Experimental Investigation on the Overflow Protection of Earthen embankment through vegetation

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Abstract— Bank erosion is the worst calamities that adversely affect the economy by reducing agricultural land, houses etc. Bangladesh with its repeated cycles of flood, cyclones and storm surges has proved one of the most disaster-prone areas of the world where river bank, coastal erosion and embankment failure happen continuously. Resistance of vegetation may have a considerable effect in controlling flow velocity that makes overtopping erosion. Now-a-days vetiver grass is well-known as bioengineering and establishment of this technique to rigid or hard structures accepted all over the world for riverbank stabilization and embankment erosion control due to its low cost and longevity. Therefore, to minimize the impact of natural disasters and to achieve the aim of agricultural production, sustainable and cost-effective maintenance of those embankments is prerequisite for Bangladesh. In this study, it was aimed to investigate the effects of different vegetation density for controlling flow velocity during overtopping flow and their related hydraulic characteristics. Experimental results revealed that vegetation markedly reduced the overtopping and sloping velocity and also revealed no supercritical flow condition both on the d/s slope and bed of embankment model which is the main influencing factor for causing overtopping erosion.

Index Term— Earthen embankment, vetiver grass, overtopping flow, vegetation, erosion.

I. INTRODUCTION

In a number of tropical countries Vetiver grass (Vetiveria zizanioides) is well-known as bioengineering. Recently, Vetiver grass has been planted on downstream slope as sea dike or river embankment protection. The sustainable development of river management is paid more and more attention at present all over the world. Bangladesh is so much vulnerable and one of the most disaster-prone areas of the world in this respect. River bank and coastal erosion, and embankment failures happen continuously throughout Bangladesh. The State budget for such works is never sufficient which confines rigid structural protection measures to the most acute sections, never to the full length of the river bank or coastline and embankment. Hard engineering structure makes the scenic environment unpleasant and helps only to transfer the problem to another place, to the opposite site or downstream, which aggravates the problem rather than reducing (Grimshaw, 2008).

Scientists on river management and restoration claim that the river not only includes nonliving substances (flow, sediment) but also organism, so the vegetation in the watercourse should be included in the river dynamic system, at the same time, the vegetation will cause flow resistance, rise of water level and reduction of discharge capacity (Wu, 2008). Powledge et al. (1989a) observed that the initial erosion process begins anywhere within the supercritical flow region i.e. from d/s slope and toe of the embankment. A large number of sea dikes or river embankments failure have been initiated from damages induced by wave or flow overtopping (Islam, 2000). To minimize the impact of natural disasters as well as to achieve the aim of agricultural production, sustainable and cost-effective maintenance of those embankments is a sine qua non for Bangladesh. For earth coastal dikes or river embankments, overtopping is one of the most damaging factors for the downstream slope. Eventually a failure of the downstream slope may lead a failure of the dike. Water infiltrates into dike crest, downstream slope and reduces the shear resistance of the soil (Hanson et al., 2001).

Vegetation planted in the downstream slope may have a considerable effect in reducing overtopping erosion. Vegetative barriers increase the surface roughness and slow the flow rate. It dissipates energy and protects the slope from erosion. Recently, Vetiver grass has been planted on downstream slope as sea dike or river embankment protection. However the understanding of the processes and properties between waves and Vetiver grasses are still limited. More insight on affection of Vetiver grass to reduce overtopping velocity will be carried out. However, the understanding of the processes and properties between flows and Vetiver grasses and the flow characteristics of d/s slope of sea dikes or river embankments covered with grass during overflow are still limited. Therefore, the emphasis of this study is to investigate the flow resistance in open channel with vegetation cover and their related hydraulic characteristics.

II. MATERIALS AND METHODS

A. Material Setup in Experimental Flume

A small scale physical model tests is carried out to investigate the effects of vegetation (commercially available vegetation model with 5% and 20% blocking) on the characteristics of flow, in a water re-circulating flume of
hydraulic and environmental engineering laboratory at Saitama University, Japan. Laboratory experiment is performed with three different densities of vegetal cover considering different discharges on the d/s slope. Three different phases of vegetal covers are, (a) row type or 2D vegetation case, maintaining ratios of 0.25 (5cm spacing case) and 0.75 (15cm spacing case) respectively (where, ratio= width of spacing within vegetation rows over width of vegetation rows, here 5cm and 15 cm spacing and 20 cm fixed vegetation width is used), (b) all over vegetation case i.e. both vegetation on slope and bed and finally all results are compared with no or WOV case. A model of wooden embankment was constructed and placed at the middle of the flume which separated the flume along its length, forming main stream on one side (called upstream) and the floodplain on the other side (called downstream). The size of embankment is 0.25 m in height, 0.25 m in crest width and 1.5 m in length, with slopes 3H:1V and 2H:1V in the upstream and downstream sides, respectively as shown in fig. 1.

