

**FLOOD AND RIVERBANK EROSION
RISK MANAGEMENT INVESTMENT PROGRAM (FRERMIP)
PROJECT-1**

ADB LOAN NO. 3138-BAN (SF) AND GRANT NO. 0396-BAN (EF)

**TECHNICAL NOTE: 3-D NUMERICAL MODELLING OF TOP BLOCKED
SPURS**

Prepared for:

Bangladesh Water Development Board (BWDB)
Dhaka, Bangladesh

Prepared by:

Institutional Strengthening and Project Management Consultant (ISPMC)

Joint Venture
NORTHWEST HYDRAULIC CONSULTANTS LTD/EUROCONSULT MOTT MACDONALD

July 2017

Prepared by:

Principal Author: Angela Thompson, Numerical Modeller
Erik Mosselman, Morphologist

Reviewed by:

Knut Oberhagemann, ISPMC Team Leader

Name, Designation
Job Title

Name, Designation
Job Title

DISCLAIMER

This report has been prepared by **JV Northwest Hydraulic Consultants – Euroconsult Mott MacDonald** for the benefit of the **BANGLADESH WATER DEVELOPMENT BOARD (BWDB)** for specific application to the **FLOOD AND RIVERBANK EROSION RISK MANAGEMENT INVESTMENT PROGRAM (FRERMIP) PROJECT-1; ADB LOAN NO. 3138-BAN (SF) AND GRANT NO. 0396-BAN (EF)**. The information and data contained herein represent **JV Northwest Hydraulic Consultants – Euroconsult Mott MacDonald** best professional judgment in light of the knowledge and information available to **JV Northwest Hydraulic Consultants – Euroconsult Mott MacDonald** at the time of preparation, and was prepared in accordance with generally accepted engineering practices.

Except as required by law, this report and the information and data contained herein are to be treated as confidential and may be used and relied upon only by **BANGLADESH WATER DEVELOPMENT BOARD (BWDB)**, its officers and employees. **JV Northwest Hydraulic Consultants – Euroconsult Mott MacDonald** denies any liability whatsoever to other parties who may obtain access to this report for any injury, loss or damage suffered by such parties arising from their use of, or reliance upon, this report or any of its contents.

TABLE OF CONTENTS

TABLE OF CONTENTS	I
LIST OF TABLES	II
LIST OF FIGURES	II
1 PURPOSE AND BACKGROUND	3
2 PERMEABLE SPUR DESIGN PARAMETERS.....	3
3 MODEL OUTLINE.....	6
4 RESULTS AND DISCUSSION	9

LIST OF TABLES

Table 1: Equation parameters	4
Table 2: Permeability of the spur	6
Table 3: Modelling parameters	8
Table 4: Effectiveness of the different spurs compared to the simulation with no spurs	14

LIST OF FIGURES

Figure 1: Lower Bhadra (image from Google Earth, November 2016)	3
Figure 2: Design graph for permeable spurs made of steel (from the FAP 21/22 guideline)	5
Figure 3: Cross sectional view of the model domain	7
Figure 4: Dimensions of the model	7
Figure 5: Convergence of the monitoring points	8
Figure 6: Y^+ values along the riverbed	9
Figure 7: Mesh independence	9
Figure 8: Lines where measurements were extracted (1.5 m from the surface level)	9
Figure 9: Total velocity along cross sections of the four simulations	10
Figure 10: Velocity in the lateral direction along cross sections of the four simulations	10
Figure 11: Velocity in the vertical direction along cross sections of the four simulations.....	11
Figure 12: Velocity in the stream-wise direction along cross sections of the four simulations.....	11
Figure 13: Streamlines along two vertical planes for the top-block spur simulation	12
Figure 14: Three-dimensional shear stress along the bed for the four simulation.....	13
Figure 15: Lateral (perpendicular to the bank) shear stress component for the four simulations	13
Figure 16: Float track along the Lower Bhadra showing how the tidal effects change the flow	15

1 PURPOSE AND BACKGROUND

The following report assesses the feasibility of top-blocked semi-permeable, oblique spurs (top-blocked permeable spurs) through 3-D numerical modelling analysis, and concludes on the suitability and if needed, alternative options of how to proceed with respect to meaningful pilot works for Blue Gold and FRERMIP.

Top-blocked permeable spurs have been proposed by the Royal Netherlands Embassy (RNE) to be built as pilot projects for river training purposes. Both RNE funded projects, the Flood and Riverbank Erosion Risk Management Investment Program (FRERMIP) Project-1 and the Blue Gold programme conducted initial studies in 2015/16 regarding top-blocked permeable spurs. Application in the Blue Gold programme regarded riverbank protection against further embankment breaches along an outer bend of the Lower Bhadra river at Polder 29. During mid-April 2017, detailed discussions were held between the Bangladesh Water Development Board (BWDB), RNE, Blue Gold and FRERMIP regarding the practicality of this approach for riverbank protection along the outer bend at Polder 29. The critical reach is approximately 1.6 km long (Figure 1). To this end, the Blue Gold and FRERMIP team have conducted detailed numerical modelling to provide further insight into the applicability of top-blocked permeable spurs in comparison to conventional permeable spurs. This numerical results add further clarity regarding the application of top-blocked permeable spurs as a suitable tool for protecting the riverbank of Polder 29 against critical erosion.



Figure 1: Lower Bhadra (image from Google Earth, November 2016)

The top-blocked permeable spurs are intended to prevent bank erosion by reducing flow velocities and instigating sedimentation near the bank. The top-blocked portion of the spurs are intended to direct the flow in the upper portion of the water column (the supposedly, less sediment laden flow) towards the center of the channel and away from the bank. The bottom portion of the spurs are intended to allow the sediment laden lower portion of the water column to flow through at slower velocities, potentially leading to sedimentation. Three-dimensional (3-D) computational fluid dynamics (CFD) has been used to help understand how the top-blocked semi-permeable spurs will influence the flow field.

