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EFFECT OF INITIAL WATER CONDITION AND MATERIAL COHESIVITY ON EMBANKMENT EROSION

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***Key Words**: Embankment, Overtopping, Initial Water Condition, Erosion*

1. INTRODUCTION

Levees or embankments are structures formed naturally or constructed artificially along a channel to protect against flooding.1) Embankments are built along the parallel direction of the water flow of the channel. The urban area needs to be protected against flood hazards by the construction of embankments to save human life and property and the feeling of safety created by the embankments further accelerates urbanization, which in turn increases the importance of protecting the embankment itself.2) As the construction of embankments requires huge construction materials, earthen embankments are generally constructed. For instance, in the United States of America, about 80% of all embankments are earthen.3) However, to decrease the chance of failure of an embankment, proper selection of an appropriate mixture of material is crucial.4)

There are several methods for embankment failure, but overtopping is considered to be the most common reason.1),5) Recent statistics show that about 34% of embankment failure occurs due to overtopping, while 30% and 28% are due to foundation defects and piping failure respectively.4),6) Although there is much research on overtopping failure, the data on this sector is still limited.1) Different researchers approached solving this overtopping related problems differently. Some constructed large-scale embankments to study the overtopping failure,7) while some utilized small models.8)–12) Among these researchers, some suggest that headcut erosion is the main reason for embankment failure during overtopping.7),10)–12)

In this research, to imitate the first overtopping, the initial water condition was applied in terms of ponding of water. The end of ponding of water of different heights was considered as the end of the first overtopping and then actual overtopping was applied, which was termed as second overtopping. The behavior of embankment is studied focusing on the second overtopping in the research. The study showed that the noncohesive material plays an important role in increasing the stability of embankments with the addition of even small initial water conditions.

2. Methodology

(1) Materials

Granitic Sand, locally known as Masado in Japan, and artificial clay, commercially known as DL clay were used in the experiments. DL Clay consisted of Particle Size below 45μm of 97.2-97.6% and bulk density of 1.03-1.04. While using Masado, particles bigger than 0.85mm were removed by sieving and only smaller particles were used.

(2) Description of the Flume and Camera Setup

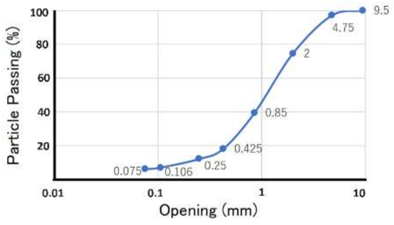


Fig.1 Grain Size Distribution Curve of Masado Sand

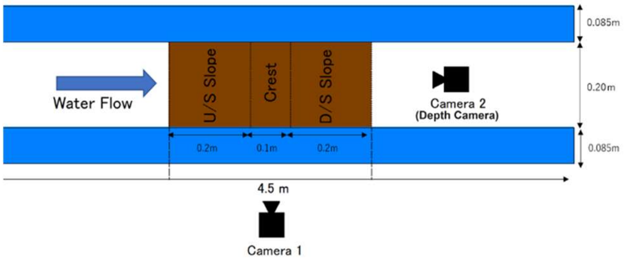


Fig.2 Top View of Flume, Embankment and Cameras

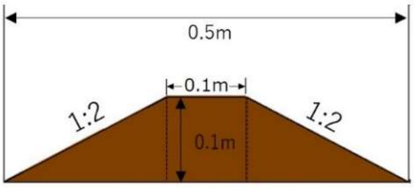


Fig.3 Cross Section of the Model Embankment

A flume with a rectangular-shaped channel was used for the hydraulic tests. The internal width of the flume was 0.2m and the internal height was 0.25m. The total length of the flume bed was 4.5m. The flume was wooden, but some portions of the side walls were made of acrylic glass so that side views of the model embankments could be observed.

Three cameras were installed. Two cameras were fixed as shown in Fig.2 and another one captured video from the top.

(3) Embankment Model Description

Small model embankments made of soil were used for the hydraulic experiments. The soil was made by mixing different ratios of granitic sand and clay. The base width of the embankment along the flow direction is 0.5m. Height is 0.1m and slope along both upstream and downstream sides is 1:2 (V: H). As the channel width of the flume is 0.2m, the width of the embankment is also 0.2m. The average height of embankments in Japan is 5m.[6)] Hence the model was created in 1/50 scale.

