DESIGN SCOUR DEPTH AROUND THE PIER OF THE RAILWAY BRIDGE ACROSS THE JAMUNA RIVER IN BANGLADESH: A PHYSICAL MODEL BASED APPROACH

A. K. M. Ashrafuzzaman[1*], M. J. Islam[1], M. Shahabuddin[1], S. K. Ghosh[1], M. Tofiquzzaman[1], M. K. Eusufzai[2], M. Moniruzzaman[3,4] and M. E. A. Mondal[5]

Abstract

For further enhancement of the capacity and to overcome the loading restriction of existing Bangabandhu Sheikh Mujib Multipurpose Bridge, it would be essential to construct a parallel railway bridge, dedicated to railway, while the existing bridge could carry road traffic only. In this context, Bangladesh Railway has decided to construct the proposed Bangabandhu Sheikh Mujib Railway Bridge over the Jamuna River which will be located 300 m upstream of the existing bridge. Therefore, a study was undertaken by River Research Institute (RRI) to support the design required for the proposed railway bridge using scale modelling having scale 1:100. The study shows that maximum scour occurred around the bridge piers is 27.5 m (-21.0 mPWD) at pier-3 (of existing Bangabandhu Sheikh Mujib Multipurpose Bridge) & 39.4 m (-31.9 mPWD) at pier -3 (of proposed Bangabandhu Sheikh Mujib Railway Bridge) when a barrier is provided to impinge the flow on the revetment and bridge piers. The study also shows that maximum velocity around the bridge piers is 3.68 ms^{-1} & 4.52 ms^{-1} at existing bridge pier-2 & proposed bridge pier-2 respectively under 60-degree oblique flow attack at the bridge corridor guide bund. In addition, maximum scour around the revetment of west guide bund (WGB) is 29.5 m (-23.5mPWD) when the approach flow condition has been changed by providing a barrier to concentrate the flow around the upstream tip of revetment. Moreover, maximum velocity found around the revetment of WGB is 5.3 ms^{-1} (at the upstream tip of WGB) when the launching portion of revetment is strengthened as per design under 200-yr water level (WL) 14.49 mPWD and discharge (Q) 111,000 m^3s^{-1}.

Keywords: *Bangabandhu bridge, calibration, guide bunds, Jamuna River, River Training Work (RTW), Scour depth, Undistorted model and West Guide Bund (WGB).*

Introduction

Bangladesh is a riverine country having three major rivers namely the Ganges, the Meghna and the Jamuna. The Jamuna River, which is the mightiest of the three and which ranks as the fifth largest river in the world in terms of volumetric discharge and highest silt carrying river in the world. The construction work of Bangabandhu Bridge Project started in October 1994 and opened to traffic on 23 June 1998. The length of the bridge is 4.8 km and lengths of west & east guide bunds are 3.26 km and 3.07 km respectively. The guide bunds direct the river into a single channel under the bridge. A west channel closure has also been constructed to close the western channel of the Jamuna, thereby reducing the width of the river at the bridge site from about 10 km to 4.8 km. The main objective of the construction of the Bangabandhu Bridge was to establish a strategic link between the east and the west region of Bangladesh and to integrate the country by generating multifaceted benefits for the people, promoting better inter-regional trade and economic and social development. It enables quick movement of goods and passenger traffic by road and by rail across the Jamuna River.

In addition, its facility promotes transmission of electricity, transfer of natural gas and integration of telecommunication links. For further enhancement of the capacity and to overcome the loading restriction of Bangabandhu Bridge, it would be necessary to go for construction of a parallel Bangabandhu railway Bridge, dedicated to railway, while the existing the Bangabandhu Bridge could carry road traffic only. The proposed railway bridge is under construction. The model study was done before starting of the bridge construction in the field. The model boundary of West Guide Bund (WGB) is shown in **Fig.1.** The bridge will be located on the strategic Asian Highway and the Trans-Asian Railway which, when fully developed, will provide an interrupted international road and railway link from S.E. Asia to N.W. Europe. The roadway bridge is quite capable to connect the Asian Highway. But the existing Rail Track Bed over the Bangabandhu Bridge is not enough to link to the Trans-Asian Railway. The construction of Railway Bridge over the river Jamuna would also be helpful to ensure safe and less costly movement of passenger and goods between East and West region of Bangladesh as well as to promote the interconnectivity from S.E. Asia to N.W. Europe.

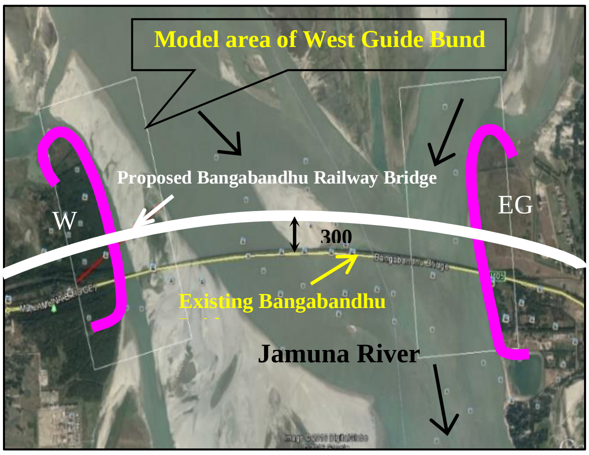

Fig. 1. Boundary of West Guide Bund (WGB) Model.

