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Laboratory Study on Hydraulics of Threshold Characteristics of Underwater Erosion Resistant Material

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Original Research Article

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Abstract: River bank erosion has always been a challenging problem in Bangladesh. Conventional method of designing erosion protection structures are governed by the hydraulic loads resulting from currents and waves. In practice, toe protection elements are dumped into flowing water and settle somewhere on the river bed to form an apron. The present study has been undertaken to investigate experimentally the aspect of underwater threshold condition of toe protection elements. The experiments are conducted in the large tilting flume of the Hydraulics and River Engineering Laboratory of Water Resources Engineering Department, BUET. Cube-shaped Concrete Block (CC block) is considered as erosion resistant material. A geometrically similar undistorted scale factor of 20 has been selected to conduct the experiment. Hydraulic parameters and CC block are selected based on typical field condition and the experiment is designed according to the scale. Two different initial water level (set-up 1 and set-up 2) is deliberated for the same size of CC block to investigate the hydraulics of threshold characteristics. During experimentation various observations are made and the measured data are used to analyze various hydraulic features of threshold condition. Gradual smooth increment of flow is ensured to reach threshold condition. At this stage, water level is 0.212 m, section average velocity is 0.55 m/s and depth averaged velocity is 0.54 m/s for set-up 1. While for set-up 2, water level is 0.256 m, section average velocity is 0.54 m/s and depth averaged velocity is 0.53 m/s. Though the threshold velocity magnitude for set-up 1 and set-up 2 are very close, the corresponding water level is quite different since initial depth of flow is different. It is expected that the results obtained here can be useful to develop predictive expression for estimating the threshold velocity of CC blocks. Scope of detailed analyses in this area of interest is in progress.

Keywords: Threshold velocity, River bed/bank protection, CC block, Laboratory study.

INTRODUCTION

Rivers, especially large rivers of Bangladesh are unique in behavior because of its dimensions, discharge, sediment characteristics and morpho-dynamic activities. To address river bank and bed erosion in these rivers, artificial covering of the riverbank and bed with erosion resistant material is constructed. Cement-Sand Concrete block (CC block) with geosynthetic products have increasingly been used in erosion control and bank protection projects, especially as toe protection elements of revetment works. During construction of toe, CC blocks are delivered directly from vessel for placement of protective elements at designated position in the settling fashion as shown in Photograph 1.

Photograph-1: CC blocks are being dumped for toe protection in the Jamuna River at Sirajgonj Hard Point, Shirajganj, Bangladesh

When water flows over a material, the drag and lift forces are created by flow velocities adjacent to the material to make it unstable. Threshold conditions are said to have been reached if the hydrodynamic force (lift force, drag force) acting on a material has reached a certain value that, if increased even slightly will put the material into motion. When incipient conditions obtain values of such quantities as the mean velocity, bed shear stress or the stage of a stream are said to have their critical or threshold values.

The driving forces are strongly related to the local near bed velocities. In turbulent flow conditions the velocities are fluctuating in space and time. Also the randomness of both the particle size, shape and position is there. Therefore, initiation of motion is not simply a deterministic phenomenon but also a stochastic process as well.

A good number of studies had been conducted for incipient motion of sediment particle. Examples are, works of Neill [1], Van Rijn [2], Ünal and Bayazit [3], Smith and Cheung [4], Beheshti and Ashtiani [5], Marsh *et al.* [6], Göğüş and Defne [7] and many others. Inglis [8], Maynord *et al*. [9], USACE [10], NHC [11], Zhu *et al.* [12] proposed relationship regarding incipient motion of underwater erosion resistant material. However, limited study had been done on incipient behavior of CC block considering as toe protection elements simulating the actual method of construction practiced in the field.

In this study, an attempt has been made to conduct experimental investigation of underwater threshold behavior of CC block for varying flow condition.

DESIGN OF EXPERIMENTATION

Selection of scale and various model parameters for experimentation

A geometrically similar undistorted scale factor 20 has been selected to conduct the experiment. This selection of scale is based on (i) the available laboratory flume facilities and (ii) the Froude law criteria. From these considerations, various scale ratios of model parameters are designed as shown in Table 1.

Table-1: Scale ratios of model parameters

Quantity	Dimension	Scale ratio
Length	L	1:20
Volume or weight	L^3	1:8000
Velocity	$L^{1/2}$	1:4.47
Discharge	$L^{5/2}$	1:1789

It is assumed that the material and porosity remain unchanged for the experiment and prototype [12]. Therefore, protection elements used for the laboratory experiment should be the same as those designed for field construction except for the reduced dimension.