The embankment model was compacted in two layers with 150 blows from a 2.5kg rammer on each layer. The rammer is the same one usually used in the optimum moisture content test for geotechnical engineering. The dry density of the embankment model of group A and B soil are 1459.52kg/m^3 and 1611.87kg/m^3 respectively. The Maximum dry density of Group A and B soil are 1615kg/m^3 and 1734kg/m^3. Optimum moisture contents are 17.03% and 14.78% respectively for Group A and Group B soil. More about Group A and B soil are discussed in the later portion. The water content for the soil materials was kept at 10% while making the models.

(4) Procedure for Ponding

To make changes in the water condition of model embankments before the overtopping related experiments ponding of water was done for six hours with different heights of 2.5cm, 5cm, 7.5cm, and 10cm. In dry conditions, there was no ponding.

(5) Internal Seepage Condition and its Expression

To understand the water condition inside the embankments, seepage-related experiments were conducted. In this experiment first, ponding of water was allowed for 6 hours. Then soil samples were collected from different points of the embankment. Samples from the inner portion of the embankment were collected by cutting layers of soil using the iron-made thin tool. Then the water contents were calculated by oven-drying the samples. After that, water content values were written on the respective points, and in the end, some contour lines of the same water content were drawn.

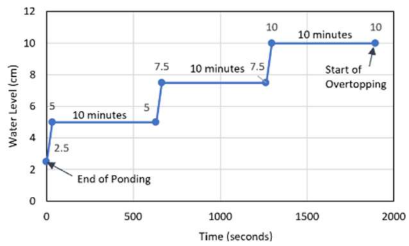
(6) Experimental Cases

18 cases of experiments were performed for overtopping related experiments as shown in Table 1. These cases were broadly divided into two categories A and B. A group represents experimental cases where the soil of the model embankment consisted of 25% granitic sand and 75% clay. Similarly, the granitic sand and the clay percentage were 50% for

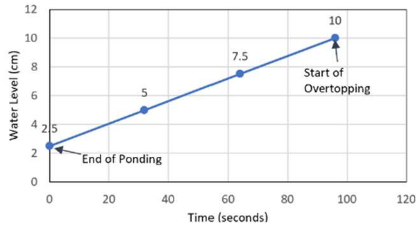
Fig.4 Ponding with 7.5cm Height of Water

Table1 Experimental Cases

Group	Granitic Sand (G) and Clay (C) Percentage	Case Name	6 Hour Ponding Height (cm)	Water Rising Speed after Ponding
A	Granitic Sand 25% and Clay 75%	10R	10	Rapid
		A7.5R	7.5	
		A5R	5	
		A2.5R	2.5	
		ADR	N/A	
		A7.5S	7.5	Slow
		A5S	5	
		A2.5S	2.5	
		ADS	N/A	
B	Granitic Sand 50% and Clay 50%	B10R	10	Rapid
		B7.5R	7.5	
		B5R	5	
		B2.5R	2.5	
		BDR	N/A	
		B7.5S	7.5	Slow
		B5S	5	
		B2.5S	2.5	
		BDS	N/A	



a) Slow Rise Category



b) Rapid Rise Category

Fig.5 Illustration of Rising of Water for Rapid and Slow Rise Category

group B cases.

The numerical term with the case name represents the ponding height. The ponding height varies from 2.5cm to 10cm. No ponding is referred to as dry condition and expressed in the alphabet D. Moreover, based on rapid or slow rise of ponding water R or S characters are added to the case name.

(7) Overtopping Related Experiment

The main experiments are overtopping related. Overtopping was allowed for one minute. The rising of ponding water was divided into two categories, Rapid rise category and Slow rise category.

a) Rapid Rise Category

In the rapid rise category, the rising of water until the crest height is done without any pause after the ponding.

b) Slow Rise Category

In the slow rise category, the rising of water is paused for 10 minutes after each 2.5cm rising of water.

Figure 5 illustrates the rapid and slow rise categories for easy understanding with an example of 2.5cm ponding depth.

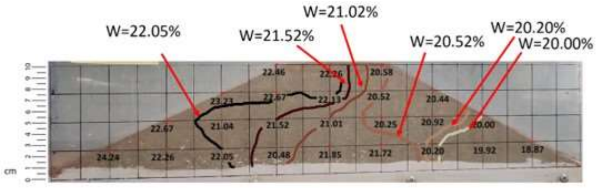
(8) Erosion Measurement

Erosions were measured using ImageJ software. Side views of the embankments after overtopping were analyzed. The erosion of embankments created emptied spaces which were measured from the side views in terms of area in cm².

