# INFLUENCE OF SATURATION CONDITION AND GRAIN-SIZE DISTRIBUTION ON EMBANKMENT EROSION DURING REPEATED OVERTOPPING

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## 1. INTRODUCTION

Bangladesh frequently experiences multiple flood events within a single monsoon season. Many other regions of the world are also experiencing increasingly frequent flood events due to climate change.[1),2)] Consequently, embankments that have already experienced one overtopping event may be subjected to another overtopping before repair or reconstruction. In addition, emergency repair or reconstruction of damaged embankments cannot always be completed before the next flood because of financial and logistical constraints. Therefore, assessing embankment vulnerability under repeated overtopping has become increasingly important.

In Japan, following the severe flood and embankment failures caused by Typhoon Hagibis (2019), increasing attention has been given to resilient river embankments.[3),4)] Previous studies have investigated embankment erosion from various perspectives. Lee et al. (2026) investigated the failure mechanism of covered embankments after overtopping. However, as the construction of covered embankments requires a large quantity of construction materials, this research will focus on earthen embankments as it is a cost-effective solution. Tanaka (2025) stated that nappe flow has a strong impact on scour development.[5)] Nappe flow occurs when free-falling overtopping flow gets separated from the embankment slope. Similarly, Hanson et al. (2005), Zhu et al. (2007), and Zhao et al. (2019), found that headcut erosion is a significant phenomenon for the breaching of cohesive soil.[6)–8)] Although Nappe flow and headcut erosion are not the same phenomena, they are closely related.

Despite these advances, several important limitations remain. First, previous studies generally considered only a single saturation condition, although the saturation state of an embankment before overtopping depends on various field conditions, and only one saturation condition cannot represent the actual field condition. Second, previous studies investigated only a single overtopping event, even though repeated overtopping is becoming increasingly important. Finally, previous studies mainly evaluated erosion of the original embankment geometry and did not consider the embankment shape changes caused by the first overtopping.

To address these limitations, Arzu et al. (2024) investigated the influence of saturation conditions and material cohesivity on embankment erosion during a single overtopping.[9)] The study showed that erosion behavior is governed not only by soil cohesivity but also by internal water conditions. Subsequently, Arzu et al. (2026) investigated embankment erosion after two overtoppings and changes in embankment geometry, and showed that the hydraulic conditions before and after the first overtopping significantly influence erosion during the second overtopping.[10)] However, the experiments were conducted using only one embankment material. In addition, only the depth of the first ponding condition was varied, while the influence of ponding duration remained unclear.

Therefore, the present study introduced additional

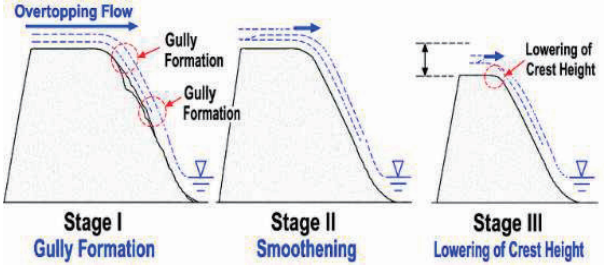



**Fig. 1** Stages of Breach of Embankments

experiments using a comparatively well-graded material with larger particle size and reduced first ponding duration to investigate the effects of grain-size distribution and antecedent saturation on embankment vulnerability. The objective of this study is to clarify the factors governing the vulnerability of the embankments during repeated overtopping and to propose a practical guideline for the assessment of vulnerability.

Based on preliminary experiments, embankment breaching was classified into three stages, as shown in Fig. 1. In the first stage, some gullies develop on the downstream slope, then the downstream slope becomes smoothened, and finally, crest erosion starts until the complete failure of the embankment. This observation also supports the works of Hanson et al. (2005) and Li et al. (2021).[11] The smoothening stage was considered for the end of the first overtopping to modify the embankment geometry, to represent more realistic field conditions.