Design of size of CC block

Different methods regarding calculations of unit dimensions of revetment cover layers and toe protections [13-15] show only marginal deviations within the range of application for the rivers of Bangladesh. Since the widely used Pilarczyk formula [14, 16] includes the turbulence intensity, velocity and shear stress, it is followed to determine the nominal thickness of a protection unit. The formula is:

$$D_n = \frac{\phi_c K_T K_h}{\Delta K_s} \frac{0.035}{\theta_c} \frac{\bar{u}^2}{2g} \quad (1)$$

The values of the parameters of Equation (1) are considered according to Zaman and Oberhagemann [17]. Here, D_n = nominal thickness of protection unit, m; ϕ_c = stability factor = 0.75 for continuous protection of loose units; K_T = turbulence factor = 1.5 for non-uniform flow with increased turbulence; K_h=depth and velocity distribution factor= $(h/D_n+1)^{-0.2}$, h=water depth, m; Δ=relative density of protection unit= $(\rho_s-\rho)/\rho$=1; K_s = slope reduction factor $=(1-\sin^2\alpha/\sin^2\varnothing)^{0.5}$ = 0.72, α = slope angle = 26.57^0 (for 1V:2H); $\varnothing$ = angle of repose = 40^0 (for CC blocks); θ_c = critical value of dimensionless shear stress = 0.035 for free blocks; $\bar{u}$ = depth averaged flow velocity, m/s. Experimental size of CC block is found to be 23 mm which represents a prototype size of 460 mm. Sample calculation is given in Appendix 1.

Design of apron

Design scour depth can be estimated by Lacey [18] since it is widely used in these subcontinental alluvial rivers. This empirical regime formula is:

$$R = 0.47\left(\frac{Q}{f}\right)^{1/3} \quad (2)$$

$$D_s = XR\text{-}h \quad (3)$$

Where D_s = Scour depth at design discharge, m; Q = Design discharge, m^3/s; h = Depth of flow, m; may be calculated as (HFL-LWL); f = Lacey's silt factor = $1.76\ (d_{50})^{1/2}$; d_{50} = Median diameter of sediment particle, mm; X = Multiplying factor for design scour depth.

Table-2: Hydraulic parameters of typical field condition

High Flood Level, HFL	9.0 m PWD
Low Water Level, LWL	3.0 m PWD
Design discharge, Q	20,000 m^3/s
Median diameter of sediment particle, d_{50}	0.12 mm
Multiplying factor for design scour depth, X	1.25 for straight reach of channel

Considering a typical field condition presented in Table 2 and from Equation (2) and Equation (3), it is found that D_s = 9.75 m. Therefore,
Width of apron, $W_{apron} = 1.5\ D_s$ = 14.63 m.
Width of apron in the flume, W_{apron} = 14.63/20 = 73 cm.
Thickness of protection over scoured slope, $T = 1.25\ D_n$.
Shape of the apron in the laboratory flume is followed according to Rao [19], as shown in Figure 1.

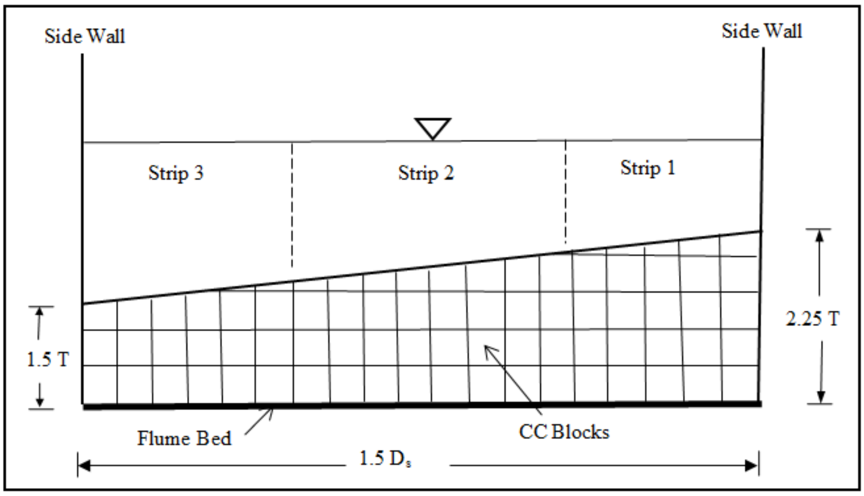


Fig-1: Schematic diagram for shape of a typical apron constructed in the flume

Quantity of CC block
According to Figure 1, the quantity of CC block is determined as follows:
Inside thickness of apron = 1.5 T m
Outside thickness of apron = 2.25 T m
Total volume of CC block per unit length, $V_{block} = 1.5D_s\,(1.5T + 2.25T)/2$ m^3/m
Number of block per unit length = V_{block}/D_n^3

This amount of block is dumped so as to achieve a qualitative shape according to Figure 1, over the width of apron per unit length to investigate its threshold condition.

