Journal of Engineering Science 03(1), 2012 86-98

JES

an International Journal

PHYSICAL MODEL STUDIES TO SUPPORT THE DESIGN OF MAIN SPILLWAY OF THE PROPOSED GANGES BARRAGE

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Received 01 September 2012; Accepted 18 October 2012

ABSTRACT

A barrage across the Ganges River at Pangsha has been proposed by feasibility consultants to store water and augment dry season flow into the distributaries of the Ganges. The waterway width (1728m) of the barrage consists of main spillway and undersluice bays, fish passes, navigation lock and hydro-power station. River Research Institute (RRI) has conducted detail model study for main spillway to support its design in terms of afflux, discharge co-efficient, water surface profile, scour profile downstream of the stilling basin with and without block protection under submerged unregulated flow conditions and nature of flow in the stilling basin under regulated flow conditions. The scale ratio of the model is set as 1:24. The model has been constructed in a straight flume. The barrage section reproduced in the model consists of one full bay (18m), two piers of 2.5m width and half of the portion of bays on the other side of each pier. The flume width is 1.71m. The stage-discharge curve established for the barrage site has been used to conduct model investigations. This paper presents the experimental results of design alternatives of main spillway and stilling basin and discusses the results in terms of their reliability and effectiveness. It is revealed that the design of main spillway is appropriate and the low Froude number basin works well to stabilize the hydraulic jump within the stilling basin.

Keywords: *Afflux, Barrage, Froude Number, Hydraulic Jump, Main Spillway, Stilling Basin*

1. INTRODUCTION

The construction of the proposed Ganges barrage is of immense importance for effective utilization of the Bangladesh share of Ganges flow and for the benefit of the people living in the Ganges Dependent Area. The layout of barrage is shown in Figure 1. Physical model studies are being conducted in RRI to support the Feasibility Study and Detailed Engineering for Ganges Barrage Project. The maximum waterway width of 1728m is established by model studies. The total spillways and undersluices length has been taken as 1620 m, corresponding with 78 spillway bays and 18 undersluice bays with 18 m wide openings.

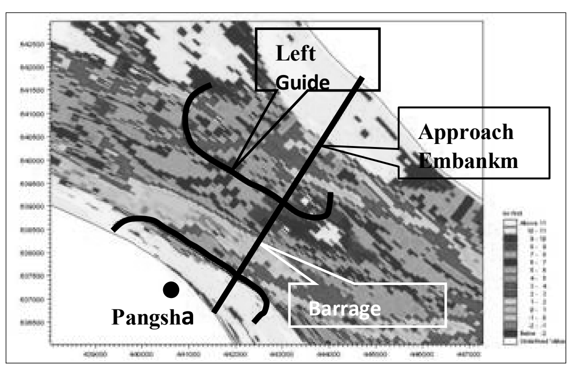

Figure 1 Layout of the proposed Ganges barrage at Pangsha

The main spillway is an important component of a barrage. Physical model studies play a vital role in planning and design of hydraulic structures like main spillway. Design of hydraulic structures is generally refined on the basis of detail physical model studies. The principal features and dimensions of the proposed Ganges barrage have been designed by the detailed engineering consultants on the basis of physical overall model and numerical

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model investigation results. The detail model for main spillway mainly aims to determine the afflux, surface water profile, discharge co-efficient etc. under different submerged unregulated flow conditions and to observe the hydraulic performance of stilling basin as designed and to suggest the modification of stilling basin if any for better performance in gated conditions. Appropriate scale between model and prototype structure plays imperative role in terms of rationality and reliability of the model results. This type of models gives best results if undistorted because of three-dimensional nature of flow pattern. Such undistorted models are also well fit for study of scour and stability of scour protection, which in many cases are an integral part of the local studies. The main spillway is the main body of the proposed Ganges barrage, normal RCC slab that supports the steel gate. The section of the main spillway is shown in Figure 2.

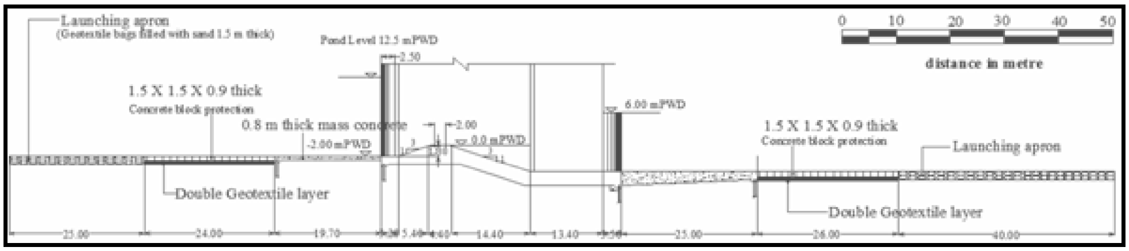

Figure 2 Section of main spillway (RRI, 2011)

The section of the main spillway consists of upstream concrete floor at elevation -2 mPWD, crest at elevation 0 mPWD, upstream slope (3:1), downstream slope (3:1) and downstream concrete floor at elevation -5 mPWD. There are also upstream sheet piles, downstream sheet piles, intermediate sheet piles and concrete block protection and launching apron both upstream and downstream.