## 2. METHODOLOGY

### (1) Materials

Two kinds of materials were used in the experiments, referred to as soil A and soil B. The two materials consisted of a mixture of granitic sand, known in Japan as Masado, and clay, known as DL clay. For soil A, 50% granitic sand passing through the 0.85 mm sieve and 50% clay were mixed. For soil B, 40% granitic sand passing through the 0.85 mm sieve, 20% granitic sand having particle size 0.85 mm to 0.425 mm and 40% clay were mixed. The DL clay consists of 97.2-97.6% particles finer than 45 μm, and the bulk density was 1.03 to 1.04.

### (2) Flume and Model Description

The wooden flume for experiments had an internal width of 0.30 m, an internal height of 0.25 m, and a bed length of 4.5 m. Discharge was about 940 $cm^3/s$.

As shown in Fig. 2, small-scale embankment models had a base length of 0.50 m in the flow direction, a height of 0.10 m, and side slopes of 1:2 (V: H) on both the upstream and downstream faces. Compactions were done in two layers and 150 blows in each layer using a 2.5 kg rammer. As the average height of embankments in Japan is approximately 5 m, the model embankment is one-fiftieth in geometric scale.[12] Two cameras, one from the side and another from the top, were installed to keep records of experiments.

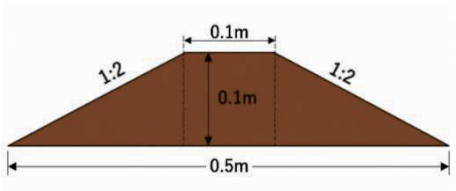


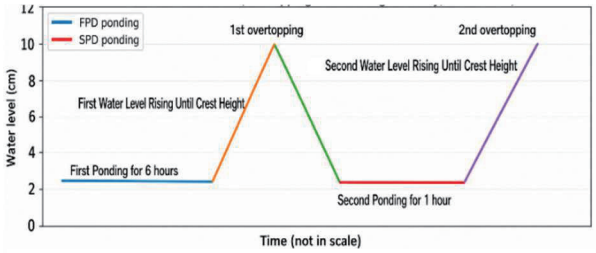

**Fig. 2** Cross-section of Model Embankment

### (3) Ponding and Water Level Rise Conditions

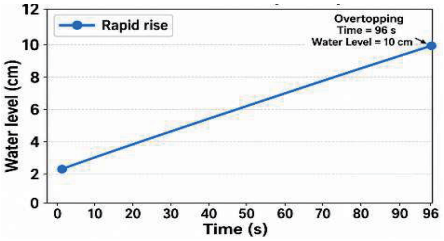
As discussed earlier, to provide internal water conditions or seepage conditions as in a real field, ponding of water for some time and changing water rising speed before overtopping were performed. Ponding of water before the first overtopping is termed as First Ponding Depth (FPD), and before the second overtopping is termed as Second Ponding Depth (SPD). For most of the cases, FPD was for 6 hours. However, for cases starting with FPD3, the duration for FPD was 3 hours. SPD was 1 hour for all the cases.

Two water-level rising conditions were designed, one called Rapid Rise (R) and another called Slow Rise (S). These rapid and slow rise conditions allow for comparing the effect of inflow hydrographs on breaching. Water level recession was controlled through a drainage pipe and maintained at the same rate.

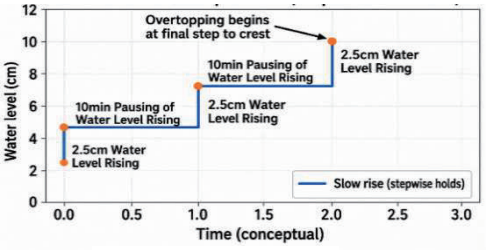
The graphical representation of FPD, SPD, rapid, and slow rise conditions is explained in Fig. 3. In the figure, before the first overtopping, an FPD of 2.5 cm




a) Graphical Representation of FPD and SPD; First and Second Water Level Rise (not to scale)




b) Rapid Rise




c) Slow Rise

**Fig. 3** Ponding, water level rise, and successive overtopping

was conducted. The duration was 6 hours or 3 hours, depending on the case. The first rise of the water was done until the crest height, following a rapid or slow rise condition. The first overtopping was done until the smoothening stage. Then the water level was reduced to the desired level, here 2.5 cm. SPD was done for one hour. Then the water level was increased until the crest height, depending on the water level rising condition. Then, overtopping was done for one minute. After that, erosion and other characteristics were observed from video analysis and ImageJ software.