Fabrication of CC block
Sand cement blocks of different sizes are prepared using iron mold. The cement-sand ratio is 1:4. After one day of preparation, curing of blocks is done for 48 hours. The blocks are cubical since cube shaped blocks are commonly used in Bangladesh context. Different blocks used for the present study is shown in Photograph 2.

Photograph-2: Cube-shaped Concrete blocks used in the study

EXPERIMENTAL SET-UP
The experiments are conducted in a settling column and in the large tilting flume of the Hydraulics and River Engineering Laboratory of Water Resources Engineering Department, Bangladesh University of Engineering and Technology (BUET), Dhaka. Schematic diagram of the flume setup is shown in Figure 2.

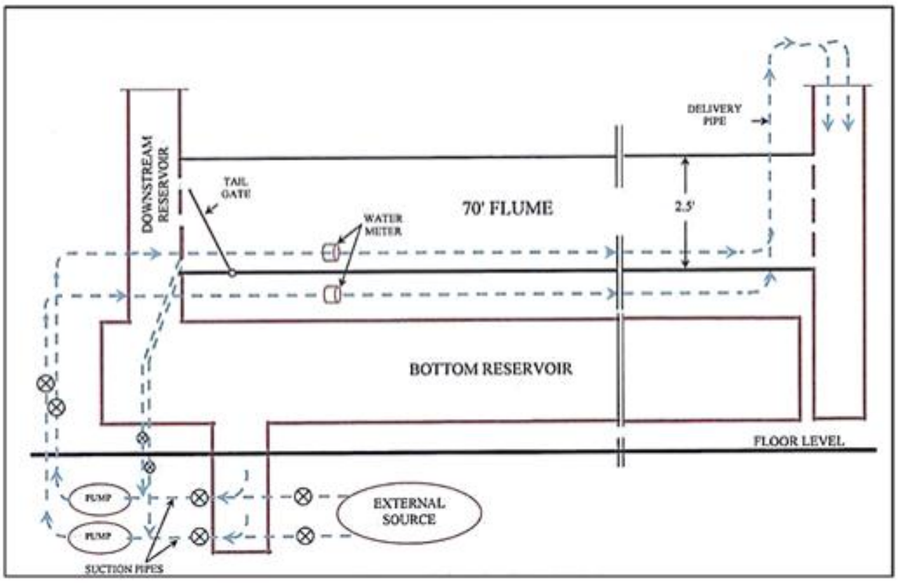


Fig-2: Schematic diagram for shape of the flume set-up

Flume setup

The experiment has been carried out in a 21.34 m long, 0.762 m wide and 0.762 m deep rectangular tilting flume in the Hydraulics and River Engineering Laboratory. The side walls of the flume are vertical and made of clear glass. The bed is painted by water resistant color to avoid excess bed friction. A tail gate is provided at the end of the flume to control the depth of flow. Two pumps are there to supply water from the reservoir to the flume through a recirculating channel. The flume is shown in Photograph 3. Point gauge is used to measure the depth of flow. The gauge is mounted on a trolley laid across the width of the flume. The whole structure of point gauge could be moved over the side rails. The point gauge can measure within ±0.10 mm accuracy.

Discharge measurements are taken from the electromagnetic flow meter. Of the two flow meters one is 200 mm and the other is 150 mm diameter. The flow through the pipe is controlled by the valve. A small current meter is used for velocity measurement. It consists of three basic parts: 50 mm diameter propeller, 1 m long 9 mm diameter rod and signal counter set. Minimum depth of water for using the instrument is approximately 4 cm. It is capable of measuring velocity from 3.5 cm/s to 5 m/s. Time and impulse measurement accuracy is ±0.01 seconds and ±0.5 impulses, respectively.

Photograph-3: Laboratory flume

Hydraulic parameters

Utility of an experimental investigation in field practice lies in the simulation of the field situations in the experimental setup. In order to simulate field conditions observed in different bank protection works already undertaken in Bangladesh, it is necessary to keep the velocity, water depth within a range. The flow depth is selected considering the High Water Level (HWL) and Low Water Level (LWL) in a typical field condition. This will facilitate the tasks of engineers and researchers to compare the test results with the field circumstances and to search for the option best suited for a given site condition for sustainable bank protection works.

Total maximum discharge of the two pumps together is about 750 to 780 m^3/h. Discharge can be varied from 80 m^3/h to 760 m^3/h. For incipient motion experiments the hydraulic parameter is set based on the typical field Low Water Level (LWL) condition and is given in Table 3.