This report will first outline the spur design parameters (length of spur, diameter of piles, and permeability) according to standards applied to semi-permeable spurs. The report will then present the background for the 3-D numerical models and the results. This report will conclude with alternative ways of how to proceed, for Client decision.

2 PERMEABLE SPUR DESIGN PARAMETERS

Top blocked spurs are derived from well-known and tested permeable spurs and therefore, permeable spurs provide a useful foundation for the design of top-blocked permeable spurs. Permeable spurs could be an alternative to top-blocked permeable spurs for protecting the bank at Polder 29 against

riverbank erosion. By integrating convention permeable spur design into the top-blocked permeable spur piloting, useful riverbank protection structures could still be implemented, in the event of unsatisfactory performance of the top-blocked idea. A single line of piles provides an ideal arrangement for testing an additional top-blocked screen. While the following design analysis follows the FAP 21/22 Guidelines and Design Manual for Standardized Bank Protection Structures (2001), the extra forces on the piles from the potential top blocking screens have not been included.

Following the FAP 21/22 Guidelines and Design Manual for Standardized Bank Protection Structures (2001) for designing permeable spurs the follow calculations have been made to determine the length of the spur, pile diameter, permeability, spacing and rough costing.

1. Length of spur:

The following equations are used to estimate an appropriate spur length. Details of the calculation are in Table 1.

$$L_G = \Delta L + n(h_o + y_{s,o}) + 0.5l_s \tan(\beta + \theta) \quad \text{Equation 1}$$

$$y_{s,local} = k \left[h_1 \cdot u_1 \cdot \frac{B_{ch}}{B_{ch}-b} \right]^{2/3} - h_1 \quad \text{Equation 2}$$

Note that this scour approximation is for non-cohesive rivers, which the Lower Bhadra is not.

Table 1: Equation parameters

Variable	Description	Value	Source
L_G	Spur length	70 m	Found from Equation 1
ΔL	Added safety factor	0	
n	Slope	1V:3.5H	Average slope from the cross sections presented in the IWM report
h_o	Design depth	10 m	From cross sections from the IWM report
$y_{s,o}$	Scour depth caused by spur	8.1 m	From Equation 2 (as $y_{s,local}$)
l_s	Scour length caused by spur	32.5 m	As design manual suggests, $4 \cdot y_{s,o}$
β	Fictitious angle of flow separation	15°	Design manual suggestion, which was not double checked because this term has a negligible effect on the total length
θ	Angle of flow attach	15°	Assumption. Upstream conditions require stabilization to provide a well-defined flow firection
$y_{s,local}$	Local scour depth caused by spur	32.5 m	Found from Equation 2
k	Empirical coefficient	1.6	From design manual, assuming a permeability of 80%, with bed protection and floating debris less than 1 m thick

h_1	Water depth	10 m	See h_o above
u_1	Water velocity	2 m/s	ADCD survey data
$\frac{B_{ch}}{B_{ch} - b}$	Construction factor (where B_{ch} is the channel width and b is the protrusion length)	1.6	Extrapolated from Fig. 4.4-4 in the design manual

The found spur length of 70 m is for a spur perpendicular to the riverbank. For orthogonal spurs, the effective length and the linear spur length are identical. Therefore, when the spurs are placed on an angle they will have to be longer. An equivalent spur placed at a 45° angle will need to be 100 m long, however to keep the same permeability for flow parallel to the bank, an equal number of piles would be required. Since top-blocked permeable spurs must be placed at an angle, the permeable spurs would also need to be placed at an angle.

2. Pipe diameter:

Using the following figure taken from the design manual the pipe used for the individual piles, assuming steel pipes are used, is suggested to be 558.8 mm, or 0.6 m in diameter.

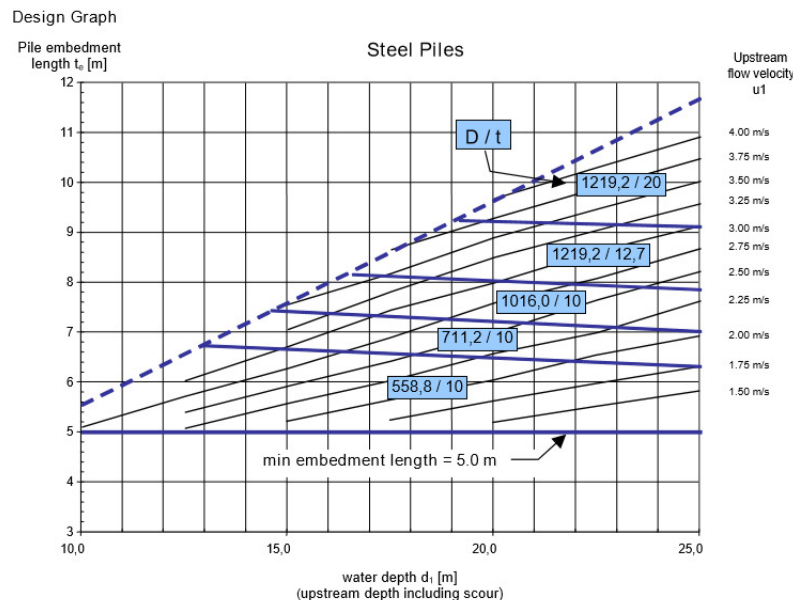


Figure 2: Design graph for permeable spurs made of steel (from the FAP 21/22 guideline)

3. Permeability

The manual has suggested a variable permeability along the spur. Based on the individual spur diameter the number of piles required for a single spur has been found (Table 2). Note that Station 0 m is at the bank. Permeability cannot be less than 50% for construction purposes and so the number of piles is rounded down.