Scouring Process around Bridge Piers

Local scour involves the removal of material from around piers, abutments, spurs, and embankments. It is caused by an acceleration of the flow and resulting vortices induced by the flow obstructions. Local scour occurred at bridge piers are caused by the interference of the piers with flowing water. This interference will result in a considerable increase in the mean velocity of the flowing water in the channel section.

[1] Hydraulic Research Directorate, River Research Institute, Faridpur-7800, Bangladesh.
[*] Corresponding Author: (E-mail: ashrafcebuet89@gmail.com)
[2] Dhaka Laboratory, River Research Institute, Dhaka-1205, Bangladesh.
[3] Geotechnical Research Directorate, River Research Institute, Faridpur-7800, Bangladesh.
[4] Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh.
[5] Administration and Finance Directorate, River Research Institute, Faridpur-7800, Bangladesh.

Scouring vortex will be developed when the fast moving flow near the water surface (at the location of the maximum velocity in the channel section) strikes the blunt nose of the pier and deflected towards the bed where the flow velocity is low. Portion of the deflected surface flow will dive downwards and outwards. This will act as a vacuum cleaner and suck the soil particles at the pier site and result in a considerable increase in the scouring depth at this location. Local scour can occur as either 'clear-water scour' or 'live-bed scour'. In clear-water scour, bed materials are removed from the scour hole, but not replenished by the approach flow while in live-bed scour the scour hole is continually supplied with sediment by the approach flow and an equilibrium is attained when, over a period of time, the average amount of sediment transport into the scour hole by the approach flow is equal to the average amount of sediment removed from the scour hole. Under these conditions, the local scour depth fluctuates periodically about a mean value. The interaction between the flow around a bridge pier and the erodible sediment bed surrounding it is very complex (Cheremisinoff, 1998). In fact, the phenomenon is so involved that only very limited success has been achieved by the attempts to model scour computationally, and physical model remains the principal tool employed for estimating the expected depths of scour. In this paper, a physical model was used to investigate the effect of the variables affecting the clear-water local scour around piers.

Scour Depth Prediction

Scour around bridge piers has been the subject of many investigations throughout the world, and numerous scour prediction formulas have been published. Selected scour formulas related to the studied topic are described below. Shen (1971) suggested the following equation:

$$\frac{d_s}{b} = k_1\,k_2\,\frac{v}{2g} - \frac{30d}{b} \qquad \text{Eq. (1)}$$

where k_1 is a coefficient depending on pier dimensions, k_2 is a coefficient depending on the ratio of flowing depth to pier width and pier's Froude number, d_s is scour depth, v is the mean velocity of flow, b is pier width, g is acceleration due to gravity, and d is bed particle size. The unit of d in Eq. (1) is in centimetres, while the units of the rest of the parameters are in meters and seconds.

The scour depth is related to the Pier Reynolds number which is defined as the flow velocity multiplied by pier width divided by the kinematic viscosity of the flowing water, since the horseshoe vortex system is a function of the Pier Reynolds number. Shen *et al*. (1969) used laboratory data and limited field data to develop the following clear-water scour equation:

$$d_s = 0.00022R^{0.619} \qquad \text{Eq. (2)}$$

where R is Pier Reynolds number. Eq. (2) is valid only for a bed of particle size of 0.52 mm or less. The following linear equation was given by Shen (1971) to estimate the scour depth:

$$d_s = 1.4b \qquad \text{Eq. (3)}$$

Also, there were several non-linear formulas proposed by many researchers for the purpose of estimating the local scour depth, but the following formulas are famous and given by Cheremisinoff (1988):

$$d_s = 1.05kb^{0.75} \qquad \text{Eq. (4)}$$

$$d_s = 3b^{0.8} \qquad \text{Eq. (5)}$$

where k is a coefficient depending on pier shape and the value of k is equal to 1

for cylindrical pier and 1.4 for rectangular pier.

Equations (4) and (5) are applicable for a pier which is aligned with the flow direction. For piers which are inclined by an angle 0 from the flow direction (called the angle of attack), the value of this coefficient k_θ is equal to 1.1 as given by Melville and Sutherland (1988). They developed a scour model based on extensive laboratory experiments.

$$d_s = K_i K_d K_y K_\alpha K_s b \qquad \text{Eq. (6)}$$

where K_i is flowing intensity factor, K_d is sediment size factor, K_y is flowing depth factor, K_α is pier alignment factor, and K_s is pier shape factor.

Qadar (1981) studied the mechanism of the local scour around the bridge pier using physical model. The local scour depth is related to some of the basic characteristics of the scouring vortex as described by the following formula:

$$d_s = 538\,(C_0)^{128} \qquad \text{Eq. (7)}$$

where C_0 is the initial strength of the vortex. Equation (7) is applicable for sediments with a diameter up to 0.5 mm. Colorado State University's pier scour equation is commonly used within the United States and this equation is described by the following equation (USDT, 1993):

$$d_s = 2.0K_1K_2K_3\left(\frac{b}{y}\right)^{0.65} F^{0.43} \qquad \text{Eq. (8)}$$

where y is the flow depth directly upstream of the pier, K_1 is the shape factor for pier, K_2 is the factor for the angle of attack for the flow, K_3 factor for bed condition, and F is Froude number. The HIRE (2024) equation is based on field data of scour at the end of spurs in the Mississippi River (obtained by the USACE). The HIRE equation is:

$$y_s = 4y_1\left(\frac{K_1}{0.55}\right)K_2{Fr_1}^{0.33} \qquad \text{Eq. (9)}$$

Table 1. Description of Symbols.