The scale ratio of the model is set as 1:24. The model has been constructed in a straight flume using indoor modelling facilities of RRI. The barrage section reproduced in the model consists of one full bay, two piers of 2.5m width and half of the portion of bays on the other side of each pier. The flume width is 1.71m for the selected scale ratio. The test section of the model is constructed in this flume one side of which is fitted with steel sheet and the other side with transparent plastic panels to facilitate visual observations inside the flume. The radial gate, cement concrete blocks and loose protection works have been fabricated in the model as per design.

Detail model investigations for main spillway have been conducted with some specific objectives in view. Five test series have been conducted for determination of the needed information in unregulated and gated conditions for different discharges.

The information derived for unregulated submerged flow conditions are (i) water surface profiles (ii) discharge co-efficient (iii) reduction of discharge co-efficient with submergence with and without basin elements in place and (iv) water surface profiles and scour profiles downstream of the stilling basin with and without block protection and launching apron in place. The information derived for gated conditions are the nature of the hydraulic jump and the position and depth of maximum scour downstream for a critical downstream release condition with alternative designs of stilling basin in place. The other tests in gated conditions are yet to be conducted. Some findings of the model study have been presented in this paper.

2. METHODOLOGY

2.1 Model Design

The model for main spillway has been constructed using RRI indoor modelling facilities. The model has been designed to accommodate a short section of the main spillway. In the model the prototype situation has been replicated in a flume on a scale ratio of 1:24. The model is undistorted and the geometric scale is selected based on the available laboratory space, pumping capacity, measurements, dimension of the structure, governing processes to be simulated and scale conditions to be fulfilled. With this scale the model is of sufficient size that surface tension is minimized and that surface resistance is not greatly out of scale. In order to reproduce water flow and scour downstream of the structure following scale conditions are to be fulfilled (Sharpe, 1981).

i. Geometric Condition

The geometric condition is important to be fulfilled in order to diminish scale effects related to the three dimensional flow. The geometric condition is fulfilled when the length scale is equal to the depth scale i.e.

$L_r = h_r$ ....(1)

Where, L_r = length scale and h_r = depth scale

ii. Roughness Condition

In an undistorted model the roughness condition is fulfilled when the scale of the Chezy roughness is equal to 1 or when the water slope in the model is equal to the water surface slope in prototype *i.e.*

$C_r^2 = L_r / h_r = 1$ ....(2)

Where, C_r = roughness scale

iii. Froude Condition

The Froude condition is important to have a dynamic similarity for free surface flow with respect to the influence of gravity. The Froude condition is fulfilled when

$V_r = L_r^{0.5} = h_r^{0.5}$ $(L_r = h_r)$ ....(3)

The discharge scale for the undistorted model can be determined from

$Q_r = L_r^{2.5} = h_r^{2.5}$ ....(4)

iv. Transport Intensity

One of the main objectives of the model study is to determine scour downstream of the structure under different discharges. The following scale condition has to be satisfied for reproduction of the transport intensity when most of the sediment in the prototype is transported as suspended load.

$V_r = C_r D_r^2 \Delta_r$ ....(5)

Where, V_r = velocity scale
C_r = roughness scale
D_r = diameter scale and
Δ_r = relative density scale

The above scale condition has led to the selection of appropriate d_{50} of the model bed sand so that the velocity scale needed for fair reproduction of the transport intensity in the model almost corresponds to the velocity scale according to Froudian law of similitude. The relationship of dimension and hydraulic quantities between model and prototype, which is based on Froudian law is given in Table 1.

Table 1 Relationship of dimensions and hydraulic quantities between model and prototype

Parameters	Unit	Scale
Length (*L*)	m	24
Depth (*h*)	m	24
Velocity (*V*)	m/s	4.9
Discharge (*Q*)	m^3/s	2822
Time (*T*)	s	4.9
Froude number (*Fr*)	-	1
Roughness co-efficient (*n*)	$m^{-1/3}s$	1.7

2.2 Model Setup

The model setup includes model scale, model discharge, water re-circulation system, gauging stations, tailgate and proposed structures. The layout of the model is shown in Figure 3. The model discharges are selected from the established stage-discharge curves of the river at the barrage site. The stage-discharge curves consist of upper, middle and lower curve. The middle curve has been used as tailwater rating curve during model investigations. The maximum discharge required by the model of about 0.75 m^3/s has been supplied by pumping. Two 1.8m rectangular weirs, located in an extension of the main flume have served as a means of measuring the inflow discharge. 4 (four) gauge wells, two in the upstream and two in the downstream have been installed with point gauge to read water surface elevation. Besides, there are two staff gauges upstream and downstream (near the toe of the glacis) of the weir for visual observation of water level. A hinged tailgate at the end of the flume has been installed for controlling downstream water level. The design of the structures reproduced in the model (Figure 4) has been done by the detailed design consultants. The radial gate, cement concrete blocks and loose protection works have been fabricated in the model as per design.