**(4) Experimental Cases**

Experimental cases were classified according to hydraulic conditions and overtopping hydrographs. Four principal saturation categories, m-R, m-S, f-R, and f-S, were established using the first ponding depth (FPD) and the first water-level rise pattern, where *m* and *f* denote moderate and full hydraulic conditions, respectively. The third and fourth terms in the case notation indicate the second rise pattern and SPD, respectively; for example, *m-R-R-2.5* denotes a moderate saturation case with rapid first and second rises and an SPD of 2.5 cm. Similarly, cases with first ponding duration of 3 hours were also performed. A total of 35 experimental cases were performed with the combinations of experimental parameters summarized in Table 1.

## 3. RESULTS AND DISCUSSIONS

The erosion of embankments was calculated by analyzing the side views. As the embankment width was always the same and equal to the flume width, which is 0.25 m, the erosion is expressed in terms of $cm^2$.

**(1) Effects of Saturation**

From Fig. 4, it is clearly visible that the highest erosion occurs for experiments with A material, followed by cases with B material, and the lowest for cases of FPD3. The main difference between FPD3 cases and other cases is the degree of saturation. For FPD3 cases, FPD was 3 hours, whereas all other cases had FPD for 6 hours. This change in FPD made the embankment significantly less saturated for FPD3 cases compared with other cases. This means that in real field conditions, embankments become very weak or vulnerable after the second overtopping if the embankment material is highly saturated after the first overtopping. This can happen after prolonged rainfall events, when a higher water level is retained for a longer period before the first overtopping and when the water level rises to the crest level gradually. On the other hand, we can expect embankments to be stronger against overtopping and retain much of their strength after the second overtopping when there was little or no rainfall, the water level before the first overtopping was very low for a long time, and when the water level rose very fast so that most of the embankment material did not get a chance to be saturated. This opposite relation between saturation and embankment strength supports the findings of Matsushi et al (2006), which states that soil strength is inversely proportional to the volumetric water content of soil.[13)]

**(2) Effect of Particle Size**

Fig. 5 and Fig. 6 compare the total erosion and crest erosion between soil A and soil B under the identical hydraulic loading conditions. Here, total erosion refers to the loss of embankment volume between the first and second overtopping events, whereas crest erosion refers to the vertical lowering of the embankment crest after the second overtopping. The percentages shown in the figures represent the