(a)

(b)

Fig. 1. Profile of testing facility (a) front view and (b) top view

The steady flow with three different unit discharges as 0.018, 0.013 and 0.010 m$^3$/s (later we called it discharge 1, discharge 2 and discharge 3) was taken in our experiments. The longitudinal flow velocities and water depths were measured along the centre line of the flume at 26 points with an interval of 0.10 m up to upstream (u/s) crest of the model and later 0.05 m interval from u/s crest to the d/s end of the flume until steady flow condition was established. A scale factor (ratio of a variable in the model to the corresponding variable of its prototype) 0.0625 was kept constant throughout the tests. In the tests the velocities and the water depths were measured for situations with and without vegetation in the flume. The height of the vegetation model was kept constant, 0.05 m and width and length was kept same as the d/s side of the embankment model considering emergent flow conditions.

B. Data Collection

The discharges were measured with an electromagnetic flow meter (model: MK -515/ 8510 -XX, paddle flow sensor, Georg Fischer Signet LLC, USA). An electromagnetic velocity meter (type of main amplifier: VM-2000; type of sensor: VMT2–200 -04P, Kenek Company, Ltd.) was used to measure the flow velocities at the centreline of the channel and the model. The water surface elevation was measured at the same locations as the velocity profiles by the point gauges (with accuracy up to 0.1 mm), fixed and mounted on a movable sliding carriage.

(a)

(b)

(c)

Fig. 2. Experimental setup top view- (a) embankment model in the flume, (b) electromagnetic velocity meter with sensor setup for measuring flow velocity and (c) setup for measuring water surface elevation by point gauge placed on the d/s slope and bed in the flume.
III. RESULTS ANALYSIS AND DISCUSSION

The resistance to flow is a strong function of the flow parameters with vegetation (Baptist et al, 2007). The flow parameters i.e. overtopping depth, overtopping velocity, Froude number (Fr), Reynolds number (Re) etc. are measured with three different discharges as mentioned in the earlier section. The threshold values of overtopping height, velocity and discharges checked by Froude law of similitude between model and prototype for comparison and the results found within the permissible limit based on the previous researches and case studies (Powledge et al., 1989a&b, Nadal and Hughes, 2009).

The analysis of hydraulic characteristics of overtopping flow in without vegetation condition shows that the flow was static at the beginning upstream, accelerating sub-critical flow state over a portion of the embankment crest; through critical flow on the crest and supercritical flow over the remainder of the crest; and supercritical flow on the downstream slope and extend to the further downward (Fig. 3a) same as observed in the previous study (Powledge et al., 1989b).

On the other hand, the hydraulic characteristics of overtopping flow in W V condition shows the flow was static at the beginning of upstream, accelerating sub-critical flow state over a portion of the embankment crest; through critical flow on the crest and supercritical flow over the downstream slope and extend to the further downward (Fig. 3b). The flow was turbulence in nature for both of the cases but it was more than 2 times higher in case of vegetative model than without vegetation due to combined effect of steep slope and dense vegetation cover. Vegetation may protect the embankment in many ways but most important one is the reduction of velocity of water at the soil surface below the value that required causing erosion.

Fig. 4 shows that the percentage variations of overtopping velocity due to back water affect by vegetation blocking. Average overtopping velocity reduction found significantly high (50%) by increasing water depth (1.5 times of WOV) in case of 80% porosity (20% blocking) due to blocking and resistance by vegetation. The reduction of overtopping velocity for row type or 2D vegetation in case of 5cm spacing vegetation also high. Whereas the overtopping velocity reduction and increment of water depth was very little for both row type 2D (15cm spacing or 0.75 ratios) and all over vegetation effect in case of sparse vegetative density. However, the maximum reduction of overtopping velocity is found due to all over vegetation effect with 20% blocking and resistance by vegetation.