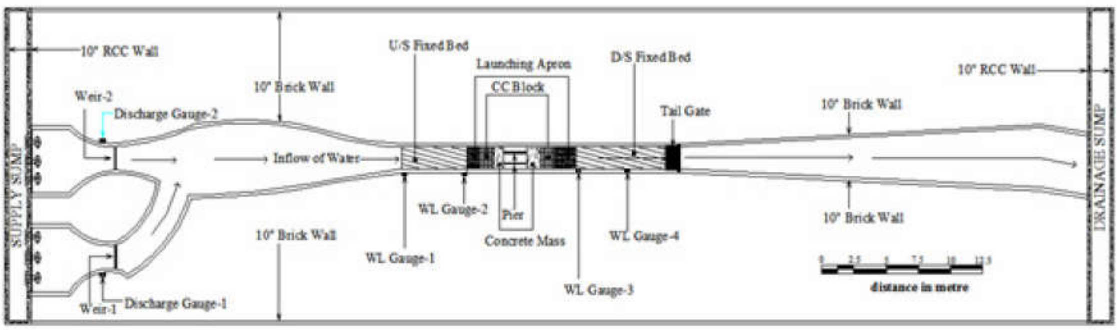

Figure 3 Layout of the detail model for main spillway (RRI, 2011)

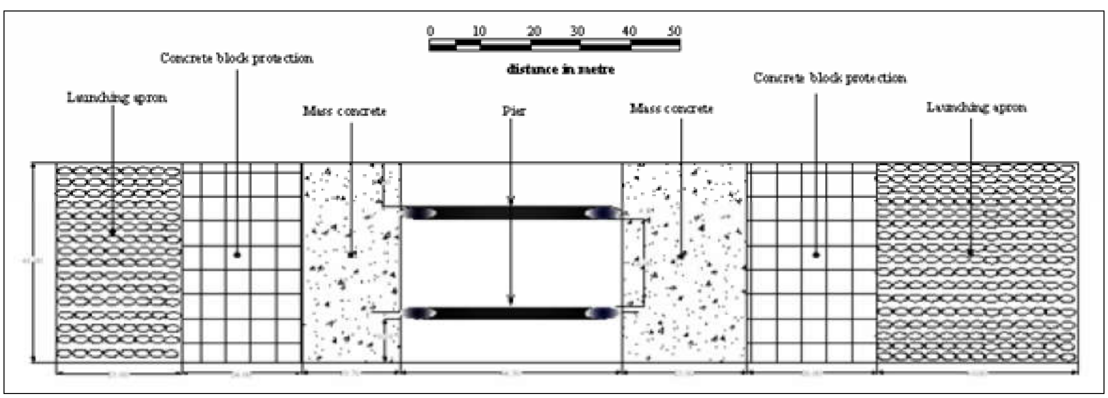

Figure 4 Plan of barrage portion for flume test (RRI, 2011)

2.3 Test Procedures

The test conditions have been established in order to achieve the study objectives. Five test series have been conducted for determination of the needed information in unregulated and gated conditions for different discharges. The discharges and corresponding tail water levels have been selected from the stage-discharge curve. Model discharges corresponding to different prototype discharges have been determined for 2(two) bays. It is to be noted here that initially prototype discharge for 2 bays (36m opening) has been determined considering 90 bays (including undersluice bays) of the barrage and tests have been conducted accordingly. Afterwards some of the important tests have been repeated as because it is known that the Feasibility Consultants have decided to increase the total numbers of bays from 90 to 96. In case of submerged unregulated flow the model measurements include water level at pre-fixed locations including headwater level, water depth upstream and downstream of the weir, velocity of approach, downstream velocity and downstream scour level. On the other hand, a critical downstream release condition has been tested for regulated flow with alternative designs of stilling basin. The tests involve measurement of headwater level, water level at jump initiation point and after jump, velocity of approach, velocity after jump and distance of the jump initiation point from the middle of the crest for varying gate openings. The equipment that have been used for recoding different data include A-ott propeller type (vertical axis) current meter, levelling instrument, point gauge, stop watch, meter scale and video and still camera.

3. TEST RESULTS AND DISCUSSION

Necessary measurements have been taken during the tests and the measured data has been processed and analyzed. The test results are discussed hereafter.

3.1 Head-discharge and Head-discharge Co-efficient Curve

The tests have been conducted for a number of discharges ranging from 1000 m3/s to 100000 m3/s and both with and without basin blocks in place to gain understanding of the effects of basin blocks on discharge co-efficient and afflux. It is to be noted here that for each discharge tailwater level has been varied between a range of water levels higher and lower than the water level obtained from the intermediate tailwater water curve to see its effect on discharge co-efficient, submergence ratio and afflux.

During the tests for determination of co-efficient of discharge the velocity of approach has been measured by current meter and also computed on a discharge area basis. The total head-discharge curve has been plotted first. Since the co-efficient of discharge is very sensitive to slight errors, points of head and discharge have been read from the curve and substituted in the following expression for establishing the shape and position of the co-efficient curve.

$C_d = Q/LH^{3/2}$ ....(6)

Where, Q = Measured discharge (m^3/s)
C_d = Co-efficient of discharge ($m^{1/2}/s$)
L = Length of crest exclusive of pier (m) and
H =Total head on the crest (m)

The above equation indicates that the co-efficient of discharge is not dimensionless. The prototype to model ratio of the discharge co-efficient when expressed dimensionally gives $C_{dr} = g_p/g_m$. Since the acceleration of gravity in model and prototype is same, $C_{dr} = 1$. It means the co-efficient of discharge obtained from the model can be applied directly to the prototype (RRI, 1961). The head-discharge and head-discharge co-efficient curves have been plotted for the prototype. It is thus possible to determine the co-efficient of discharge for the design headwater from the head-co-efficient of discharge curve. The head-discharge curves for different conditions appear in Figure 5 to 7. The head-co-efficient of discharge curves for different conditions appear in Figure 8 to 10.