Table-3: Initial hydraulic parameters regarding experiment of incipient condition

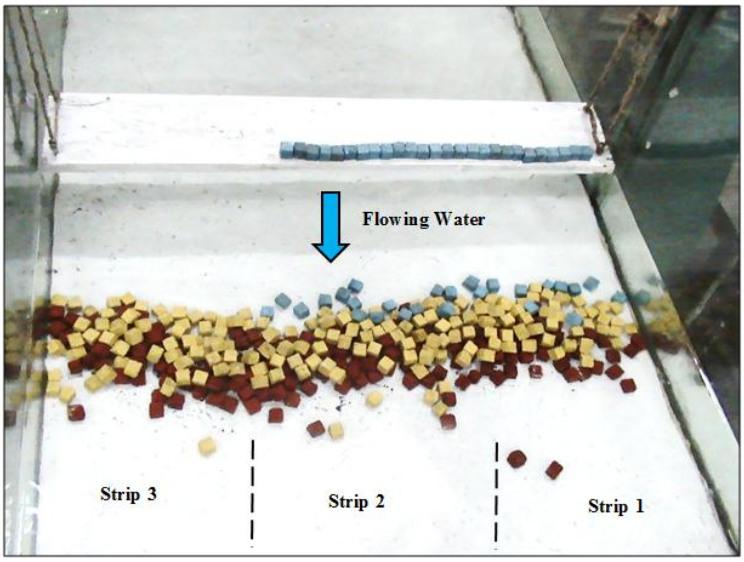
Set-up Type	Flume discharge, Q (m^3/h)	Experimental value		Corresponding field value	
		Depth of flow, h (m)	Velocity, V (m/s)	Depth of flow, h (m)	Velocity, V (m/s)
Set-up 1	140	0.15	0.35	3	1.56
Set-up 2	186	0.20	0.35	4	1.56

Test duration

After dumping the elements from water surface, they are allowed to be stable on the bed and then the measurements are made. For incipient motion tests, the duration of a run is about 40 minutes to 60 minutes depending on their sizes and threshold hydraulic features.

Procedure followed for incipient motion experiment

- The shape of apron and number of element required per unit length is determined as mentioned previously. This amount is dumped during the run.
- Two different combinations of hydraulic parameters are investigated. The elements are dumped from 4 cm above the water surface in all run.
- Red, yellow and blue colored blocks are used in first, second and third layers to observe their post dumping condition (Photograph 4).
- For a particular set up, the discharge is set by the valve and the depth of flow is fixed by adjusting the tail gate. Depth averaged flow velocity is measured using a small current meter (Photograph 5).
- Then discharge is increased very slowly at a rate of 5 m^3/h and observed for five to eight minutes. After that if there is no movement in apron material flow is increased again. This process continues till the incipient motion occurs.
- Incipient motion is considered as the displacement of an element from its initial position. When this condition is satisfied, the flow depth and depth averaged velocity of approach flow is measured at upstream and downstream of the apron by dividing the width of the flume into three equal strip (Photograph 4).
- Initial water depth in the flume is 0.15 m and 0.20 m for set-up 1 and set-up 2, respectively (Table 3).
- The significant feature of the test is that elements are dumped in the flowing water rather placed in a dry bed prior to flow of water. This procedure depicts the real field condition.



Photograph-4: Dumping of CC block to construct apron in the flume and velocity measurement locations

Photograph-5: Velocity measurement using current meter to investigation of threshold condition of CC block

RESULTS AND DISCUSSIONS

Observations during Experiment

- The water surface downstream of the test section was slightly lower.
- As the velocity increases and reaches a certain magnitude, the CC block starts vibrating.
- CC blocks moved individually when it reaches the threshold condition.
- Nature of movement was sliding and rolling.

Point Velocity

At depths of 0.2h, 0.6h and 0.8h (h=depth of flow at the beginning) from the water surface, point velocities are measured at three strips as shown previously in Figure 1 and Photograph 4. For set-up 1 in the upstream of apron, Figure 3 shows that velocity magnitudes are lower in strip 1 than the others, however, the velocity magnitude are very close (0.28 m/s to 0.32 m/s). Almost same velocity variation (0.34 m/s to 0.37 m/s) among strips are observed. Strip 2 and 3 have almost same velocity. Along the depth (h) the average velocity variation is 5.95%.

While for the downstream of apron, Figure 4 shows velocity at depths close to the flume bed are very low due to the obstruction caused by the apron. However, at this location, strip 3 has higher velocity since thickness of apron at this strip is lower than other two strips and difference among the velocity magnitude is relatively higher (0.06 m/s to 0.25 m/s) than upstream. The surface velocity of the strips is close to each other since the effect of apron shape is negligible here. Along the depth (h) the average velocity variation is 35.24%.