Symbol	Description	Units
ys	Scour depth	m
$Fr1$	Froude number based on velocity and depth adjacent and just upstream of the abutment toe	
$y1$	Depth of flow at the toe of the abutment on the overbank or in the main channel, taken at the cross section just upstream of the bridge.	m
$K2$	Correction factor for angle of attack (θ) of flow with abutment. θ = 90 when abutments are perpendicular to the flow, θ < 90 if embankment points downstream, and θ > 90 if embankment points upstream. $K2=(\theta/90)0.13$	
$K1$	Correction factor for abutment shape (see table below)	

Table 2. Correction Factor for Abutment Shape, K1.

Description	K1
Vertical-wall Abutment with wing walls	0.82
Vertical-wall Abutment	1.00
Spill-through Abutment	0.55

The correction factor, $K2$, for angle of attack can be taken from the figure below.

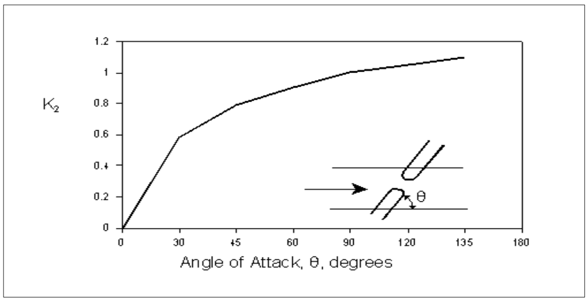

Fig. 2. Correction Factor for Abutment Skew, K2.

The scour depth calculated by Hire method is 33 m at WGB & 20 m at proposed rail bridge pier. But the maximum scour depth found from physical model study around WGB is 29.5 m, which is less than the Hire method and proposed rail bridge pier 39.4 m (around two times the Hire method).

Methodology

About 3.0 km river length and a part width of about 1.0 (one) km of the Jamuna River including existing roadway bridge and proposed rail bridge have been reproduced in the WGB model. Model bed and bank are composed of fine sand having d_{50} about 0.085mm. Maximum flood discharge of 100-year, 200-year & 500-year return period is taken into account to investigate the model with two different discharge conditions. One is Froudian discharge, and the other is scouring discharge for scour development. Froudian discharge provides the flow pattern and velocity field as a whole and the scour discharge focuses on the scour simulation and sediment transport. Each test of the model continues about 16-20 hours until a dynamic equilibrium scour is reached. The need for reliable field data on the flow and sediment transport processes is of immense importance in the scaling process. The previous information and present surveyed data were taken into consideration for calculating different parameters. The WGB model has been designed so that the scale conditions for simulation of flow field, sediment transport and local scour are satisfied. The scale conditions are described below:

a) Geometric Condition

The detail models should be undistorted *i.e.*, $L_r = h_r$, where L_r= horizontal scale and h_r = vertical scale.

b) Roughness Condition

In the model the following roughness condition is required in order to reproduce the flow field properly. But in this model some deviation is occurred as the model is rougher.

$C_r^2 = L_r/ h_r = 1$, where, Cr = roughness scale

In the movable bed model following scale condition for sediment transport should be satisfied:

$V_m>V_{cr}$, V_{cr} in the model will be calculated using the following formula:

$$V_{cr} = 0.19(d_{50})^{0.1} \log (12h/3d_{90}) \text{ for } 0.0001m \leq d_{50} \leq 0.0005m$$

Where, d_{50} = Median particle diameter (m), d_{90} = 90% particle diameter (m)

The critical velocity for sediment transport can also be calculated from the critical Shields value. The critical velocity in the model has been calculated from the following equations.

$$D_* = d_{50} \{(s-1)\, g/v^2\}^{1/3}$$

$$\theta_{cr} = 0.14D_*^{(-0.64)} \text{ for } 4<D_*<=10$$

$$\theta_{cr} = 0.24D_*^{(-1)} \text{ for } 1<D_*<=4$$

$L_r/ h_r = 1$ Where, Cr = roughness scale

c) Froude Condition

The Froude condition is fulfilled which holds when: $V_r = h_r^{0.5}$

d) Sediment Transport Condition

$$V_{cr} = \{\theta_{cr} (s\text{-}1)\, d_{50} C^2\}^{1/2}$$

In which, D_* = Particle parameter, d_{50} = Median grain size, s = Relative density of the sediment,

v = Kinematic viscosity, C = Chezy co-efficient and θ_{cr} = Critical shields parameters.

The critical flow velocity for median particle diameter of model bed sand (0.085mm) has been determined from the above equations. The investigation is aimed at the equilibrium scour depth with continuous sediment transport. A requirement in this type of model is that in the model sediment transport has to be occurred at all locations as it occurs in prototype. In order to fulfil this condition an increase in the model velocity has been considered to ensure the sediment transport upstream and downstream of the proposed bridge. In this situation the scour hole characteristics are not influenced by the size of the bed material or approach flow velocity.

Test Scenarios

In the WGB model, two calibration tests (T0-1 & T0-2) and seven application tests (T1-T7) have been conducted.