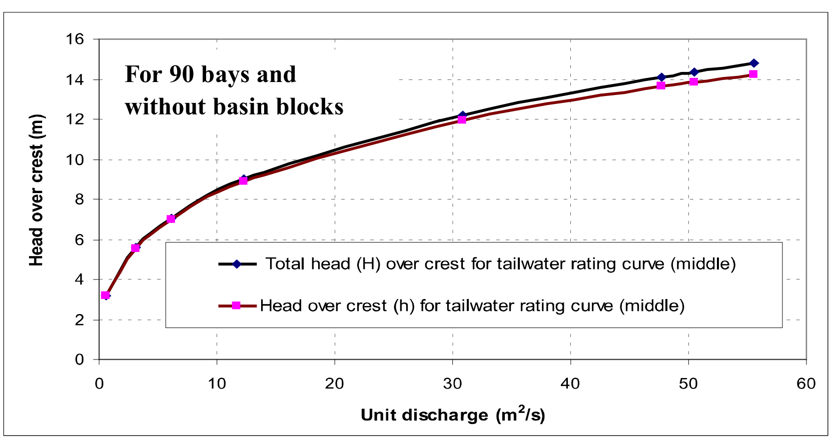

Figure 5 Head-discharge curve for 90 bays without basin blocks

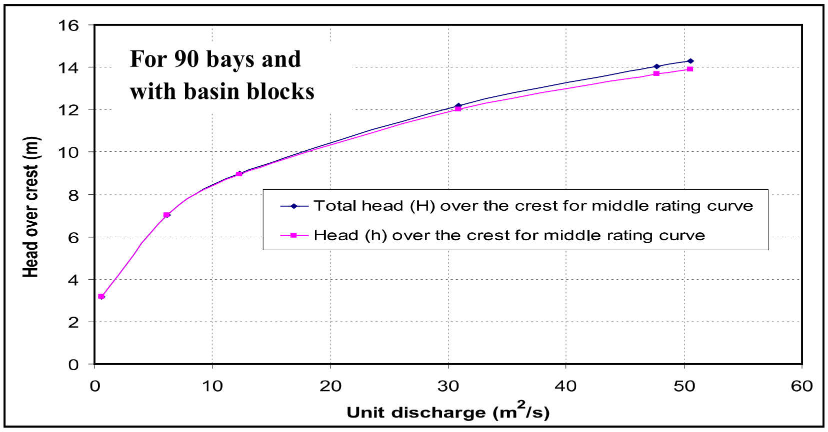

Figure 6 Head-discharge curve for 90 bays with basin blocks in place

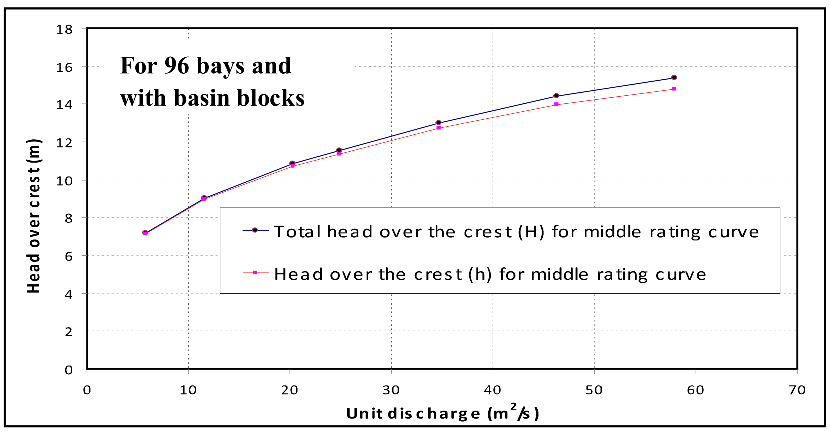

Figure 7 Head-discharge curve for 96 bays with basin blocks in place

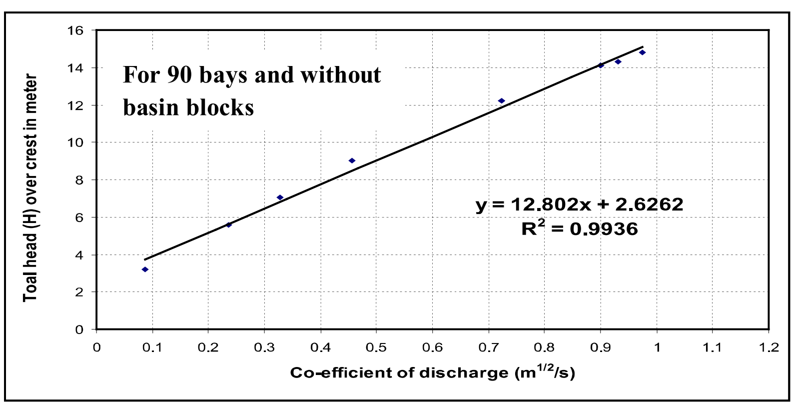

Figure 8 Head-co-efficient of discharge curve for 90 bays (without basin blocks)