Table 2: Permeability of the spur

Spur Section – Station (m)	Suggested Permeability	Number of piles
0-17.5	50%	14
17.5-35	60%	11
35-52.5	70%	8
52.5-70	80%	5
Total		38

4. Spacing

The manual suggests a spur spacing of 1.5 to 5 times the spur length. If the conventional value of 2.5 is used, the spur spacing will be 175 m.

5. Spur Cost

The approximate price of one spur is shown below.

Assumptions:

- 20 mm pipe thickness
- 20 m pile length
- Price of steel is 2000 USD/t
- 1 m³ of steel is 8 t

$$\text{Material required} = (\pi \cdot r_{\text{outside}}^2 - \pi \cdot r_{\text{inside}}^2) \cdot (\text{Pile length})$$

$$\text{Material required} = (\pi \cdot (300 \text{ mm})^2 - \pi \cdot (290 \text{ mm})^2) \cdot (20 \text{ m})$$

$$\text{Material required} = 0.37 \text{ m}^3$$

$$\text{Price for 1 Spur} = (\text{Material required}) \cdot (\text{Steel price}) \cdot (\text{Number of spurs})$$

$$\text{Price for 1 Spur} = (0.37 \text{ m}^3) \cdot \left(2000 \frac{\text{USD}}{\text{t}}\right) \cdot \left(8 \frac{\text{t}}{\text{m}^3}\right) (38 \text{ spurs})$$

$$\text{Price for 1 Spur} = 250,000 \text{ USD}$$

At a spacing of around 175 m, 5 spurs will be needed per kilometer, which amounts to around 1.25 million USD per km. This can be compared to the IWM report cost, which quotes 49 million BDT/500 m or 1.22 million USD per km. The two costs are comparable. Furthermore, the price of 250,000 USD per spur is higher than the 175,000 USD for a concrete top-blocked spur designed by BWDB. However, the steel piles can be adjusted or re-used elsewhere, in contrast to concrete piles.

3 MODEL OUTLINE

Overview

The CFD model uses ANSYS CFX. The model simulates the 3-dimensional flow field by solving the Reynolds averaged Navier-Stokes Equations for momentum and mass conservation. The model does not include sediment transport. The bed levels and the water levels do not change in the model.

Study Area and Spur Geometry

A portion of a schematized river bed was used for the model. A straight river reach of approximately 335 m long was modelled, with 175 m of spacing between two spurs. The cross-sectional profile has been approximated from the IWM report. Four different simulations were run: the river without any works, with permeable spurs orientated 90° from the bank, with permeable spurs orientated 45° from the bank and with top-blocked permeable spurs orientated 45° from the bank. The dimensions of the spurs are based on the design manual from the FAP 21/22 studies. The geometry of the study area, including the works (the top blocked permeable spurs) can be seen in Figure 3 and Figure 4. The screen of the top blocked spurs extends a constant amount of 1.5 m below the surface level.

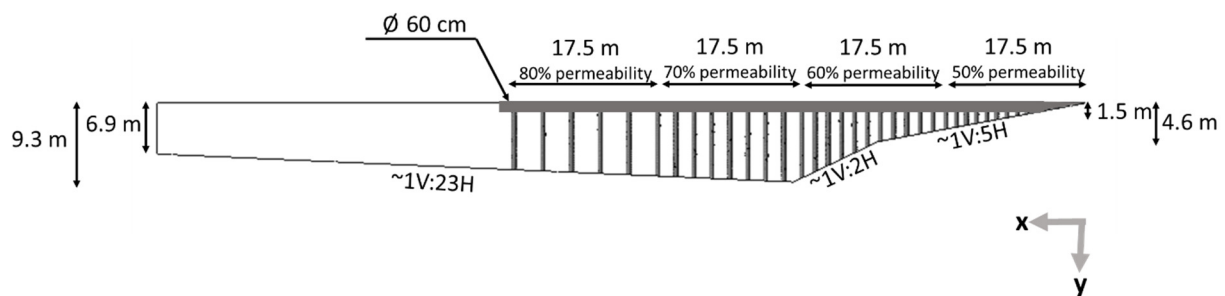


Figure 3: Cross sectional view of the model domain

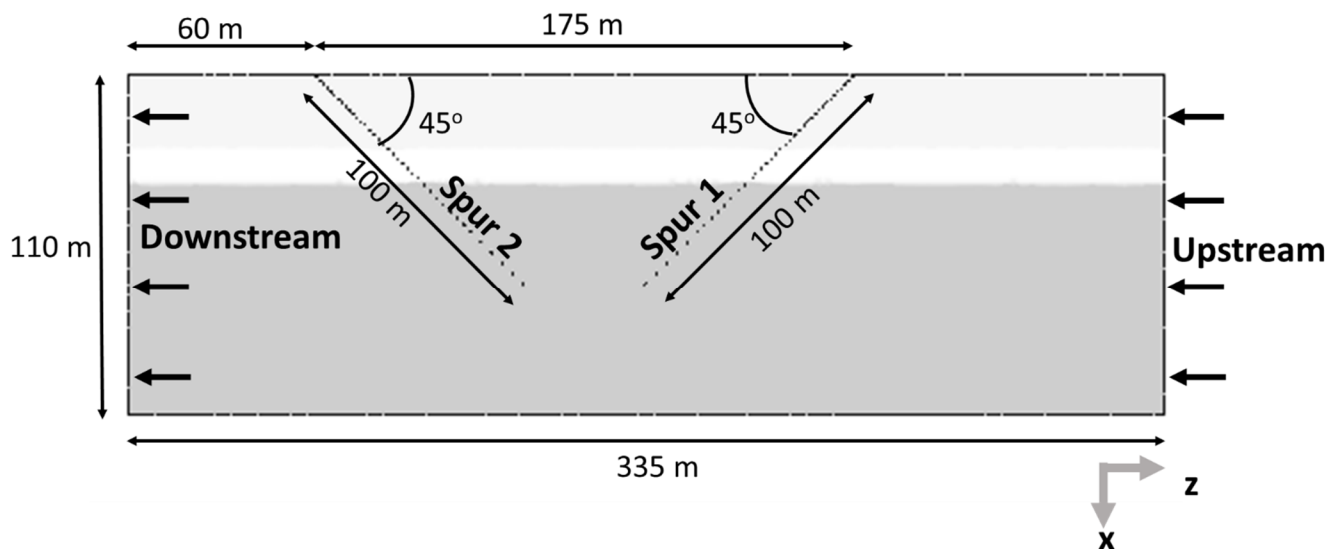


Figure 4: Dimensions of the model

Boundary Conditions

The following boundary conditions were applied to all four simulations:

