short fibre reinforced soil*

The slope of the plotted lines in Figure 2 indicates the coefficients of permeability. In all cases, the coefficients of permeability were almost the same regardless of the fibre content.

2.2.3 *Piping resistance of the fibre reinforced soil*

Values of hydraulic gradient, seepage flow velocity, and real seepage flow velocity when the piping occurred are shown in table 3. Real seepage flow velocity is the volume of overflow divided by the pore area. These critical values were calculated from flow rate immediately before the piping took place.

The specimen with higher content of short fibre had the larger value of critical hydraulic gradient. For example, in test case 4, the critical seepage flow velosity and critical hydraulic gradient were 1.4 times and 2.2 times of that in test case 1, respectively.

Short fibres appeared to effectively restrict soil particles' movement, due to which the resistance to the piping improved.

Table 3. The test results

No.	Critical hydraulic gradient	Critical seepage flow velocity V (cm/s)	Critical real seepage flow velocity Vr (cm/s)
1	1.86	0.026	0.056
2	2.69	0.028	0.061
3	3.21	0.035	0.077
4	4.18	0.037	0.081

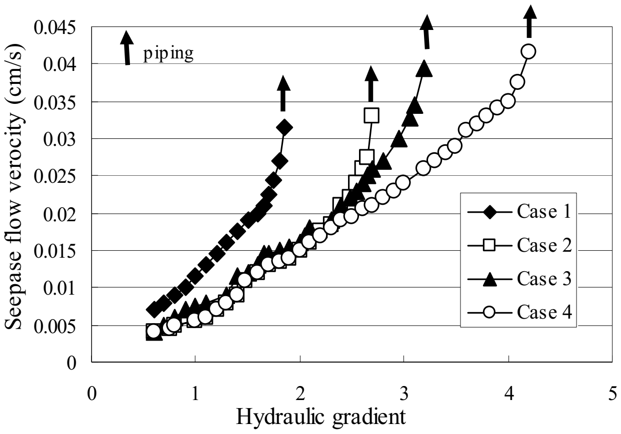


Figure 2 Hydraulic gradient and seepage velocity

3 MODEL TEST ON THE PIPING RESISTANCE

3.1 *Outline of the test*

Large-scale model tests simulating a levee failure by rainfall or flood were conducted in order to study the applicability of the short fibre reinforced soil layer to the river levee structure.

3.1.1 *Model levees*

The model levee was about 3 m of height and had a slope of 1:2. The cross section of the model is resented in Figure 3. The material for the levee model was river sand, properties of which are given in Table 4.

3.1.2 *Test patterns*

Three patterns of the model were tested;

Case 1: No layer of short fibre reinforced soil

Case 2: The slope was covered with short fibre reinforced soil layer

Case 3: The slope was covered and underlain with short fibre reinforced soil layer.

0.4 % of fibre content was used for the experiments. Characteristics of the short fibre reinforced soil are shown in Table 5.

3.1.3 *Process of the tests*

In the preparation of the model levees, the materials were well compacted to ensure that the degree of compaction was greater than 90 %. Piezometers and bole holes were positioned at various locations in order to measure the water level of inside of levee. Marking of 1m meshes was made on the slope to observe the deformation (see Photo 2.). A water level behind the model was kept 2.3 m to simulate high water level due to flood. Artificial rain of 10 mm per hour was applied to the model. Rainfall intensity of 10 mm per hour was found to be appropriate for the experiment, since the rain did not fully permeate the soil and flew on the surface when the rainfall intensity was larger.

Table 4. Physical properties of the tested materials

Maximum dry density (g/cm^3)	1.66
Optimum water content (%)	16.3
Specific gravity (g/cm^3)	2.644
Gravel content (%)	1.3
Sand content (%)	96.5
Silt and clay content (%)	2.2
Coefficient of permeability (cm/sec)	5.91×10^{-3}

Table 5. Characteristic of the short fibre reinforced soil

Maximum dry density (g/cm^3)	1.686
Optimum water content (%)	19.1
Specific gravity (g/cm^3)	2.616
Coefficient of permeability (cm/sec)	8.73×10^{-3}