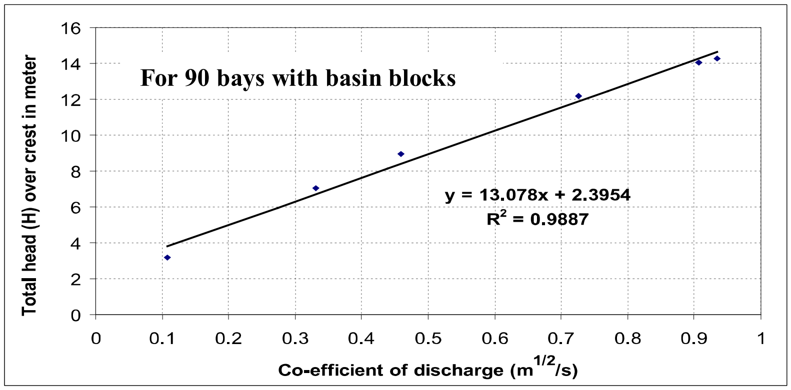

Figure 9 Head-co-efficient of discharge curve for 90 bays with basin blocks

It is observed from Figure 5 to Figure 7 that the basin blocks do have small influence on head over the crest for all discharges. A slight decrease in the head is observed for initial design of basin blocks. On the other hand, for the same design of basin blocks an increase in the numbers of bays from 90 to 96 causes a reduction in the velocity head but a small increase in the total head for all discharges under submerged unregulated flow condition. For design discharge total head over the crest is found to be 14.2 mPWD and 14.4 mPWD for a total numbers of 90 bays and 96 bays respectively with basin blocks in place. As to co-efficient of discharge it can be seen from Figure 8 and Figure 9 that the initial design of basin blocks does not have any noticeable effect on the same for any discharge. However, co-efficient of discharge does decrease due to increase in the total number of bays as can be seen from Figure 9 & Figure 10. For the design headwater the co-efficient of discharge is found to be 0.93 $m^{1/2}/s$ & 0.85 $m^{1/2}/s$ for total numbers of 90 bays and 96 bays respectively with basin elements in place.

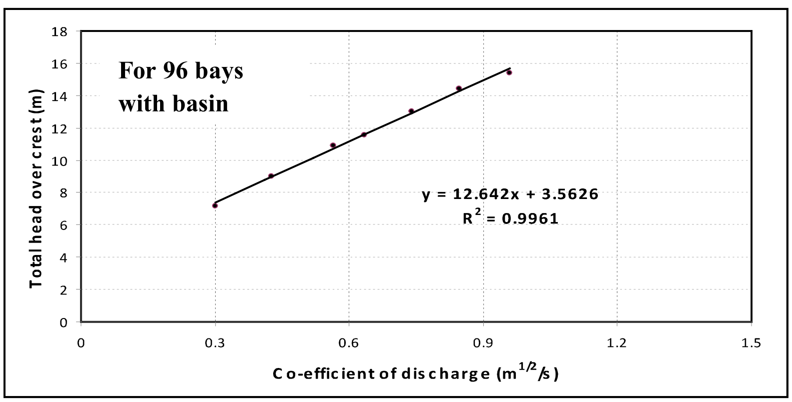

Figure 10 Head-co-efficient of discharge curve for 96 bays with basin blocks

3.2 Effect of Submergence on Discharge Co-efficient

The reduction in the co-efficient of discharge with submergence is shown in Figure 11 and Figure 12 for without and with basin blocks in place respectively. Cs/CF in the Figures is the ratio of co-efficient of submerged discharge to free discharge, corresponding to the same headwater level. On the other hand, h1/H is the ratio of downstream head over the crest to upstream total head over the crest. During the tests the tailwater level obtained from the rating curve for each discharge has been varied within a range. In reality the variation of the tailwater level for a particular discharge due to likely future retrogression and accretion will be high for low discharges and low for high discharges. For a particular discharge afflux is found to have increased with a decrease in the tailwater level i.e. afflux varies with submergence. It is to be noted here that a decrease in the tailwater level for a particular discharge results in a corresponding decrease in the headwater level and an increase in the approach flow velocity. It can be seen from the Figures that for the same submergence discharge co-efficient is higher for basin blocks in place compared to without basin block situation. Based on the test results for submerged unregulated flow afflux has been determined. It can be stated from the test results that the afflux value will be very less due to high submergence and as tailwater rating curves show that there will be little variation in the tailwater level for a particular high discharge. However, for design discharge a likely drop in the tailwater level by about 1m may result in an afflux of about 0.5m.

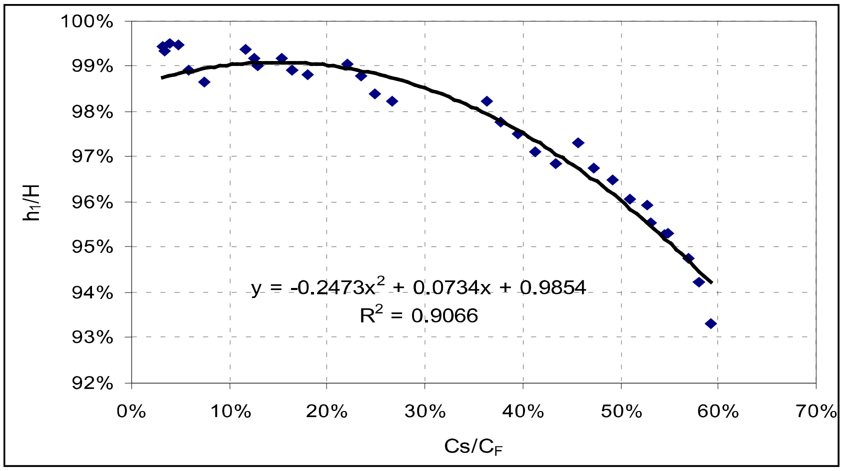

Figure 11 Reduction of discharge co-efficient with submergence (without basin blocks)