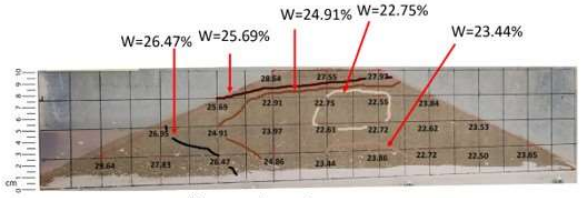
4. RESULTS AND DISCUSSIONS

(1) Internal Seepage Condition after Ponding

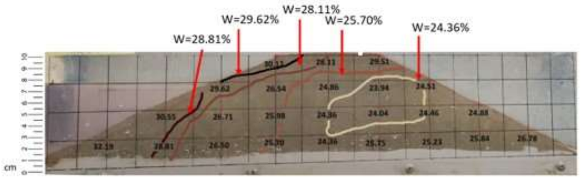
The internal seepage conditions of group A and group B soils are shown in Figures 6 and 7. From the



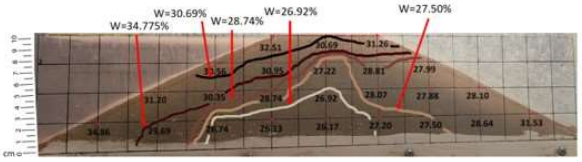
a) 2.5cm Ponding Height



b) 5cm Ponding Height

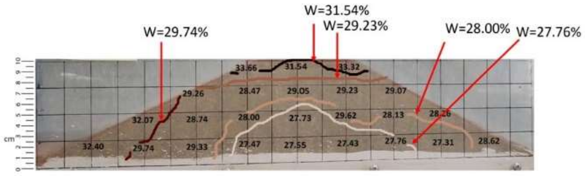


c) 7. 5cm Ponding Height

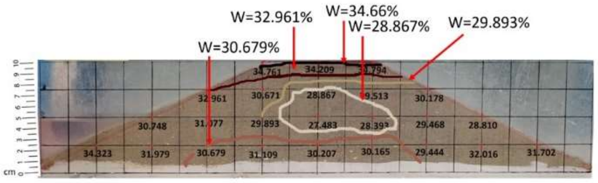


d) 10cm Ponding Height

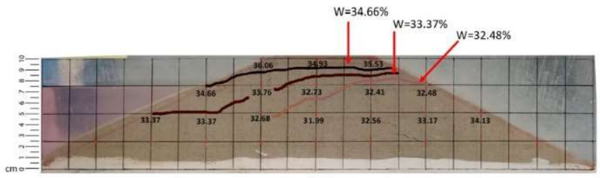
Fig.6 Internal Seepage Condition of Group A Soil



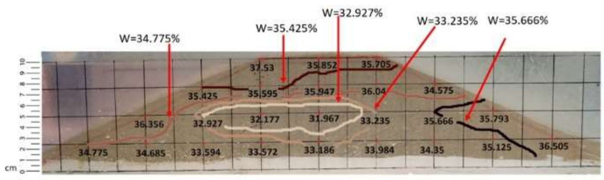
a) 2.5cm Ponding Height



b) 5cm Ponding Height



c) 7. 5cm Ponding Height



d) 10cm Ponding Height

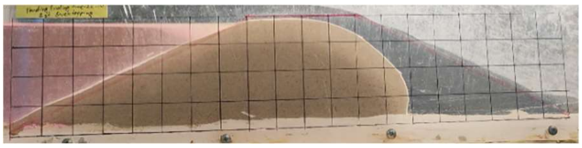
Fig.7 Internal Seepage Condition of Group B Soil

a) Case ADR

b) Case A2.5R

c) Case A5R

d) Case A7.5R



e) Case A10R

Fig.8 Final Shape of Rapid Rise Cases of Group A Soil

figures of the internal seepage condition of group A and group B soil, it is found that the water content at each point of group A soil is higher than that point of group B soil. As group A soil contains a higher amount of clay content, it can be said that, with the increased amount of clay content in the soil, it can hold more water. On the other hand, water can pass through sandy soil easily and it has lower soil holding capacity.