- The downstream boundary was assigned an average static pressure of 0 Pa.

- The free surface, as well as the boundary open to the main channel, was modelled as a free slip wall, meaning that no fluid can pass through the boundary but no resistance is applied to the flow.
- The riverbed was assigned a roughness of 5 cm. This accounts for the average grain size of 0.141 mm in the Lower Bhadra (from the IWM report) and the roughness of the bed forms.
- The structures were assigned a roughness of 5 mm.
- The flow entering the upstream boundary was assigned a constant velocity of 2 m/s.

Modelling Parameters

The following modelling parameters were used for the simulations:

Table 3: Modelling parameters

Analysis Type	Steady State
Advection Scheme	Upwind
Maximum Iterations	500
Timescale factor	1
Convergence Criteria	RMS
Residual Target of Velocity and Pressure	1×10^{-9} m/s (velocity) 1×10^{-9} Pa (pressure)
Wall Function	Scalable
Discretization Scheme	Euler
Turbulence model	k- ϵ (5% intensity)

Mesh

An unstructured, primarily tetrahedral, mesh was used for the models. The mesh has approximately 505,000 nodes.

Solution Verification

Convergence: To ensure the steady state solution converged, the calculated values must reach a constant value. The convergence graph for the monitored points (which were put in places that converge slowly) in the simulation can be seen in Figure 5.

Y plus values: Law of the Wall is applied to resolve the boundary regions at the riverbed and around the spurs. To ensure the model complies with the Law of the Wall assumptions, the Y^+ values for the model are all well above 60. This has been checked in the model (Figure 6).

Mesh Independence: To ensure that the solution was no longer dependent on the number of nodes, a mesh sensitivity test was performed (Figure 7).

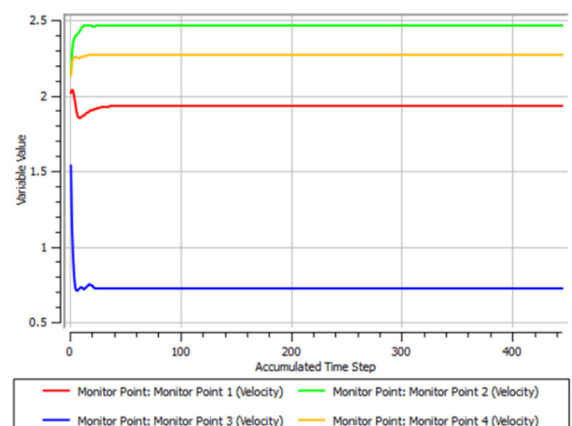


Figure 5: Convergence of the monitoring points

The solution was found to be mildly mesh-dependent because the actual shape of the piles differed for different mesh resolutions.

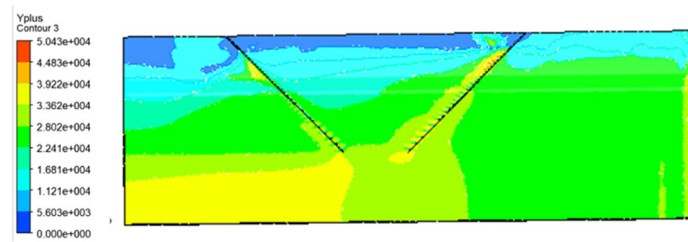


Figure 6: Y^+ values along the riverbed

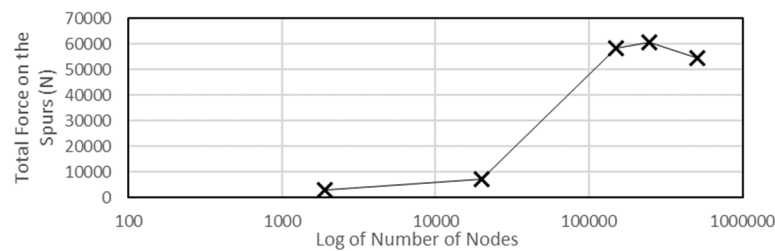


Figure 7: Mesh dependence test

4 RESULTS AND DISCUSSION

The velocity of the four simulations can be compared (Figure 9-Figure 12). These figures show the velocity along five different lines which extend across the channel, shown in Figure 8. These lines are placed 2 m below the surface level (which is 0.5 m below the screen level of the top- blocked permeable spurs). It can be seen that all of the works reduce the near bank velocity. The velocity reduction of the 45° and the 90° permeable spurs are comparable. The top-blocked permeable spurs reduce the velocity more than permeable spurs. That being said, it can be seen in Figure 10 and Figure 11 that the top blocked permeable spurs create velocity components, not only towards the bank (along the backside of the downstream spur), but also into the bed (just before the spurs). These downward velocity components are created from the streamlines of the flow concentrating under the top blocked portion of the spur (Figure 13). Although the top-blocked portion of the spurs is intended to divert the flow into the main channel, according to the results a considerable amount of the flow is redirected towards the bed, rather than towards the main channel. If the velocity at the screen level is compared (1 m below surface level), similar trends can be seen regarding the redirection of the diverted flow (0.8 m/s towards the main channel and 0.5 m/s towards the bed). Also, it can be seen from Figure 10 that although the spur upstream redirects flow away from the bank, the downstream spur directs the flow into the bank. This effect is not seen with