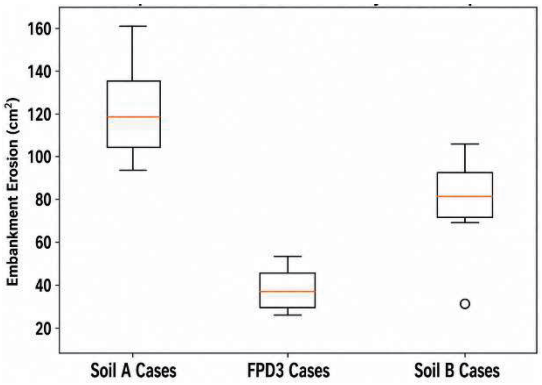



**Fig. 4** Boxplot for Embankment Erosion vs Experiment Groups

**Table 1** Parameters for Experimental Cases

| Saturation Category | First Ponding Duration (h) | FPD (cm) | First Rise | SPD (cm) | Second Rise | Material |
|---|---|---|---|---|---|---|
| m-R | 6 | 2.5 | Rapid | 0, 2.5, 7.5 | Rapid / Slow | A, B |
| m-S | 6 | 2.5 | Slow | 0, 2.5, 7.5 | Rapid / Slow | A, B |
| f-R | 6 | 7.5 | Rapid | 0, 2.5, 7.5 | Rapid / Slow | A, B |
| f-S | 6 | 7.5 | Slow | 0, 2.5, 7.5 | Rapid / Slow | A, B |
| m-R (FPD3) | 3 | 2.5 | Rapid | 2.5 | Rapid / Slow | A |
| m-S (FPD3) | 3 | 2.5 | Slow | 7.5 | Rapid | A |
| f-R (FPD3) | 3 | 7.5 | Rapid | 7.5 | Slow | A |
| f-S (FPD3) | 3 | 7.5 | Slow | 0, 7.5 | Rapid / Slow | A |

relative reduction in erosion obtained by replacing soil A with soil B for the corresponding case, using the erosion of soil A as the reference value. In other words, each soil B case is compared with its corresponding soil A case subjected to the same hydraulic conditions. The graphs show a reduction in both the material erosion and crest erosion from A material cases to B material cases. Also, it can be seen from both graphs that embankment and crest erosion decrease with the increase in the saturation of embankments. The percentage reductions were too high with lower FPD and first rapid rise conditions, and the reduction percentage decreased significantly with the higher FPD and first slow rise conditions.

Two mechanisms may explain the reasons for the reductions from A material cases to B material cases. One is that the inclusion of 20% granitic sand of 0.85 mm to 0.425 mm allowed particles to fill the void and made it more compact and denser, making the embankment stronger.

Another reason is the increase in particle size from A material to B material. The mean particle diameter $D_{50}$ of A material is 0.085 mm. With the addition of granitic sand of particle size between 0.85 mm and 0.425 mm, the $D_{50}$ increased to 0.234 mm in B material, which is about 2.75 times larger than that of A material. For non-cohesive materials, Shields' equation states that the critical shear stress of sediment is proportional to $D_{50}$. Although there is no direct equation to say critical shear stress is proportional to $D_{50}$ for cohesive soil, as many other factors like cohesion, clay bonding, etc., control erosion, a similar kind of trend of proportional relationship between critical shear stress and $D_{50}$ can be observed.[14] The higher value of critical shear stress means that flowing water requires more force to cause the movement of soil particles, and causes less erosion.

Hence, about 30-80% erosion of embankments can be reduced by the inclusion of larger particles in embankment materials depending on the saturation condition. However, excessive addition of larger particles may create voids after interlocking the previous voids, so the optimum quantity of addition of larger particles should be measured. Again, with the increase in the saturation of embankments, the erosion reduction percentages decrease. The reason may be that with the increase in saturation, the pore water pressure increases. Increased pore water pressure decreases the effective stress acting between soil particles and diminishes the effect of particle interlocking. Hence, the addition of larger particles works better in dry conditions. For wet conditions, when embankments become more saturated, the predictions of reduction of erosion by adding soil of larger soil particles to the existing one should be limited to around 30%.

### (3) Effect of First Ponding Depth

By analyzing the erosion behavior of two materials of the same higher FPD and a group of cases with smaller FPD of 3 hours, it is observed that the first ponding depth has a significant impact on the degree