For group A soil, the relatively dry portion moved from the middle-bottom part of the cross-section of the embankment to the middle part as the ponding depth increased from 2.5cm to 10cm. This is maybe because when the ponding depth is smaller, the horizontal water pressure is also smaller, hence the water only traveled due to suction pressure. But when the ponding depth increases, the higher water pressure near the bottom forces some more water movement. In the case of group B soil, the relative dryer portion is right side bottom to the middle and then to the middle bottom as the ponding depth increases. The contour lines of group B soil first showed comparatively vertical when the ponding depth was 2.5cm. In this situation, the movement of water is dominated mostly by the suction force. As the influence of water pressure increases with the increase of ponding depth, the contour lines tend to become more horizontal.

a) Case ADR

b) Case A2.5R

Fig.9 Final Shape of Crests of ADR and A2.5R

(2) Final Shape of the Model Embankments

The final shapes of the model embankments after the overtopping were recorded. Figure 8 shows the final shapes of embankments of rapid rise cases of group A soil after the overtopping.

From Figure 8 it is visible that with the increase of ponding depth erosion increases. However, case A5R showed exceptionally high erosion due to the formation of the bigger gully. The 5cm ponding depth of rapid rise case of group A soil tends to form gullies as there can be seen non-uniformity of water content after ponding in the internal seepage condition. This may have led to a sudden change in the strength along the downstream slope because the volumetric water content is inversely proportional to the cohesivity of the soil.[13)] By observing the overtopping related overtopping it is found that, for embankments on fixed foundations gully formation plays an important role in breaching.

If we compare two consecutive embankments with no ponding and 2.5cm ponding; 5cm ponding and 7.5cm ponding of the same group and same water rising condition we find that in most of the cases if crest erosion decreases then the toe erosion increases. This implies, there is an inverse relationship between crest and toe erosion. The reason behind this is the tendency of water to make a channel regime while flowing through it. Larger crest erosion may bring larger stability of the crest portion which results in lower energy dissipation at the toe area. This lower energy dissipation in the toe area causes lower erosion. Let us explain this phenomenon with cases ADR and A2.5R. In Fig.9 we see that case ADR had less crest erosion than case A2.5R.

a) Case ADR

b) Case A2.5R

Fig.10 Final Shape of Toes of ADR and A2.5R

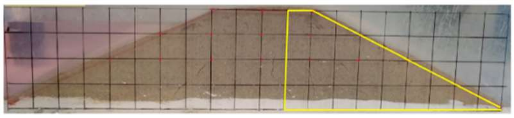


Fig.11 Area for Downstream Slope Erosion

On the other hand, by analyzing the empty grids at the bottom of the images in Fig.10 we can say that the toe erosion of ADR is greater than the A2.5R. That means when overtopping water made larger erosion at the crest level, it made greater changes in the crest profile. This crest profile change brings greater stability, which results in less erosion at the toe section. This means by modifying the shape of the downstream crest profile, there is a possibility to make overtopping water exert less impact on the downstream toe of an embankment.

(3) Downstream Slope Erosion

The erosion of the downstream slope was measured using ImageJ software by measuring the eroded area inside the area outlined by the yellow line in Figure 11.

The downstream slope erosion measurement led to the two graphs of Fig. 12 and 13. Fig. 12 represents the downstream slope erosion of Group A soil. In the graph, rapid rise cases show a gradual rise in erosion. On the contrary, the slow rise cases show less erosion while there was no ponding but, the erosion suddenly rose rapidly at 2.5cm ponding. Again, there is a large difference in erosion for dry cases of rapid and slow rise of Group A soil. The reason behind this may lie in the optimum moisture content of group A soil. The optimum moisture content of group A soil is about 17%, whereas in the experiments the moisture contents were kept at 10%. This big difference in water content at the beginning of the experiment and the optimum moisture content may have given the Group A soil in dry conditions and under slow rise conditions plenty of room before exceeding the water content of the value of optimum moisture content. The downstream slope erosion graph of slow rise cases of Group B soil from Fig. 13 shows a different picture. The erosion rapidly lowered from the dry condition to 2.5cm ponding and then from the 2.5cm ponding height it gradually increased with the increase of ponding height.