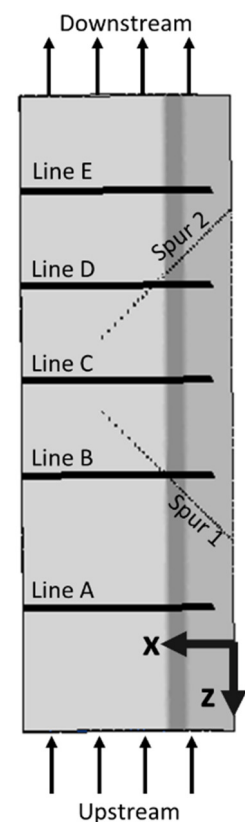


Figure 8: Lines where velocity extracted (1.5 m from

the permeable spurs. At the screen level (1 m below the surface level), this velocity component towards the bank can be as high as 0.5 m/s.

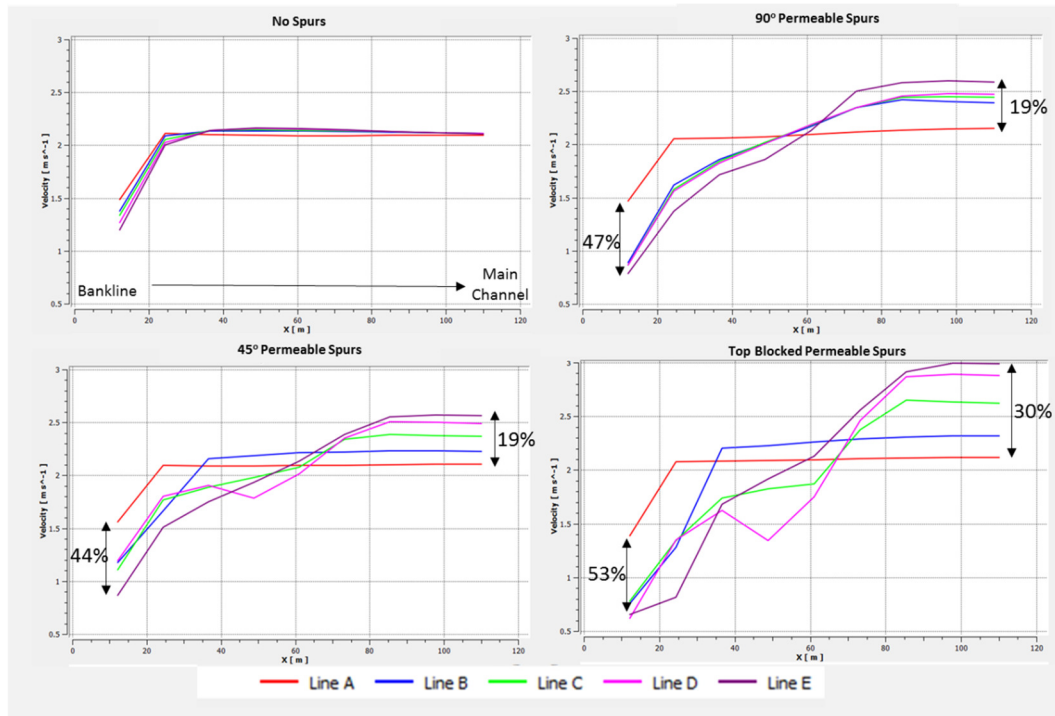


Figure 9: Total velocity along cross sections of the four simulations

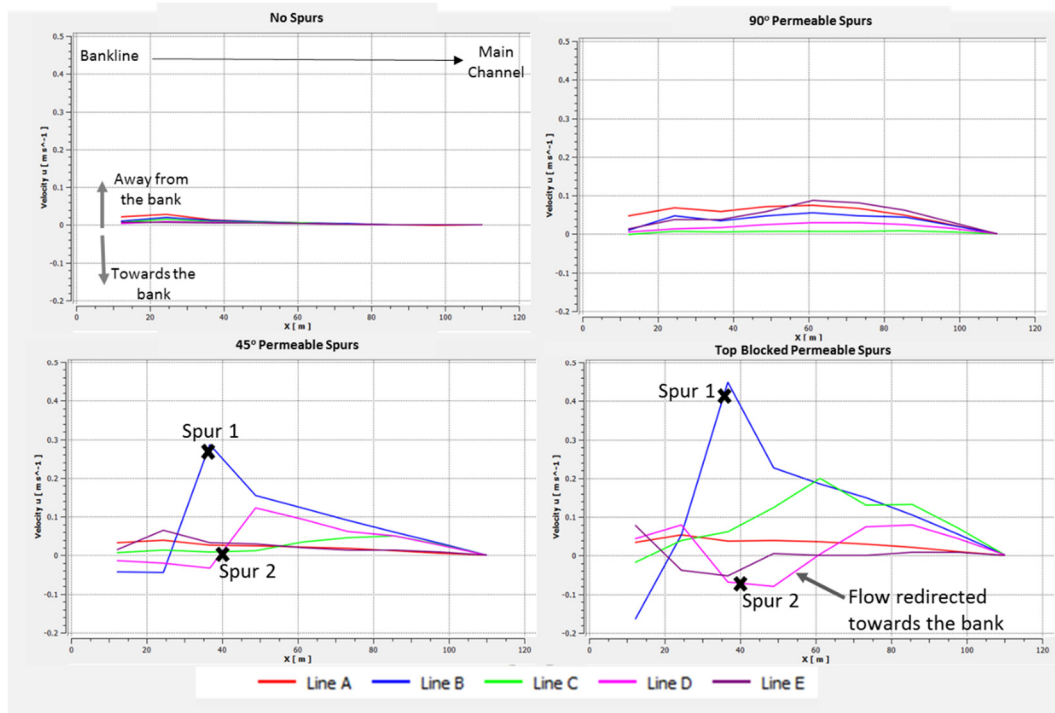


Figure 10: Velocity in the lateral direction along cross sections of the four simulations