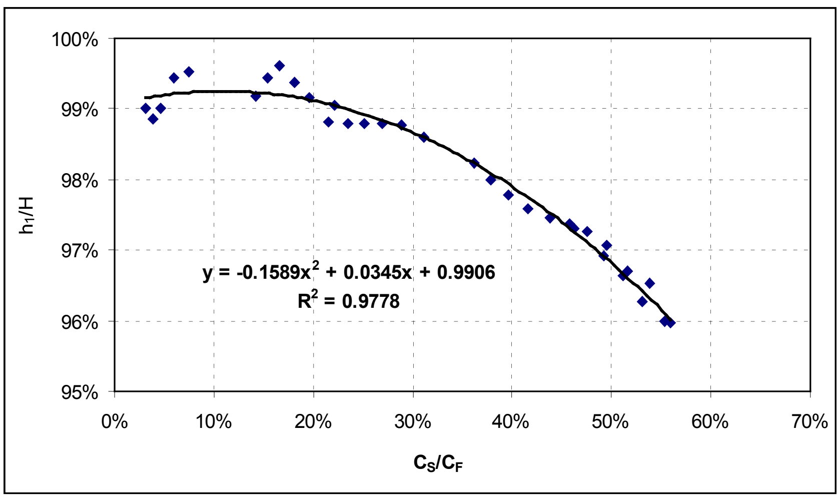

Figure 12 Reduction of discharge co-efficient with submergence (with basin blocks in place)

3.3 Water Surface Profiles

Water surface profiles for different discharges throughout the barrage section have been measured. For a particular discharge the profiles have been recorded for different levels of tailwater. The variation of water surface profile under varying tailwater levels for a discharge of 81820 m^3/s is shown in Figure 13.

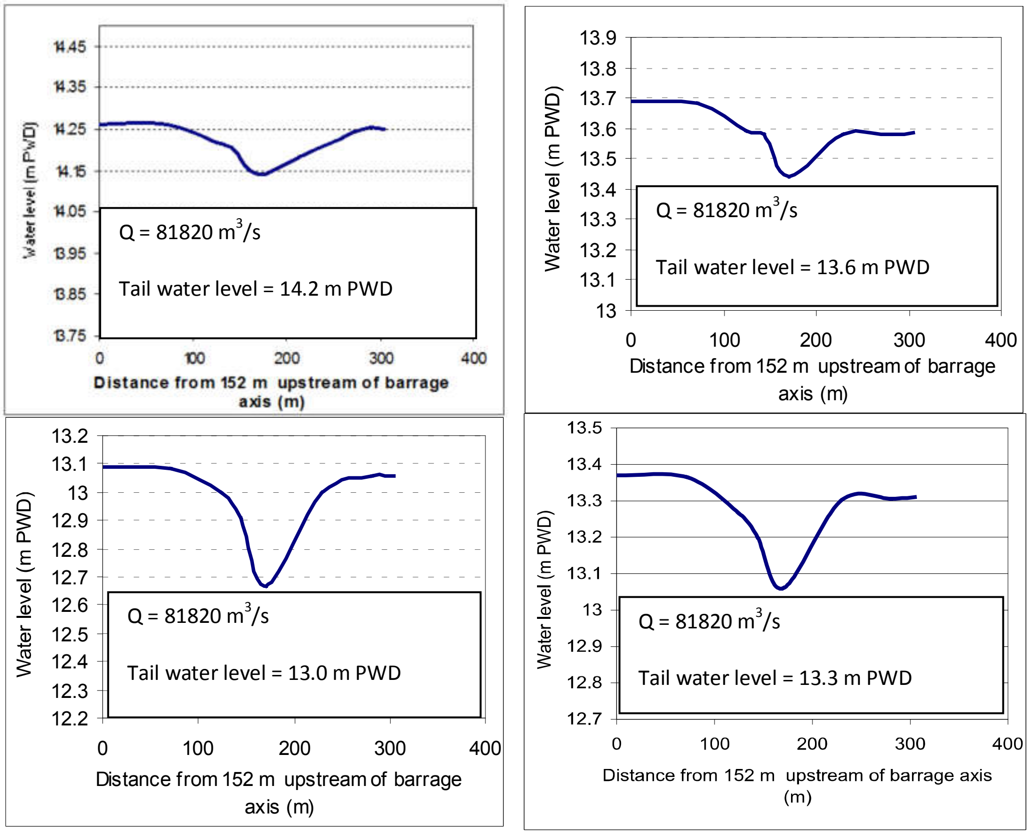

Figure 13 Variation of water surface profile under different tailwater levels for a discharge of 81820 m^3/s

It is to be noted here that 5 (five) well gauges have been installed in the model to record the water levels for determining water surface profiles. Among the five well gauges two lie in the upstream and three lie in the downstream of the barrage axis.