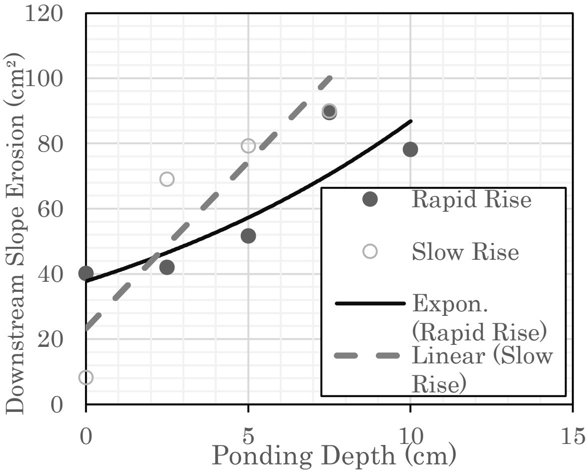


Fig.12 Downstream Slope Erosion of Group A soil

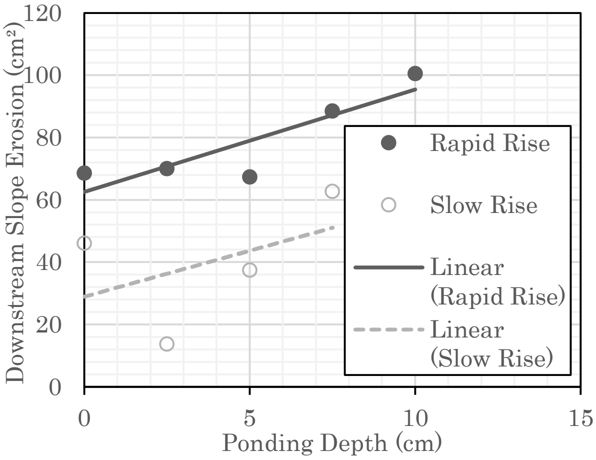


Fig.13 Downstream Slope Erosion of Group B soil

Comparing the dry conditions of the experiments we see that erosion was lowest for the slow rise of Group A soil. Whereas, the dry condition of the rapid rise of Group A soil also shows comparatively less erosion. Group A soil comprises of larger clay content in other words Group A soil has higher cohesivity. This means cohesive soils perform better when there is no initial water condition. The erosion gradually increased for the rapid rise cases of Group A soil with the increase of ponding height whereas, the rapid rise of erosion from dry condition to the 2.5cm ponding of Group A soil explains that the cohesive force of soil is weak against the presence of water. On the contrary, the sudden reduction in the erosion from the dry condition to the 2.5cm ponding of Group B soil implies that less cohesive soils are stronger against the initial water content as the

Group B soil contains a higher percentage of sand. This is because less cohesivity means the particles of the soil possess a higher ability of free movement. Water during the ponding acts as a lubricating material for the soil particles, which allows self-compaction by weight and more stability of the embankments with higher sand content.

From the discussions above it can be said that, for dry conditions, Group A soil performs better. With initial water conditions or ponding depths, Group B soil performs better when the water rising speed is slow. Comparing the rapid rise cases, Group A showed less erosion whereas, Group B showed less erosion in the slow rise cases. Ponding of water causes a mixed impact on the erosion of the embankments. Group A soil performs better with ponding of water in rapid rise cases while Group B soil performs better in slow rise cases with ponding depths.

The above information can be used in the design of embankments in the real field. The dry condition of the embankments can be the situation when there is no flow of water for a long time or when the freeboard of the embankment is much larger than the depth of water flow. In those cases, clayey or cohesive soil should be selected as the embankment materials. When there are some depths of water flow along the upstream of the embankment and if the record suggests the rising of water during flooding is rapid then again soil with a higher clay percentage should be selected. Again, when there are some ponding and the record shows the usual rising of water during flooding is slow then the choice of embankment material should be sandy or soil with less cohesivity.

5. Conclusions

It is normal practice to find a higher clay percentage for the embankment materials. Also, in our experiments, the cases with no ponding or internal water condition performed better by showing less erosion when the soil material had higher clay content. However, the situation changes with the addition of some initial water conditions. With initial water conditions, sandy soil performed better by showing less erosion when the water rising speed was slow. The experiments have two limitations. One is that as only two kinds of soil materials were tested, the optimum sand and clay content for the strongest embankment cannot be found. More experiments with more varieties of ratios of sand and clay materials are needed to find the optimum ratio. Another one is that as the experiments were done in a controlled environment using flume, the material behavior may differ in the real field. In the real field, the small particles of sandy soil may change to larger rocks to exert the same non-cohesive effects found in the laboratory. Again, it was found that changes in crest shape at the downstream side cause less erosion on the downstream toe section. Hence, more studies with different downstream crest profiles can be performed to find the best downstream crest shape with a less breaching effect on the downstream toe section.

The purpose of the experiments was to study embankments after a second overtopping. However as initial water condition and seepage conditions are similar, this study can also be used to understand the seepage mechanism of embankments.

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