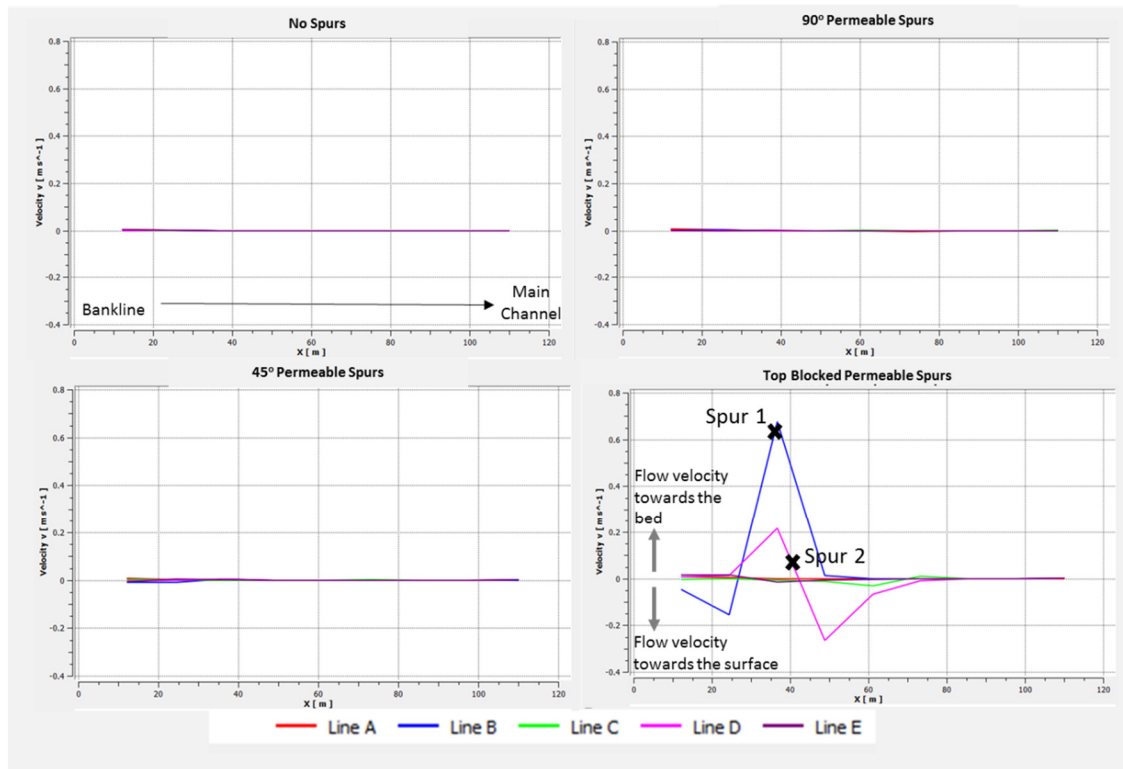


Figure 11: Velocity in the vertical direction along cross sections of the four simulations

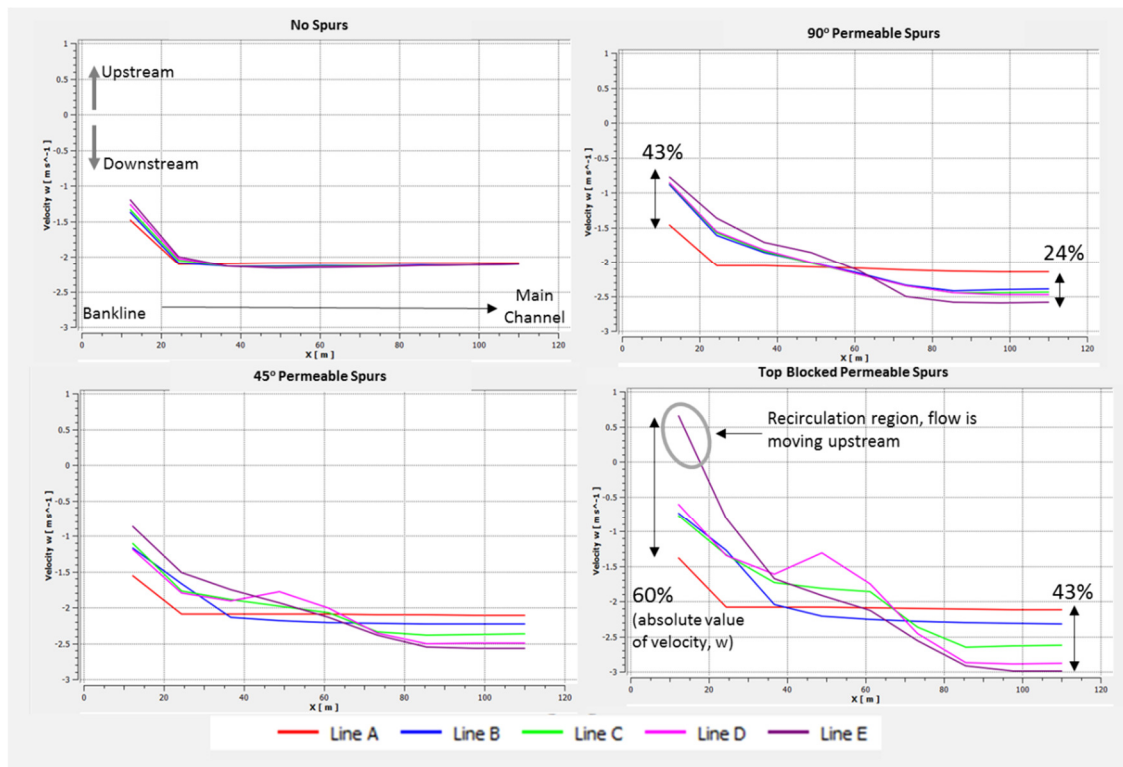


Figure 12: Velocity in the stream-wise direction along cross sections of the four simulations