3.4 Scour and Water Surface Profiles

Tests have been conducted to determine the scour and water surface profiles downstream of the stilling basin with and without block protection and launching apron for different discharges in unregulated submerged flow conditions. Basin blocks have been reproduced according to the initial design (USBR Type II). During the test run for each discharge the development of scour with time has been recorded at a regular time interval and test run is continued until an equilibrium scour condition is reached. It is found that the scour holes for different discharges have reached an apparent state of stability within 2 (two) hours to 3 (three) hours. This will represent about 10 (ten) hours to 15 (fifteen) hours in the prototype. The test results without block protection and launching apron appear in Figure 14. The scour potential downstream of the stilling basin can be seen from Figure 14. For design discharge scour level downstream of the stilling basin could be as low as about -10.0 mPWD. Scour level can go down to -12.0 mPWD for a discharge of 100000 m3/s. During these tests a few test runs have been conducted keeping the bed beyond the upstream floor exposed to erosion. Large bed scour potential is also observed upstream of the barrage. However, no scour measurement has been taken there. Based on this information next tests have been conducted with block protection and launching apron both upstream and downstream of the barrage.

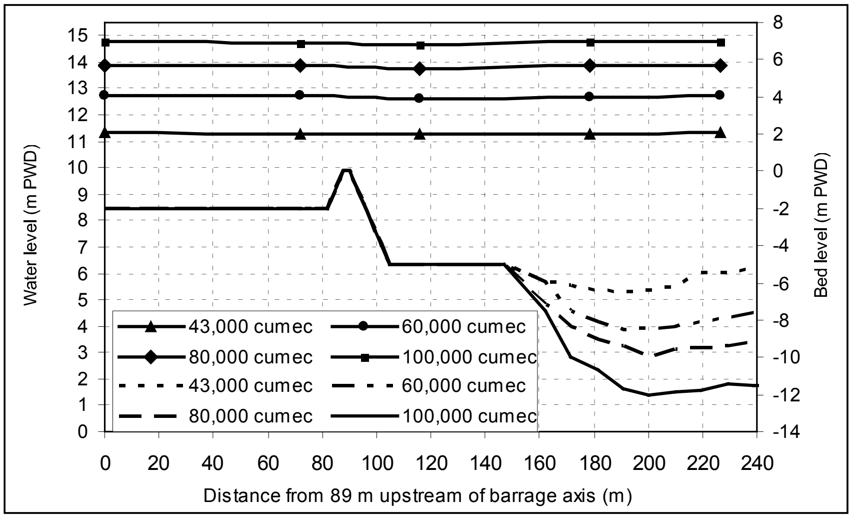

Figure 14 Water surface along with scour profiles downstream of stilling basin for different discharges

The block protection and launching apron both upstream and downstream of the barrage have been fabricated as per design. The placement of block protection downstream of the stilling basin is shown in Figure 15. The model is run with different discharges until equilibrium scour condition is reached. The water surface and scour profiles downstream of the block protection and launching apron for different discharges have been shown in Figure 16. It can be seen from Figure 16 that the deepest scour level downstream of the launching apron (assorted cc blocks) is as low as -8 mPWD and -10 mPWD for a discharge of 80,000 m^3/s and 100,000 m^3/s respectively. It is observed during the tests that bock protection remains fully intact for all discharges both upstream and downstream of the barrage.

3.5 Investigation of Stilling Basin

For investigation of the hydraulic performance of the stilling basin as designed, tests have been conducted in gated conditions. A critical test condition has been considered for the investigation. The downstream release through one bay is 200 m^3/s with tailwater elevation at 2.0 mPWD. The pond level is 12.5 mPWD. It is obvious that under this condition the amount of gate opening will have influence both on the nature of hydraulic jump downstream of the barrage and headwater level upstream.

Figure 15 Placement of block protection downstream of the stilling basin (RRI 2011)

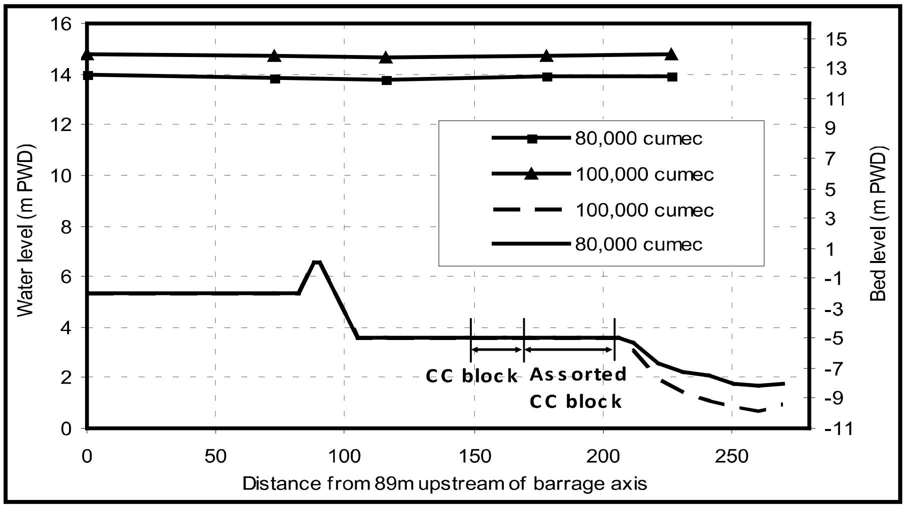

Figure 16 Water surface as well as scour profile downstream of the bed protection works for different discharges