The test scenarios of these test run along with various discharge / WL conditions are mentioned in **Table 3.**

Table 3. Test Scenarios of the WGB Model.

Test Scenarios	Discharge & Water Level Conditions
T0-1: Calibration test with existing structure (Bangabandhu Roadway Bridge) using bathymetry of July 2017 and measured field velocity.	Observed Water Level 13.72 mPWD and discharge 89,600 m^3s^{-1}.
T0-2: Calibration test with existing structure (Bangabandhu Roadway Bridge) using simulated velocity corresponding to 100-yr discharge.	100-year Water Level 14.14 mPWD and discharge 101,506 m^3s^{-1}
Application Test-T1 With piers and revetment of Bangabandhu bridge. Flow alignment near the bank/in line with pier.	100-year Water Level 14.41 mPWD and discharge 105,552 m^3s^{-1} 500-year Water Level 14.62 mPWD and discharge 118,668 m^3s^{-1}
Application Test-T2 Test to assess bridge-to-bridge pier & bridge-to-revetment interaction with proposed bridge and Bangabandhu bridge and piers of Bangladesh Railway (BR) bridge. Flow in-line with the existing and proposed bridge pier.	100-year Water Level 14.38 mPWD and discharge 105,552 m^3s^{-1}
Application Test-T3 Test to assess bridge-to-bridge pier & bridge-to-revetment interaction with proposed bridge and Bangabandhu bridge having modified revetment and piers of BR bridge. Flow alignment is at the tip in bridge corridor away from the guide bund. The proposed bridge piers are tested with an angle of 53-degree with the approach flow/revetment alignment.	200-year Water Level 14.49 mPWD and discharge 111,000 m^3s^{-1}
Application Test-T4 Test to assess bridge-to-bridge pier & bridge-to-revetment interaction with proposed and existing bridge piers and revetment. The proposed bridge piers are tested with an angle of 45-degree with the approach flow/revetment alignment. The pile cap of proposed SPSP bridge piers is raised to a level of 14.2mPWD.	500-year Water Level 14.53 mPWD and discharge 118,668 m^3s^{-1}
Application Test-T5 Test to assess bridge-to-bridge pier & bridge-to-revetment interaction with proposed &existing bridge piers and existing revetment only. The proposed bridge piers are tested with an angle of 45-degree with the approach flow/revetment alignment. The pile cap of proposed SPSP bridge piers is kept at a level of 8mPWD. Here the approach flow condition has been changed by providing a temporary brick wall as lateral boundary to concentrate the flow around the u/s tip of revetment. The objective of this test to produce additional local scour around the u/s tip of revetment by concentrating flow around it.	100-year discharge 105,552 m^3s^{-1} and corresponding Water Level of 14.41mPWD.

Test Scenarios	Discharge & Water Level Conditions
Application Test-T6	100-year, 200-year and 500-year
Test to assess the scour around the bridge corridor. A char was developed at the u/s of bridge corridor so that an oblique flow attack of about 60-degree is reproduced at the WGB corridor.	The corresponding Water Level 14.38, 14.49 and 14.53 mPWD and discharge 105,552, 118,668 and 137036 m^3s^{-1}
Application Test-T7	500-year Water Level 14.62 mPWD.
The proposed bridge piers are tested with an angle of 45-degree with the approach flow/revetment alignment. The objective of this test is to impinge the flow at the middle portion of WGB by introducing some interventions.	

Model Setup

The WGB model is setup in the indoor model bed (100mX25m) of RRI using the available facilities. On the basis of topographic, bankline and bathymetric survey of July 2017 the model bed is constructed. The model setup consists of model bed preparation, water circulation system, construction of stilling pond, installation of point gauges and measurement of water level, discharge, velocity and outflow condition. The model setup for this model is done using the available indoor facilities of RRI. After calibration of the model the application tests are conducted with 100-year, 200-year & 500-year Return Period discharges. These data are used to measure the flow velocity, scour depth and float tracking. Existing bridge piers of the Bangabandhu Bridge is composed of racking piles. On the other hand, the proposed Bangabandhu Rail bridge pile groups are SPSP type with larger diameter as a whole. The model is tested with present bathymetry as well as assumed bathymetry which might occur in severe situation. The layout of the WGB model is shown in **Fig. 3.**

The scour hole around the structure is almost independent of bed material when the average velocity in the model is about 2-2.5 times the critical velocity for sand movement. But, like on the prototype, it is influenced only by the flow pattern, the geometry of the structure and cross-section. However, field observation as well as available formulae for scour estimation can also be taken into account during the design of the piers. Thus, live bed scour condition is ensured in the model at which equilibrium scour depth is reached when, over a period of time, the eroded material equals the supplied material from upstream. Sediment is fed into the model manually. Generally, the rate of sediment feeding for a particular model discharge is determined first by using sediment transport formulae/relation proposed by different researchers. For this model the sediment transport formulae proposed by Engelund and Hansen (1967) has been used to determine the initial sediment feeding rate. The sediment feeding rate, however, has been calibrated. The calibration of sediment feeding rate has been done by taking measurements of bed levels along a few cross-sections located at different parts of the model at a regular interval of time. Calibration of sediment feeding rate involves a condition where bed level remains more or less unchanged. It means whatever sediment is fed into the model is transported out of the model.