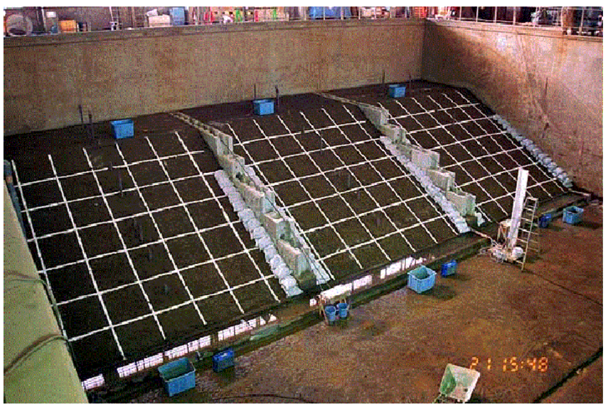
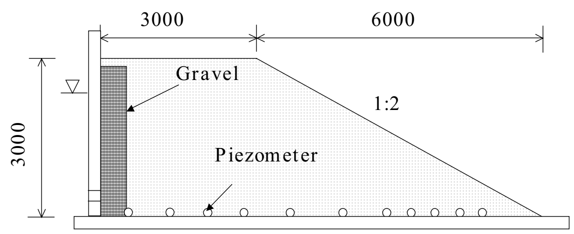
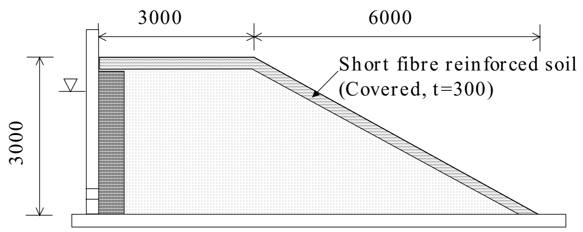


Photo 2. Overview of the models (Case 3. Case 1, Case 2 from far side)

Case 1 (No layer of short fibre reinforced soil)



Case 2 (The slope was covered with short fibre reinforced soil)



Case 3 (The slope was covered and underlain with short fibre reinforced soil)

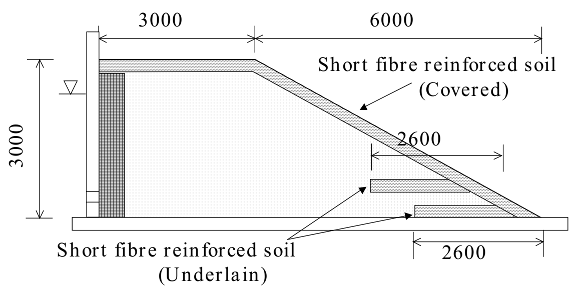


Figure 3. The outline of the model (unit: mm)

3.2 *The test result*

The experiments for three cases were simultaneously performed. The patterns of failure model test were observed as follows. The states of the model levees after the experiments are shown in Photo 3.

3.2.1 *Case 1 (No layer of short fibre reinforced soil)*

Toe of the slope started to become loose after 4 hours from the start of the rainfall. The partial failure gradually progressed from the toe to the above, until the whole slope failed after 15 hours.

3.2.2 *Case 2 (The slope was covered with short fibre reinforced soil)*

A small crack was generated at upper-middle of the slope after 15 hours. The crack was become larger and wider, and the deformation of the toe of the slope became larger in the next 2 hours. The failure was similar to circular slip. The test was ceased after 17 hours.

3.2.3 *Case 3 (The slope was covered and underlain with short fibre reinforced soil)*

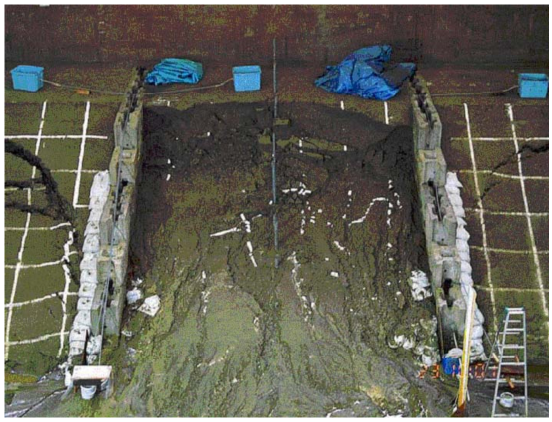
The horizontal crack of 2.2 m developed at upper part of the slope after 20 hours. The toe of the slope also swelled. (Circular slip)The crack extended to 6.6 m and deformation of the slope became distinctive in the next 1 hour.

3.3 *Discussions*

The seepage lines for each case were shown in Figure 4. The seepage line reached near the surface of the slope after 14 hours and stabilized. There was no practical difference in the seepage line's development, because the coefficient of permeability of three cases was similar, as confirmed in the previous permeability tests that the fibre content did not affect the permeability.