Also seen in the velocity profiles is the recirculation region that is created from the top-blocked portion of the spurs. Although for most of the cross section the streamlines become compressed and create a peak in velocity as the flow travels through the spurs, near the bank recirculation regions are created

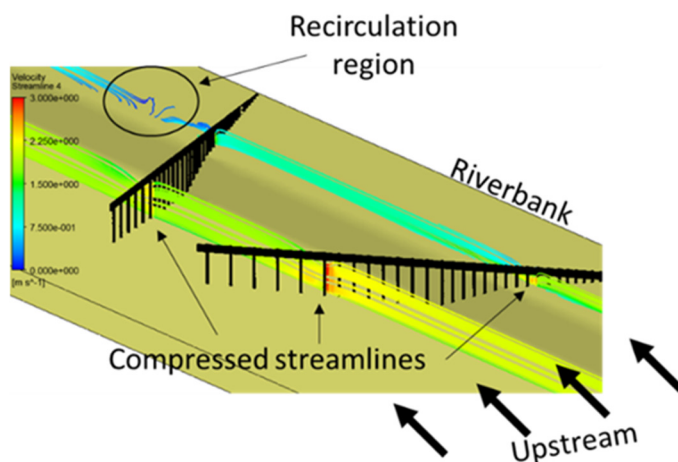


Figure 13: Streamlines along two vertical planes for the top-block spur simulation

(Figure 12 and Figure 13). As the cross section becomes shallower, the top-blocked portion of the spur begins to block more of the cross-sectional area. In the model, the recirculation region is created when the screen covers more than 1/3 of the water column.

The changing water levels of the Bhadra river should be taken into account when considering this effect. The tidal water levels differences can vary by around 4 m per day (from the 2016 IWM model report). This means that the blocked portion of the water column will vary throughout the day, and so, the size of this recirculation region will also vary.

If the screens are tested, the changing water levels should be accounted for. Depending on the size of the blocking screen, the recirculation region may be large, and with that, the adverse effects on the bed. If the size is minimized the top blocked portion of the spurs may be out of water and unused for a portion of the day. To this end, if top blocked permeable spurs are piloted, an adjustable, temporary blocking screen, possibly made of bamboo may be a wise approach to the pilot test, to determine the optimal screen placement. However, this would limit the suitability of the structure as a robust solution in tidal environments. Alternatively, the blocking screen might be placed at an average level (without 3-hourly or 6-hourly adjustments), corresponding to the phases of the tide with the highest flow velocities.

The bed shear stress can be seen in Figure 14. It can be seen that all of the works reduce the shear stress close to the bank line. In the models, there is an increase in shear stress towards the main channel as a result of the works. This increase in bed shear stress is highest for the top-blocked spurs (circled in red). This is because the top-blocked spurs decrease the velocity near the bank the most, resulting in higher velocities towards the main channel. Since the closed boundary to the main channel would be open in the river, meaning that water could flow through, the increase in channel velocity may be less in reality, and under the same reasoning, the increase in shear stress on the bed may be less. This notwithstanding, the velocity increase in the main channel would have an influence on the end scour induced by the structures.

In the case of the top-blocked permeable spur, there is an increase of shear stress locally around the piles, as well as directly downstream. This is not simple pier scour. The increased shear stress could be the result of the flow being redirected under the top-blocking screens. The bed would need to be appropriately armoured to protect against these higher shear stresses. For the top-blocked spurs the shear stress around the piles can be as high as 80 Pa for spur 1 and 50 Pa for spur 2. These concentrated shear stresses extend downstream up to 10 m (spur 1) and 20 m (spur 2). Another notable feature of

the bed shear stresses resulting from the top-blocked permeable spurs is a concentration of bed shear stress around the outer edge of the spur that is protruding into the flow (circled in black). This is a common feature seen when using conventional spurs.