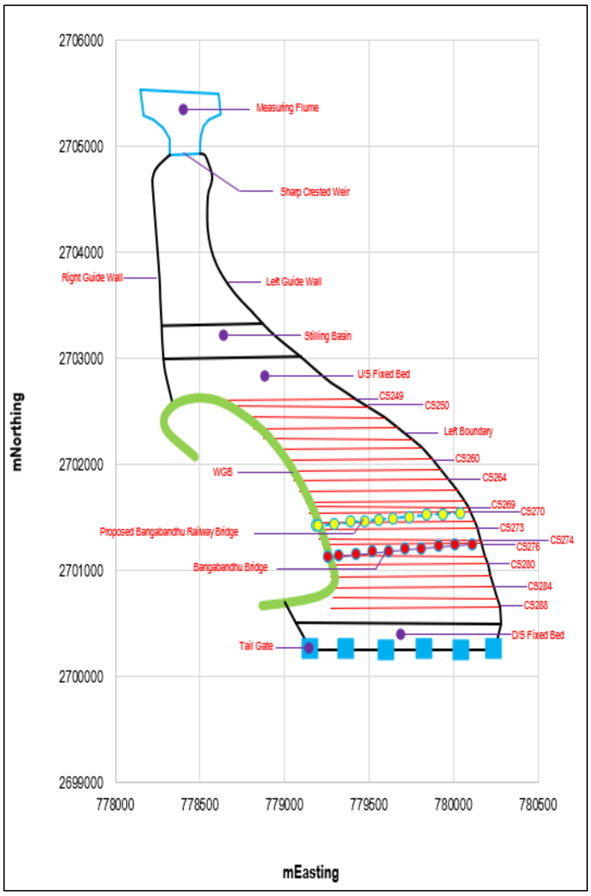

Fig. 3. Layout of the WGB Model.

As per selected scale it is found that the maximum equilibrium scour around the structure reaches within 10-15 hours in the model. One hour in the model corresponds to about 48 hours in the prototype which is computed based on Meyer-Peter and Muller Formulae that used in FAP study. That means the maximum scour which reaches in equilibrium within one day in the model is expected to happen in the prototype/in the field within 48 days. However, these are estimation. For more information, field measurement is more appropriate.

Table 5. Hydro-morphological Parameters for WGB Model

Description	Unit	Prototype	Model	Scale
Sectional length, L	m	3000	30	100
Sectional width at CS-Calibration (CS-280)	m	950	9.50	100
Sectional average water depth, h	m	4.64	0.046	100
Water surface slope, i	-	0.000075	0.000450	0.1667
Sectional average velocity, v	ms^{-1}	2.06	0.206	10
Sectional cross-sectional area, A	m^2	4178	0.4178	10000
Roughness height (K_s)	m	-	0.02500	-
Critical velocity by van Rijn, v_{cr}	ms^{-1}	-	0.100	-
Chezy roughness co-efficient, C	$m^{1/2}s^{-1}$	80	30	-
Sectional discharge, Q	m^3s^{-1}	8627	0.086	100000
Scour discharge, Q_s	m^3s^{-1}	-	0.126	82350
Median particle diameter, D_{50}	m	0.00016	0.000085	-
Dimensionless particle diameter, D*	-	3.584	1.904	-
Shields parameter, Ɵ	-	1.318	0.149	-
Critical Shields parameter, $Ɵ_{cr}$	-	0.067	0.126	-
Froude number, Fr	-	0.306	0.306	1
Shear velocity, v*	ms^{-1}	0.058	0.014	-
Critical shear velocity, $v*_{cr}$	ms^{-1}	0.01317	0.01317	-
Particle Reynolds number, Re*	-	1.756	0.933	-
Reynolds number, Re	-	7984431	7984	-
Sediment Transport by Enguland-Hansen	m^3hr^{-1}	9190.80	0.22	42638
Critical velocity by Sheilds, v_{cr}	ms^{-1}	0.336	0.126	-
Fall velocity, w	ms^{-1}	0.01918	0.00541	-
Shear velocity/fall velocity, v*/w	-	3.046	2.643	-
Drag force co-efficient, C_d	-	0.47	0.49	-

Results and Discussion

Test T0-1 is done with existing bridge structure using bathymetry of July 2017 and measured field velocity. Test T0-2 is conducted with existing structure using simulated velocity corresponding to 100-yr discharge. Test T1-a is carried out with Bangabandhu bridge and 100-yr WL 14.41 mPWD & discharge 105,552 m^3s^{-1}. Maximum scour in this test is found about 13.2m (-8.9 mPWD) at pier P2 (existing). Test T1-b is carried out with existing bridge structure and 500-yr WL 14.62 mPWD & discharge 118,668 m^3s^{-1}. Maximum scour is 13.3m (-9.0 mPWD) at pier P2 (existing). This value is little bit more than that of test T1-a because of slightly more discharge & WL. To assess bridge-to-bridge pier & bridge-to-revetment interaction with existing & proposed bridge structure, test T2 is conducted with 100-yr WL 14.38 mPWD & discharge 105,552 m^3s^{-1}. In this test, maximum scour is 11.8m (-8.5 mPWD) at existing pier P2 and 13.3m (-6.70 mPWD) at proposed pier P3. Here scour is more around proposed pier as it experienced more obstruction and turbulence compared to the existing pier. In test T3, flow impinges at an angle of 53-degree with the proposed bridge piers having strengthened revetment of WGB using 200-yr WL 14.49 mPWD and discharge 111,000 m^3s^{-1}. In this case, maximum scour is 4.4 m (-15.1 mPWD) at existing pier P4 and 13.8m (-7.40 mPWD) at proposed pier P5.