Fig. 5. Comparison of d/s sloping velocity in between different row type or 2D vegetation and all over veg. effect with no or WOV case.
The above fig. 5 represents the percentage reduction of averaged velocity with the increment of water depth along the embankment slope with different discharges due to row type or 2D and all over vegetation effect in comparison with the case WOV. The reduction of sloping velocity is almost same for either row type or 2D vegetation with 5cm spacing (0.25 ratio) and all over vegetation effect with 5% blocking case. Vegetation cover markedly reduced the averaged sloping velocity of water, 65% by increasing water depth 4 times compared with the case WOV in case of 80% porosity (that is for 20% blocking) due to resistance by vegetation.

Overtopping of earthen embankment produce fast, turbulent flow velocities on d/s side slope and initial erosion may occur within the supercritical flow region especially at a point of slope discontinuity i.e. d/s crest or at the toe of the d/s embankment. Froude no. (Fr) varies from 2.32 to 4.66 on the d/s slope and 3.96 to 5.36 on the d/s bed in case of no or WOV case. The Fig. 7 shows that supercritical flow occurs on d/s slope for 15cm spacing row (0.75 ratio) vegetation due to high flow velocity within the sparse spaces, however flow was sub-critical throughout the d/s slope and bed due to 5cm spacing (0.25 ratio) by controlling flow with dense vegetation. On the other hand, the following figure 8 shows that sub-critical flow occurs both on d/s slope and bed with all over vegetation for both 5% and 20% blocking, however velocity reduction was much higher for 20% blocking in comparison to all cases.

Here in Fig. 6 shows the percentage variation of bed velocity with different discharges due to row type or 2D and all over vegetation effect in comparison with the case WOV. The reduction trend is almost same as for sloping velocity. Whereas, the reduction of the averaged bed velocity of water is 78% by increasing back water effect 6 times compared with the case WOV in case of 80% porosity (that is for 20% blocking) due to resistance by vegetation.

The percentage variation of d/s bed velocity in between different row type or 2D vegetation and all over veg. effect with no or WOV case.

Fig. 6. Comparison of d/s bed velocity in between different row type or 2D vegetation and all over veg. effect with no or WOV case.

The reduction of the averaged bed velocity of water is 78% by increasing back water effect 6 times compared with the case WOV in case of 80% porosity (that is for 20% blocking) due to resistance by vegetation.

Fig. 7. Froude no. changes along d/s slope for row type 2D vegetation effect due to 20% blocking compared with no or WOV case.

Fig. 8. Froude no. changes along d/s slope for all over veg. due to different blocking effect compared with no or WOV case.

Fig. 9. Froude no. changes at toe and d/s bed for row type 2D vegetation effect with 20% blocking compared with no or WOV case.
The figure 9 and 10 shows that for both 5cm and 15cm spacing (0.25 and 0.75 ratio) vegetation rows on the d/s bed revealed no supercritical condition for both 2D type row vegetation as well as all over vegetation on d/s slope and bed. Laboratory experiments with an embankment slope especially for 5cm spacing rows or 2D vegetation case using 20% blocking of vegetal cover revealed no supercritical flow condition both on the d/s slope, toe and bed of the embankment. Therefore, experimental results demonstrated that a significant portion of velocity reduction can be achieved at the d/s slope, toe and bed by increasing blocking effect with vegetation.

IV. CONCLUSION

A cost effective and eco-friendly solution for stabilization of earthen embankment is presented in this paper. The study explored the effectiveness of vegetated condition on the d/s slope compared with no vegetation. Vegetation markedly reduced the flow velocity which in turn limits the extent of erosion. Results demonstrated a significant reduction of damage and risk of failure from overtopping flows can be achieved by providing vegetation cover on the d/s slope of the embankment.

Based on the results of laboratory experiments of this investigation, the following conclusions can be drawn:

- It is observed that the maximum reduction of averaged overtopping, sloping as well as bed velocity is obtained for 20% blocking all over vegetation on the d/s slope and bed of the embankment.
- According to the experiment results, for both row type 2D vegetation with 5cm spacing as well as all over vegetation case, 20% blocking vegetation cover revealed no supercritical flow condition both on the d/s slope, at toe as well as d/s bed of the embankment.
- From the consideration of economy and availability, row type 2D vegetation with 5cm spacing (0.25 ratio) cover is more effective than other type of vegetation.
- Spacing of roughness element is also the influencing factor in reducing flow velocity to keep sub-critical flow on the d/s slope of embankment.
- It is concluded that vegetation can be the effective and innovative solution for the stabilization of river or coastal embankments, especially for developing countries like Bangladesh.

REFERENCES