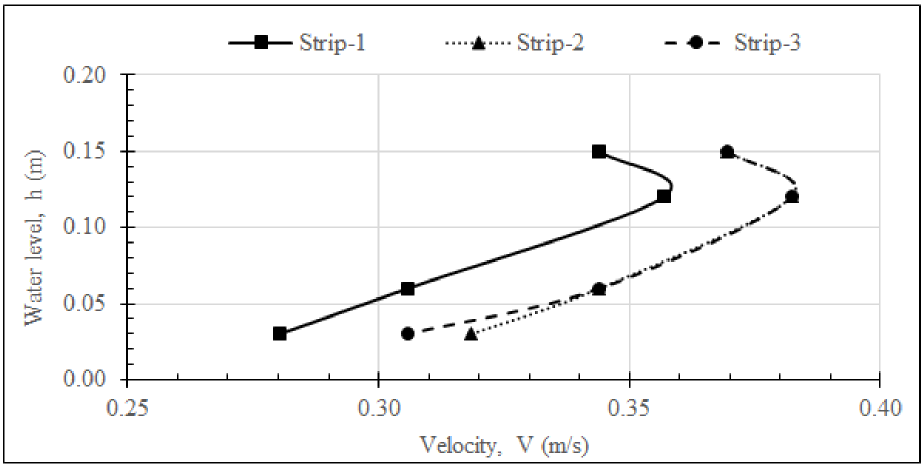


Fig-3: Approach velocity at the upstream of apron for set-up 1

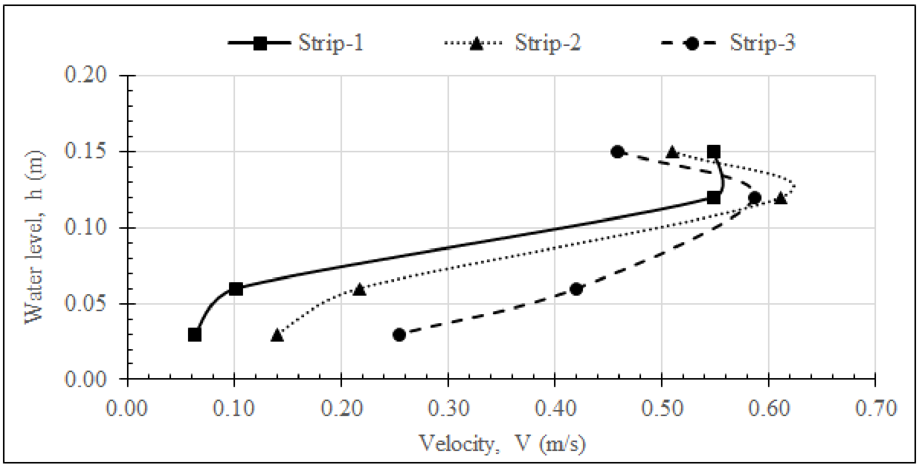


Fig-4: Velocity at the downstream of apron for set-up 1

For set-up 2 in the upstream of apron, Figure 5 shows that velocity magnitudes differ among the strips, however, they are very close (0.28 m/s to 0.33 m/s). Along the depth (h) the average velocity variation is 7.22%.

While for the downstream of apron, Figure 6 shows velocity at depths close to the flume bed are very low due to the obstruction caused by the apron. However, at this location, strip 3 has higher velocity since thickness of apron at this strip is lower than other two strips and difference among the velocity magnitude is relatively higher (0.09 m/s to 0.24 m/s) than upstream. The surface velocity of the strips is close to each other since the effect of apron shape is negligible here. Along the depth (h) the average velocity variation is 36.1%.