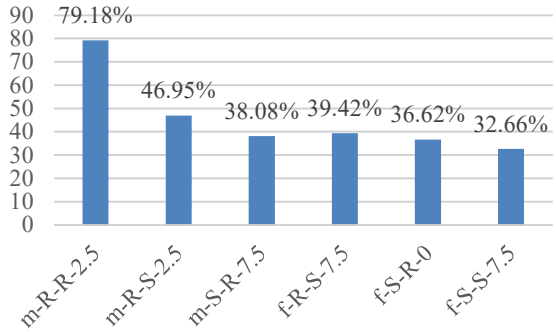



**Fig. 5** Percentage Reduction in Embankment Erosion from soil A to soil B




**Fig. 6** Percentage Reduction in Crest Erosion from soil A to soil B

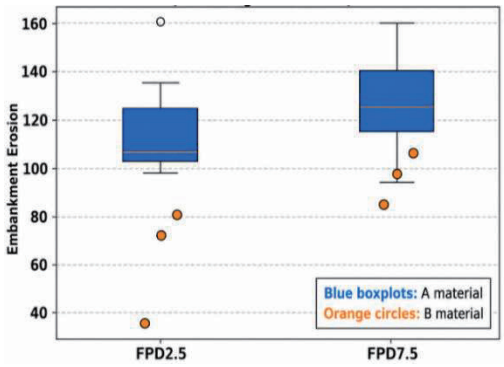



**Fig.7** Erosion vs FPD of Embankments of A and B Materials

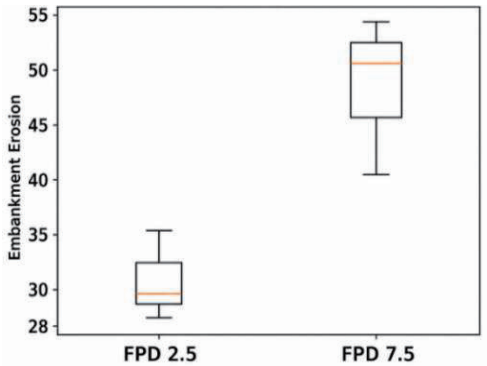



**Fig. 8** Erosion vs FPD of Embankments of FPD 3 Hours

of erosion after the second overtopping. Fig. 7 shows the increasing trend of erosion for experimental cases of both A and B materials with the increase of FPD. Fig. 8 shows the boxplots of the variation of erosion of experimental cases of FPD 3 hours with respect to two different first ponding depths. For all the groups of cases, the erosion increased with the increase of the first ponding depth. This means the first ponding depth controls the erosion patterns after the second overtopping. This is because the first overtopping largely controls the saturation of the upper part of the embankment and the pore water pressure distribution along the upper surface. Undulation created by the first overtopping may cause a concentration of water flow, which further triggers erosion. Experimental cases with material B and FPD 3 hours show a more visible increasing trend of erosion with the increase of FPD. This is because material A shows higher erosion even in low FPD, so it had little room for the sharp increase. In contrast, soil B shows smaller erosion when FPD is low. This is because the addition of larger particles promotes proper interlocking of materials and reduces voids. This makes soil B stronger against lower FPD. However, it loses much of its strength with the increase of water ponding depth. This is because as the FPD increases, water penetrates inside the soil material and causes a significant reduction of matric suction and cohesive strength. The good gradation of materials makes embankments stronger in dry conditions, but erosion suddenly increases with the increase of saturation conditions.

### (4) Presence of Inverse Slope

Fig. 9 shows the graph of the number of times the inverse slope was present after the second overtopping in different FPD and water rising conditions. Inverse slopes are unstable slopes as shown in Fig. 10. The higher occurrence of inverse slope formation under the FPD 2.5R condition suggests that nonuniform saturation conditions strongly influenced erosion localization within the embankment. Rapid overtopping after relatively shallow antecedent ponding may have caused weakening near the lower part of the downstream region, while the upper portion temporarily retained higher shear resistance. This finding implies that the evolution path of internal saturation, rather than saturation magnitude alone, may significantly affect overtopping erosion morphology and localized instability development. From a field perspective, the FPD 2.5R condition may represent rapid river-stage rise after partial antecedent wetting. The frequent inverse-slope formation observed under this condition suggests that the first overtopping can create localized lower-slope instability, which may act as a precursor to more severe erosion during a subsequent overtopping event.