Rates of runoff water from the toe are plotted against elapsed time in Figure 5, also showing the similar pattern in all three cases. The overall seepage characteristics of the three model levees seemed to be similar.

The surface layer of fiber reinforced soil contributed to delay the failure of the model levee by its higher resistance against piping. In addition, in Case 3, the lower part of the slope was strengthened by the fibre reinforced soil layers, so that the slope failure was further delayed compared to Case 2. The length of the sliding surface was also larger than Case 2.



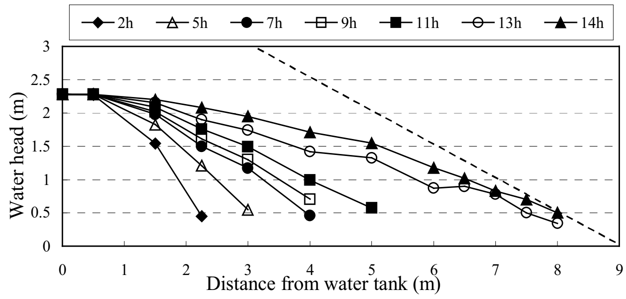
Case 1 (No layer of short fibre reinforced soil)

Case 2 (The slope was covered with short fibre reinforced soil)

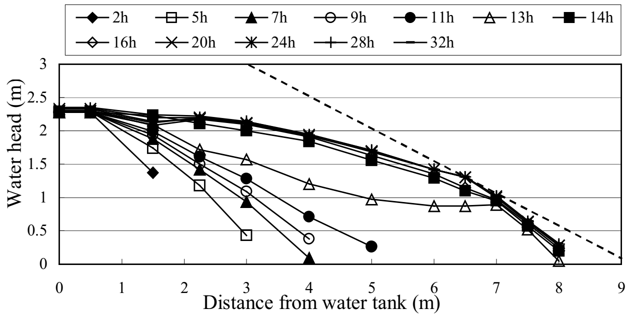
Case 3 (The slope was covered and underlain with short fibre reinforced soil)

Photo 3. After deformation

Case 1 (No layer of short fibre reinforced soil)



Case 2 (The slope was covered with short fibre reinforced soil)



Case 3 (The slope was covered and underlain with short fibre reinforced soil)

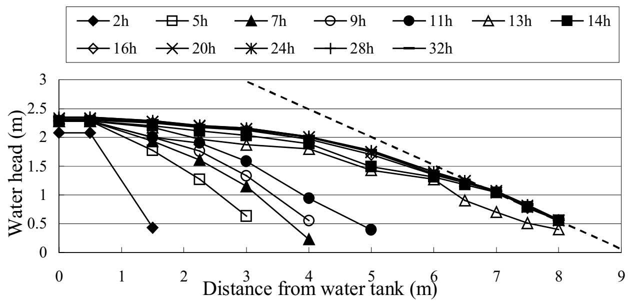


Figure 4. Development of seepage line

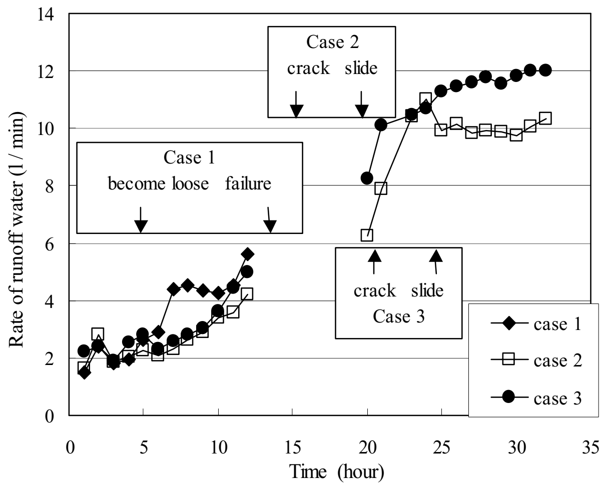


Figure 5. The volume of seepage flow

4 CONCLUSIONS

Permeability tests on short fibre reinforced soil and the large-scale model tests were conducted, and the following conclusions were obtained.

- From the permeability tests, the piping resistance of soil becomes higher by mixing short fibre. Short fibres appeared to effectively restrict soil particles movement and the resistance to the piping improved.
- From the large-scale model tests, short fibre reinforced soil layer on the slope surface increased the stability of levee against seepage of rainfall and flood. It was also effective to lay the short fibre reinforced soil layer in the levee because the sliding resistance became large.

In the future, it is necessary to establish design method of embankment strengthening countermeasure construction using short fibre reinforced soil based on the experimental result.

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