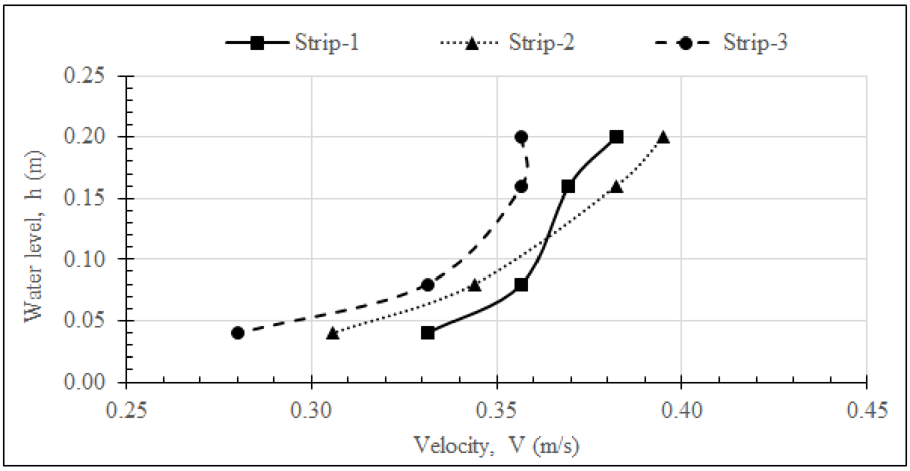


Fig-5: Approach velocity at the upstream of apron for set-up 2

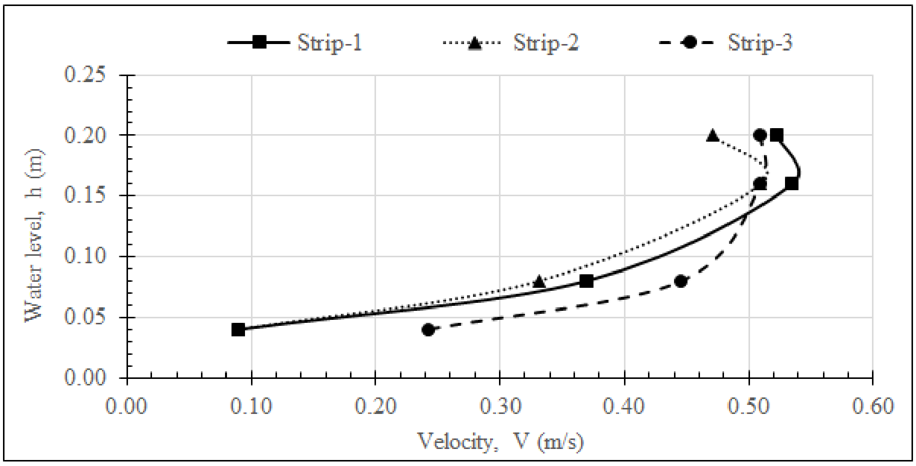


Fig-6: Velocity at the downstream of apron for set-up 2

Discharge and Water Level Features

Recorded data of discharge and corresponding time is plotted in Figure 7 for set-up 1. It is observed from Figure 7 that the discharge is increased at a slow rate. This results in a slower increase of water level as can be seen in Figure 8. It helps to investigate the threshold phenomena in a proper way. Sudden increase of discharge may generate thrust force upon CC block causing it to move which would be misleading. It is found from Figure 7 and Figure 8 that after 38 min threshold condition is achieved for which corresponding discharge is 320 m^3/h and water level is 0.212 m.