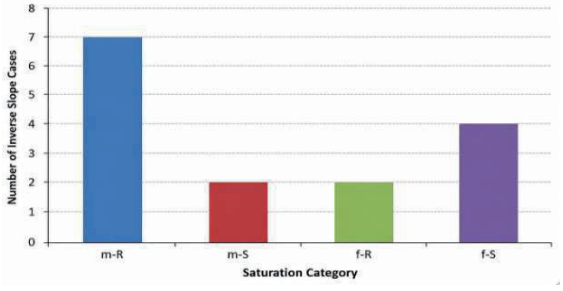



**Fig. 9** Inverse slope occurrence under different FPD and rising conditions

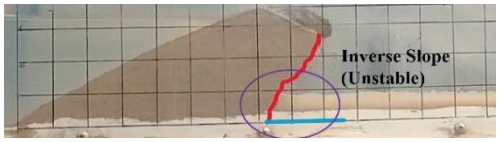



**Fig. 10** Inverse Slope

### (5) Guideline for Assessing Vulnerability

Based on the research, a guideline for assessing the vulnerability of embankments after the second overtopping based on the information after the first overtopping is prepared and shown in Fig. 11. The guideline is an engineering assessment tool based on laboratory observations and should be validated under actual field conditions.

The chart shows that the vulnerability of embankments increases with the increase of saturation. For poorly graded soil, with the increase of saturation, not only the erosion but also the

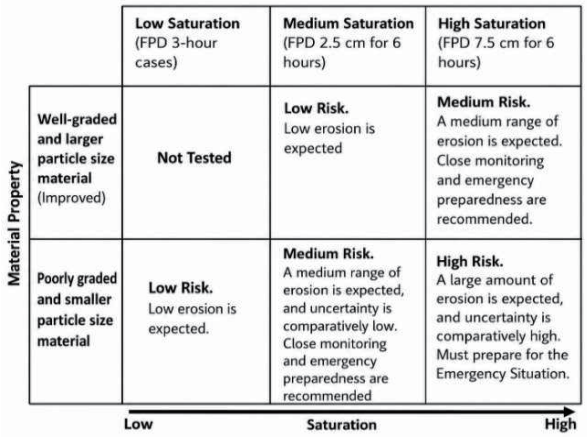



**Fig. 11** Guideline for Assessing Vulnerability after Second Overtopping

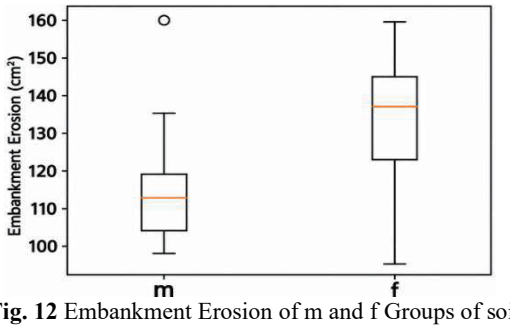



**Fig. 12** Embankment Erosion of m and f Groups of soil A

uncertainty of erosion increases, as shown in Fig. 12. In the figure, m and f groups represent 2.5 cm and 7.5 cm ponding. The range of the box plot of the f group is too long, indicating the uncertainty of the breaching. Embankments made of well-graded material perform better than those of poorly-graded soil. Well-graded material was not tested for low saturation conditions; hence, no comment was made.

## 4. CONCLUSION

This research progressively investigated the mechanism of repeated overtopping events of embankments. During the initial stages of the previous research, the influence of initial water condition and cohesivity of materials was tested by applying different water conditions but with one actual overtopping event. The study found that both cohesivity and internal water condition of embankments determine the erosion.

The following research with actual first and second overtopping events found that hydraulic conditions have a significant impact on the breaching process. Especially the hydraulic conditions just after overtopping are very important, and they have strong practical value in early warning for emergencies. The present research made it possible to predict the vulnerability of embankments during the second overtopping by assessing the hydraulic and material conditions after the first overtopping.

The research also indicates that the addition of larger and properly interlocked materials to embankments makes them perform better after the second overtopping in terms of both embankment erosion and crest erosion. However, this improved resilience of embankments decreases with the increase in saturation. Additional experiments with shorter first ponding depth further confirmed the importance of lower saturation of embankment materials.

In summary, saturation of embankment materials from different hydraulic conditions is the main factor controlling the degree of erosion after second overtopping. Although improved soil gradation enhances embankment resilience, decreasing saturation of embankment materials through the methods of relief wells or drainage systems may improve embankment resilience most. Future research can be directed towards the investigation of optimum grain-size distribution and comparison of laboratory and field saturation conditions.

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