Table 6. Maximum Scour and Velocity around Piers of WGB Model**.**

Test No.	Maximum scour (m) around existing bridge piers		Maximum scour (m) around proposed bridge piers		Maximum velocity (ms^{-1}) around existing bridge piers		Maximum velocity (ms^{-1}) around proposed bridge piers		Test conditions
	u/s	d/s	u/s	d/s	u/s	d/s	u/s	d/s	
T1-a	13.20 m (P2) (-8.9mPWD)	11.40 m (P3) (-3.8mPWD)	No pier Final bed level (-1.69mPWD)	No pier Final bed level (-1.69mPWD)	3.03 ms^{-1} (P1)	3.12 ms^{-1} (P1)	-	-	(a) With piers and revetment of Bangabandhu bridge. 100-yr WL 14.41 mPWD and discharge 105,552 m^3s^{-1}.
T1-b	13.30m (P2) (-9.0mPWD)	11.60m (P3) (-4.0mPWD)	No pier Final bed level (-1.70mPWD)	No pier Final bed level (-1.70mPWD)	3.54 ms^{-1} (P1)	3.65 ms^{-1} (P1)	-	-	(b) With piers and revetment of Bangabandhu bridge. 500-yr WL 14.62 mPWD and discharge 118,668 m^3s^{-1}.
T2	11.80m (P2) (-8.50mPWD)	11.80m (P2) (-8.60mPWD)	13.30m (P3) (-6.70mPWD)	10.30m (P3) (-4.0mPWD)	3.15 ms^{-1} (P1)	3.15 ms^{-1} (P2)	3.25 ms^{-1} (P2)	3.57 ms^{-1} (P2)	Test to assess bridge-to-bridge pier & bridge-to-revetment interaction with proposed bridge and Bangabandhu bridge and piers of proposed bridge. 100-yr WL 14.38 mPWD and discharge 105,552 m^3s^{-1}.
T3	3.70m(P4&P5) (-15.1mPWD & -14.9mPWD)	4.40m (P4) (-15.1mPWD)	13.80m (P5) (-7.40mPWD)	12.30m (P6) (-25.8mPWD)	3.36 ms^{-1} (P3)	3.36 ms^{-1} (P2)	3.04 ms^{-1} (P5,6)	3.36 ms^{-1} (P4)	Test to assess bridge-to-bridge pier & bridge-to-revetment interaction with proposed bridge and Bangabandhu bridge having modified revetment and piers of BR bridge. 200-yr WL 14.49 mPWD and discharge 111,000 m^3s^{-1}. Flow impinging at an angle of 53-degree with the proposed bridge piers. The model bed is prepared (-13.99 mPWD around the tip of WGB and -10.86 mPWD at other portion) as per design.
T4-a	-	-	-	-	2.41 ms^{-1} (P2)	2.51 ms^{-1} (P2,3)	2.51 ms^{-1} (P3)	3.25 ms^{-1} (P3)	(a) Test to assess bridge-to-bridge pier & bridge-to-revetment interaction with proposed and existing bridge piers and revetment. This test is conducted with 500-yr WL 14.53mPWD and discharge 118,668 m^3s^{-1}. The pile cap of proposed SPSP bridge piers is raised to a level of 14.2mPWD from 1.2mPWD. Flow impinging at an angle of 45-degree with the proposed bridge piers.

Test No.	Maximum scour (m) around existing bridge piers		Maximum scour (m) around proposed bridge piers		Maximum velocity (ms^{-1}) around existing bridge piers		Maximum velocity (ms^{-1}) around proposed bridge piers		Test conditions
	u/s	d/s	u/s	d/s	u/s	d/s	u/s	d/s	
T4-b	27.5m (P3) (-21.0mPWD)	25.80m (P3) (-19.8mPWD)	39.4m (P3) (-31.9mPWD)	38.6m (P3) (-28.1mPWD)	-	-	-	-	(b) This test is same as test T4.a but additionally a temporary brick wall is provided to impinge the flow on the revetment and bridge piers.
T5	15.6m (P3) (-7.8mPWD)	14m (P3) (-6.5mPWD)	22m (P3) (-14.5mPWD)	21 (P3) (-13.3mPWD)	2.41 ms^{-1} (P3)	2.62 ms^{-1} (P3)	2.09 ms^{-1} (P2,3)	2.93 ms^{-1} (P2)	Test to assess bridge-to-bridge pier & bridge-to-revetment interaction with proposed & existing bridge piers and existing revetment only. This test is conducted with 100-yr discharge 105552 m^3s^{-1} and corresponding WL of 14.41mPWD. The pile cap of proposed SPSP bridge piers is kept at a level of 8mPWD. Flow impinging at an angle of 45-degree with the proposed bridge piers. Here the approach flow condition has been changed by providing a temporary brick wall to concentrate the flow around the u/s tip of revetment.
T6	14m (P2) (-10mPWD)	13.6m (P3) (-6.0mPWD)	31.7m (P3) (-23.6mPWD)	26.3m (P3) (-18.2mPWD)	0-3.68 ms^{-1} (P2)	3.57 ms^{-1} (P2)	3.36 ms^{-1} (P2)	4.52 ms^{-1} (P2)	This test is done with about 60-degree oblique flow angle of attack at the bridge corridor guide bund. To achieve this a char is developed in the model u/s of the proposed bridge. Flow impinging at an angle of 45-degree with the proposed bridge piers. This test is conducted with 100-yr, 200-yr & 500-yr WL which is respectively 14.38, 14.49 & 14.53 mPWD. The corresponding discharge is 105,552, 118,668 & 137036 m^3s^{-1}.
T7	3.5m (P4) (1.9mPWD)	1.5m (P3) (-7.5mPWD)	18.6m (P3) (-20.2mPWD)	11.3m (P3) (-18.8mPWD)	0.6-1.13 ms^{-1} (P4-P2)	1.35 ms^{-1} (P2)	1.35 ms^{-1} (P2)	1.77 ms^{-1} (P2)	This test is conducted using the bed level of test T6 after run but there are some changed in the bed level. The proposed bridge piers are tested with an angle of 45-degree with the approach flow/revetment alignment. The test is conducted with 500-yr WL 14.62 mPWD. The objective of this test is to impinge the flow at the middle portion of WGB by introducing some interventions.