It is observed that under this condition an oscillating form of jump occurs. The entering jet intermittently flows near the bottom and then along the surface of the downstream channel. This oscillating flow causes objectionable surface waves that carry far beyond the end of the basin. The hydraulic performance of two stilling devices has been tested. The stilling devices are (i) USBR Type II Basin and (ii) Low Froude Number Basin. The performance of the USBR Type II basin appears to be not up to the mark. The test results show that 0.96 m gate opening results in a headwater level of 11.8 mPWD. The hydraulic jump is found to have formed over the glacis at about 5.25 m downstream of the barrage axis. However, in the stilling basin waves have been observed that continue downstream even beyond the end sill with much wave activity. Substantial scour is observed at loose bed in the downstream of the stilling basin. High flow velocity is found just downstream of the end sill. It means Type II basin is less effective for dissipating the bulk of energy of flow. The alternative design of stilling basin (low Froude number basin) has chute blocks, baffle piers and a dentated end sill (Figure 17). It is observed that with this design of stilling basin the hydraulic jump gets stabilized within the stilling basin very well. Immediately downstream of the end sill velocity is found to have reduced substantially. And also scour downstream of the stilling basin is reduced.

A relationship has been developed between gate opening and headwater level wherefrom it is seen that about 0.92m gate opening will be needed for maintaining pond water level (12.5 mPWD) under this condition. Pertinent information of the hydraulic jump is furnished in Table 2.

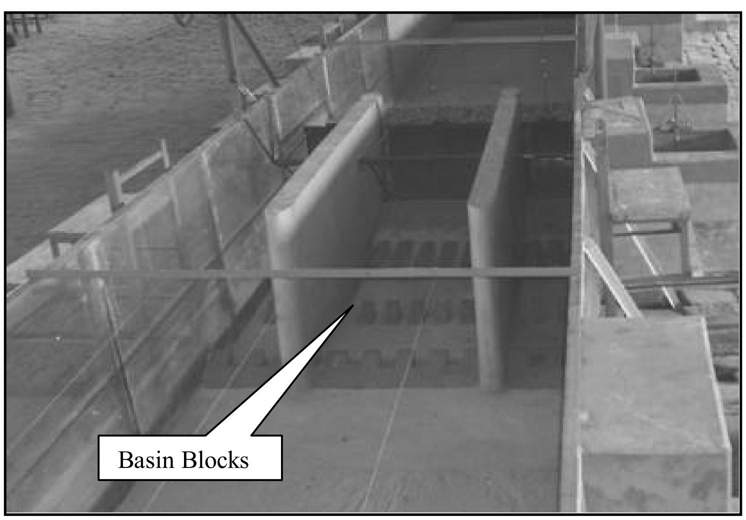

Figure 17 Arrangement of basin blocks in the model for low Froude number basin (RRI, 2011)

Figure 18 Nature of flow in low Froude No. stilling basin for the considered critical test condition (RRI, 2011)

Table 2 Hydraulic parameters of flow in low Froude number stilling basin (for critical test condition)

Prototype unit discharge (m^2/s)	Prototype Gate opening (m)	Headwater Level (mPWD)	Water Level at jump initiation point (mPWD)	Velocity at downstream of the end sill (m/s)	Distance from jump initiation point to crest (m)
11.11	0.84	13.36	-0.5000	1.47	5.20
11.11	1.01	11.56	-0.3600	1.55	4..90
11.11	1.18	9.85	-0.2200	1.65	4.56
11.11	1.34	7.52	-0.1000	1.87	4.39

4. CONCLUSIONS

The following conclusions have been drawn based on the study results:

- The adopted sill level, crest width, glacis slope and upstream and downstream floor level of the main spillway appear to be appropriate in terms of anticipated afflux, discharge co-efficient and bed scour upstream and downstream of the barrage etc.
- Total head over the crest and co-efficient of discharge for design discharge is 14.4 mPWD and 0.85 m1/2/s respectively with basin blocks in place (96 bays including undersluice bays)
- The anticipated scour level downstream of the stilling basin of the main spillway is observed to be as low as -10.0 mPWD for design discharge.
- Due to high submergence afflux will be very less for all discharges. However, a likely drop in the tailwater level by about 1m may result in an afflux of 0.5m for design discharge.
- Low Froude number basin with baffle blocks in addition to chute blocks and end sills functions well to stabilize the hydraulic jump within the stilling basin and to keep the jump position within the glacis slope. However, the adopted dimensions of the basin blocks may be reviewed for optimization of design.
- The block protection upstream and downstream of the main spillway as designed remains intact for very high (higher than design discharge) discharges.
- For a discharge intensity of 11.11 m2/s and tailwater level of +2.0 mPWD about 0.92 m gate opening will be needed for maintaining pond water level of 12.5 mPWD.
- Under prevailing tailwater condition the sweep out of hydraulic jump is unlikely to occur.

ACKNOWLEDGEMENTS

The authors are grateful to the Bangladesh Water Development board (BWDB) for financial support and Development Design Consultants Ltd. and Associates for providing necessary data, design drawings and feedback to conduct the study.

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