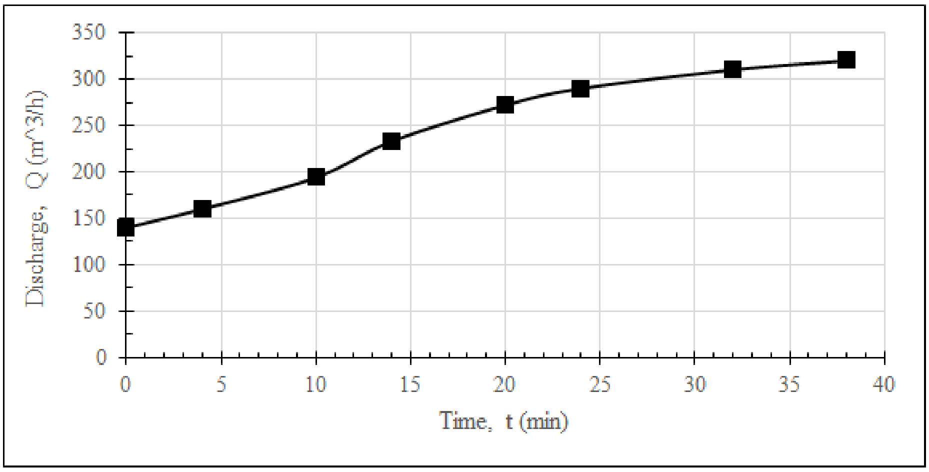


Fig-7: Plot of discharge versus time for set-up 1

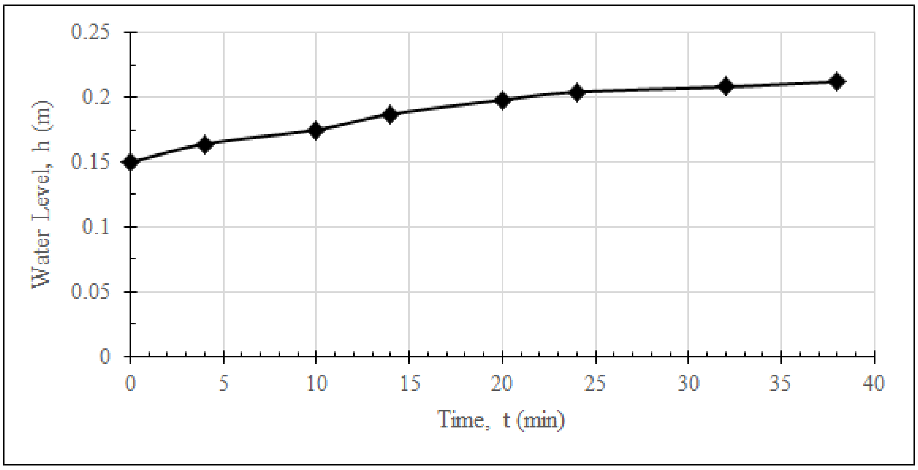


Fig-8: Plot of water level versus time for set-up 1

Figure 9 and Figure 10 are the plots of discharge and water level against time, respectively for set-up 2. However, longer time is required to achieve the threshold condition for set-up 2 because the beginning depth of flow is higher in set-up 2 than set-up 1 (Table 3). It is found from Figure 9 and Figure 10 that after 54 min threshold condition is achieved for which corresponding discharge is 377 m^3/h and water level is 0.256 m.

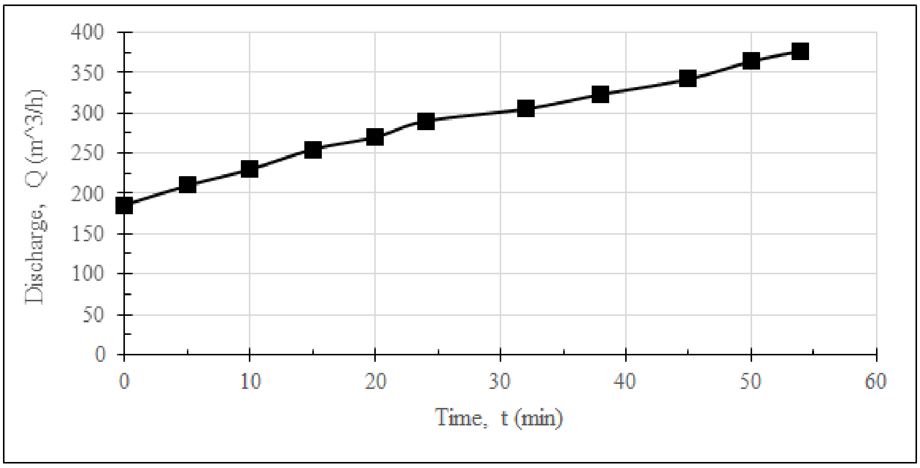


Fig-9: Plot of discharge versus time for set-up 2

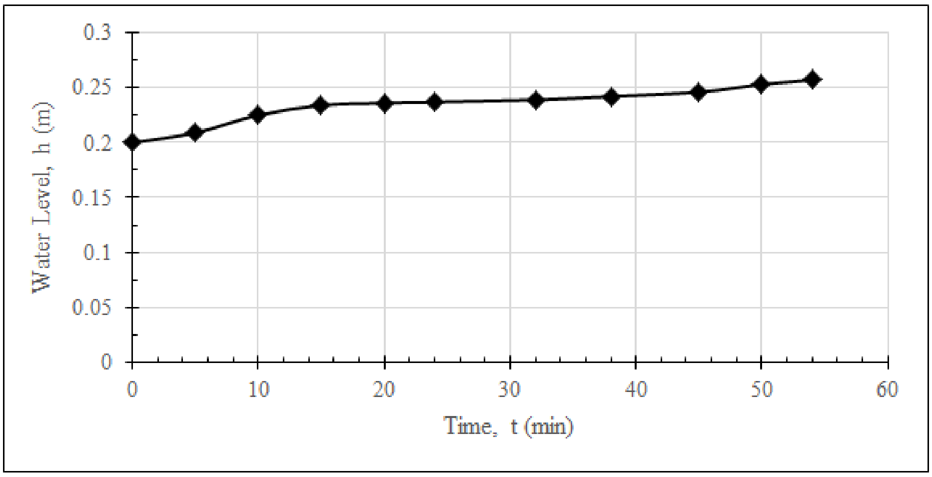


Fig-10: Plot of water level versus time for set-up 2

Section Average Velocity

The section average velocity is plotted in Figure 11 and Figure 12 for set-up 1 and set-up 2, respectively. It is found from Figure 11 (set-up 1) that threshold section average velocity is 0.55 m/s while Figure 12 (set-up 2) gives a value of 0.54 m/s. This shows that even the depth of water is higher for the later condition, the threshold velocity is slightly lower. It clearly shows the effect of hydraulic parameters, more specifically the combination of forces acting upon the CC block at that particular moment is playing the pivoting role to move it from its position at rest is. That is why the behavior of a particular type of underwater erosion resistant material has unique nature to reach its incipient condition.