Test T4.a is done with 500-yr WL 14.53 mPWD & discharge 118,668 m^3s^{-1} where the pile cap of proposed SPSP bridge piers is raised to a level of 14.2 mPWD from 1.2 mPWD. Test T4.b is same as test T4.a but here a barrier is provided to impinge the flow on the revetment and bridge piers. Maximum scour among the proposed & existing bridge piers occurred in test T4.b [39.4 m (-31.9 mPWD)] at u/s of proposed pier P3. This is due to the provision of barrier for impinging flow. In this test, maximum total scour around the existing bridge piers is 27.5m (-21.0 mPWD) at u/s of pier P3. The WGB model during running condition (T4.b) is shown in **Fig. 4.** The scour in the vicinity of proposed & existing bridge pies in WGB model (Test T4.b) is shown in **Fig. 5.** Test T5 is conducted with 100-year discharge of 105552 m^3s^{-1} and corresponding WL of 14.41 mPWD. The pile cap of proposed SPSP bridge piers is kept at a level of 8.0 mPWD instead of 14.2 mPWD. Here the approach flow condition has been changed by providing a temporary barrier as lateral boundary to concentrate the flow around the u/s tip of revetment. Maximum scour is 22 m (-14.50 mPWD) at proposed pier P3. Maximum total scour at the proposed pier P3 is 31.7m (-23.6 mPWD) of which about 20 m is general scour & confluence scour in test T6 which is conducted with 60-degree oblique flow attack at the bridge corridor guide bund. To achieve this, a char is developed in the model u/s of the proposed bridge. The objective of test T7 is to impinge the flow at the middle portion of WGB by introducing some interventions. Here maximum scour is found 18.6 m (-20.2 mPWD) at pier P3 (proposed). Maximum velocity among the proposed & existing bridge piers is found in test T6 (4.52 ms^{-1} at proposed pier P2). Maximum scour around the WGB occurred in test T5 [29.5 m (-23.5 mPWD) around the u/s tip of revetment of WGB]. Maximum velocity around the WGB occurred in test T3 which is 5.3 ms^{-1} at the u/s tip of WGB. Maximum scour and velocity found around the existing and proposed bridge piers under different test scenarios can be seen in **Table 6.** Maximum scour and velocity around the revetment of WGB is shown in **Table 7.**

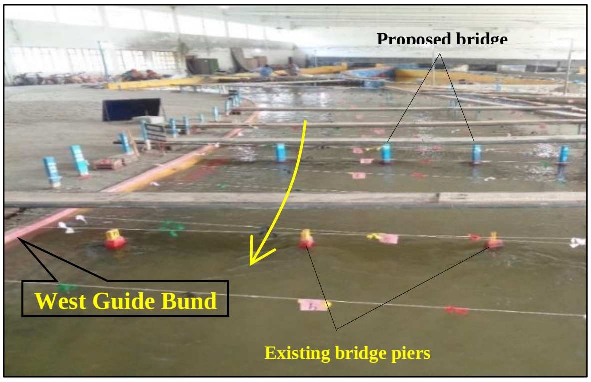

Fig. 4. WGB model during running condition (T4.b).

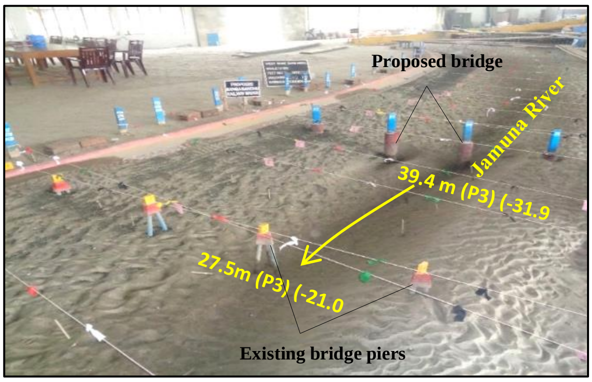

Fig. 5. Scour in the vicinity of proposed & existing bridge pies in WGB model (Test T4.b).

Table 7. Maximum Scour and Velocity around Revetment of WGB Model

Test No.	Maximum scour (m) around WGB	Maximum velocity (m/s) around WGB
T1-a	-	3.49m/s (90m away from R/B along CS-273)
T1-b	10.2m (-4.9mPWD) (160m away from R/B, CS-284)	3.76m/s (90m away from R/B along CS-273)
T2	9.3m (-4.7mPWD) (119m away from R/B, CS-282)	3.57m/s (80m away from R/B along CS-273)
T3	6.3m (-16.6mPWD) (5:778504mE, 2702818mN)	**5.3m/s (tip of WGB) (778605mE, 2702812mN)**
T4-a	-	4.21m/s (180m away from R/B along CS-250)
T4-b	19.1m (-9.9mPWD) (208m away from R/B along CS-250)	-
T5	**29.5m (-23.5mPWD) (778504mE, 2702818mN)**	3.46m/s (95m away from R/B along CS-250)
T6	12.6m (-8.6mPWD) (140m away from R/B along CS-278)	3.89m/s (95m away from R/B along CS-250)
T7	6.2m (-6.7mPWD) (165m away from R/B along CS-254)	1.88m/s (120m away from R/B along CS-254)

Conclusion

In the WGB model, 2 (two) calibration and 7 (seven) application tests are completed. The maximum scour occurred around proposed & existing bridge piers in test T4.b. This test is conducted with 500-yr WL 14.53 mPWD and discharge 118,668 m^3s^{-1}. The pile cap of proposed SPSP bridge piers is raised to a level of 14.2 mPWD from 1.2 mPWD. Here a temporary brick wall is provided to impinge the flow on the revetment and bridge piers. The maximum total scour around the proposed bridge piers is 39.4m (-31.9 mPWD) at u/s of pier P3 and 38.6m (-28.1 mPWD) at d/s of pier P3. The maximum velocity is 3.25 ms^{-1} at d/s of pier P3. The maximum total scour around the existing bridge piers is

27.5m (-21mPWD) at u/s of pier P3 and 25.8m (-19.8 mPWD) at d/s of pier P3. The maximum velocity is 2.51 ms^{-1} at d/s of pier P2, P3.

The maximum scour around the guide bund occurred in test T5 which is conducted with 100-yr discharge 105,552 cumec and corresponding WL of 14.41 mPWD. The pile cap of proposed SPSP bridge piers is kept at a level of 8mPWD instead of 14.2 mPWD. Here the approach flow condition has been changed by providing a temporary brick wall as lateral boundary to concentrate the flow around the u/s tip of revetment. The maximum scour is 29.5m (-22.60 mPWD) at the u/s tip of WGB [at point 5 (778504mE, 2702818mN)]. The maximum velocity around the guide bund occurred in test T3 which is conducted with 200-yr WL of 14.49 mPWD and discharge of 111,000 m^3s^{-1}. The proposed bridge piers are tested with an angle of 53 degree with the approach flow/modified revetment alignment. The maximum velocity is 5.3 ms^{-1} at the u/s tip of WGB [at point 7 (778605mE, 2702812mN)].

Maximum total scour at the proposed bridge piers is 30.6m (-22.5 mPWD) (u/s of pier P3) of which about 20m is general scour & confluence scour in test T6 which is done with about 60 degree oblique flow angle of attack at the bridge corridor guide bund. To achieve this a char is developed in the model u/s of the proposed bridge. This test scenario is selected as per guidelines of RRI's outsourcing Senior Design Engineer and discussing with the RTW specialist of the BRBP. Maximum total scour at the existing bridge piers is 14m (-10 mPWD) (u/s of pier P2). Maximum velocity around the proposed bridge piers is 4.54 ms^{-1} (d/s of pier P2) and around the existing bridge piers is 3.68 ms^{-1} (u/s of pier P2). The maximum scour depth found in the physical model conducted at RRI is 29.5m around the WGB and 39.4m around the proposed rail bridge pier. The maximum scour depth calculated by Hire method is 33m at the WGB & 20m at the proposed rail bridge pier. The scour depths obtained by physical model testing differs to some extent from Hire method.

The assessment of the bridge-to-bridge and bridge to RTW interactions are given below:

Existing Bridge- Scour

It is observed in general that with the same bathymetry and approach flow condition, the proposed rail bridge piers experienced more scour than the existing bridge piers since the proposed rail bridge experienced more obstruction and turbulence due its location, shape and size compared to the existing piers.

Existing Bridge- Velocity

The change in velocity to the existing bridge due to the proposed bridge is not noticeable under the tested planforms and flow conditions although the two bridges are only 300 m away from each other.

Existing Bridge- Deposition

Deposition tendency is observed between the two bridges in the model study due to the obstruction of flow.

WGB- Velocity

The change in velocity at the WGB due to the proposed bridge is not noticeable under the tested planforms and flow conditions although the same guide bund will be used for two bridges.

WGB- Scour/Deposition

The WGB model is constructed with sectional width. Moreover, different modelling techniques are adopted to create severe condition in the model. So, aggradation and degradation tendency as a whole is not possible to report. Scour & deposition both observed irregularly in WGB model and it was due to the different tested flow conditions and planforms.

Performance of Modified Design of Revetment

The modified design of the revetment is found to work effectively.

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