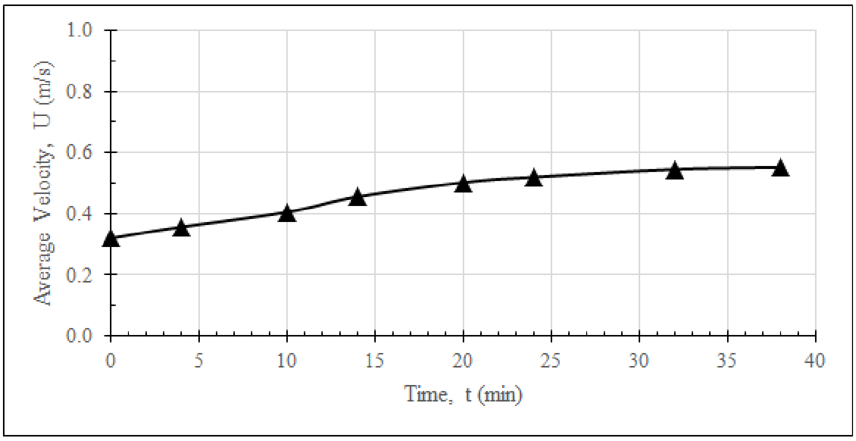


Fig-11: Average velocity versus time for set-up 1

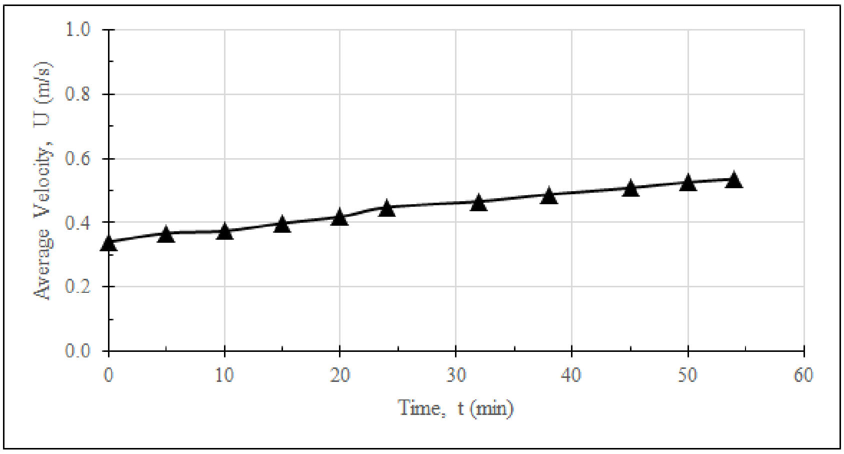


Fig-12: Average velocity versus time for set-up 2

Depth Average Threshold Velocity

Measurement of depth averaged threshold velocity (at 0.6h) for set-up 1 and set-up 2 are found to be 0.54 m/s and 0.53 m/s, respectively. This corresponds to a prototype velocity of 2.37 m/s and 2.41 m/s. However, while determining the size of the CC block the depth averaged velocity is selected as 3.3 m/s (Appendix 1) to use in Equation 1. Therefore it may possibly be said that the underwater behavior of this CC block as a part of the apron is on the verge of movement at a lower velocity than the assumed value.

CONCLUSION

Based on the experimental investigation and results obtained from the study, the following conclusions can be made:

- Initial velocity variation among the strips are high at downstream of apron. However, variation of upstream velocity distribution among the strips may be considered as negligible.
- It is observed that the variation of upstream velocity along the depth is 5.95% to 7.22% whereas that of the downstream is 35.25% to 36.10%.
- At the stage of threshold condition for set-up 1, water level is 0.212 m and depth averaged velocity is 0.54 m/s; the corresponding prototype value is 4.2 m and 2.41 m/s, respectively.
- At the stage of threshold condition for set-up 2, water level is 0.256 m and depth averaged velocity is 0.53 m/s; the corresponding prototype value is 5.12 m and 2.37 m/s, respectively.
- Though the threshold velocity magnitude for set-up 1 and set-up 2 are very close, the corresponding water level is quite different since initial depth of flow is different.
- Therefore, the effect of hydraulic parameters, more specifically the combination of forces acting upon the CC block; or in other words mutual effect of apron and CC block size and shape as well as initial and final water level at that particular (incipient) condition is playing the pivoting role to move the CC block from its position at rest.
- It is expected that the results obtained here can be useful to develop predictive expression for estimating the threshold condition of protective elements for underwater construction. Scope of detailed analyses in this area of interest is in progress.

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Appendix 1

Let, $\bar{u}$ = 3.3 m/s, h = 10 m and D_n = 0.46 m.
Then, $K_h = (h/D_n+1)^{-0.2} = 0.53$
Now from equation (1) and other values mentioned there, results in
D_n = 460 mm.
Therefore, the experimental size of CC block for present study becomes, D_n = 460/20 = 23 mm.

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