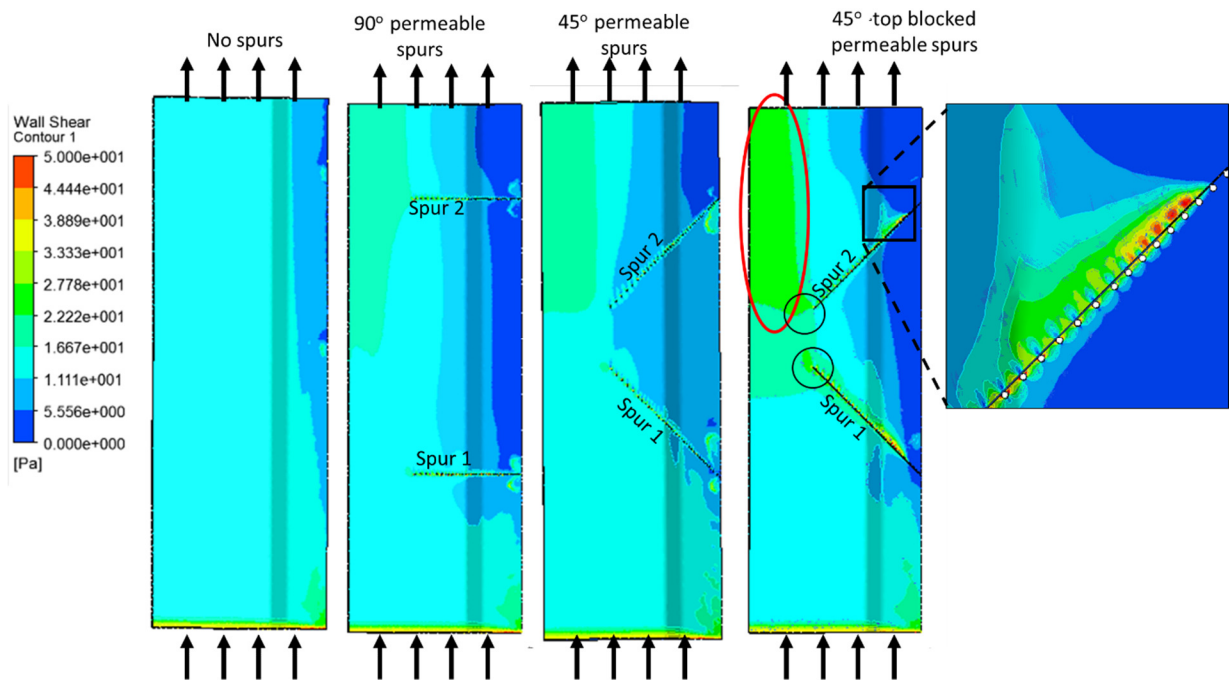


Figure 14: Three-dimensional shear stress along the bed for the four simulation

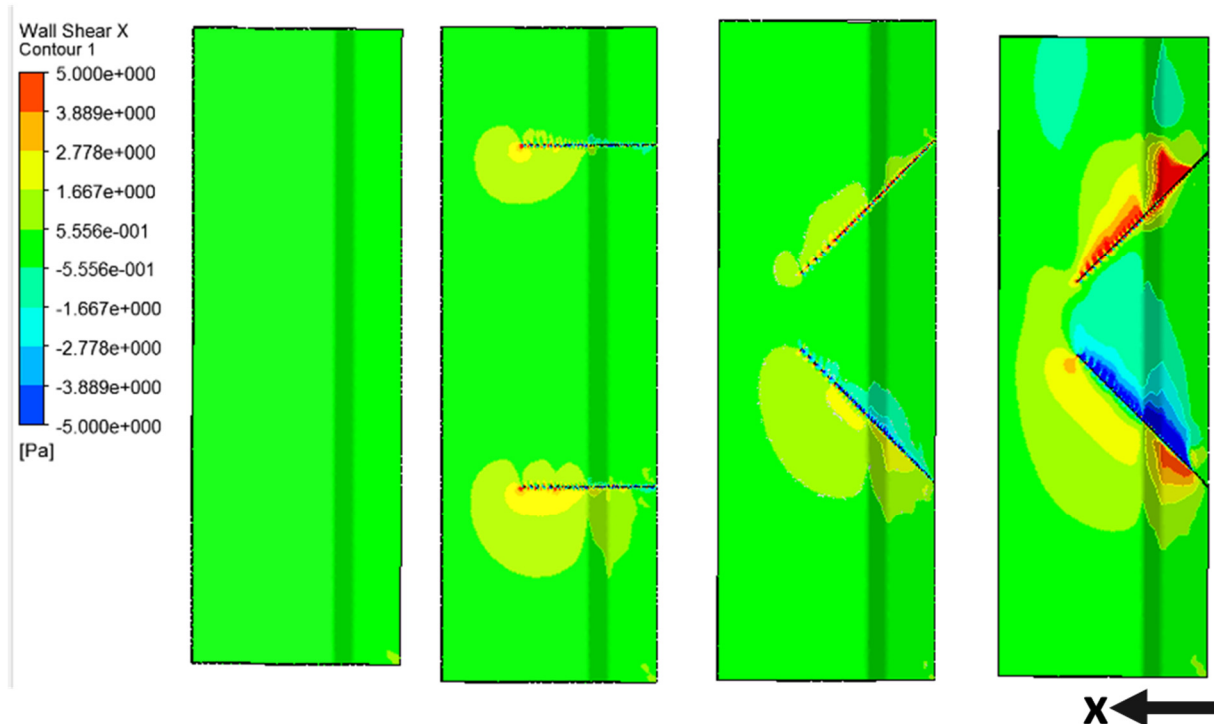


Figure 15: Lateral (perpendicular to the bank) shear stress component for the four simulations

If the bed shear stress that strictly acts in the lateral, x-direction is isolated, the effectiveness of the spurs in redirecting sediment towards the bank can be inferred (Figure 15). The structures not only change the general depth-averaged RANS flow field and turbulence, but the three dimensional helical flows that change the direction of the shear stress near the bed will change as well. The top-blocked permeable spurs cause more lateral shear stress compared to the permeable spurs. The lateral shear stress is directed towards the bank in between the spurs. On the outer edges of the spurs, the shear stress is directed away from the bank. This implies that in between the inward angled spurs there could be accretion of sediment towards the bank, which corresponds to the desired effect. Outside of these angled sections, however, there could be transport of sediment away from the bank, which counteracts the desired effect. Eventually this could lead to individual protrusions along the bank, acting as impermeable spurs with substantial eddy formation and potential bank erosion in between.

The effectiveness of the different types of spurs in reducing the near bank velocity can be seen in Table 4. The top blocked spurs do reduce the near bank velocity more than permeable spurs. However, although the velocity decreases, there is not necessarily less erosion. As a result of the top-blocked portion of the spurs, the flow field becomes more complex, resulting in highly three dimensional flow, possibly leading to bed scour and bank erosion. If the spurs are tested on a critical bank line, such as the one on the right bank of the Lower Bhadra, it is recommended to appropriately armour both bed and riverbanks. Hence the spurs themselves do not protect the bank.

One way to potentially reduce the flow that is redirected into the bank because of the alternating angles of the spurs (see Figure 10), is to further analyze the variation in the discharge because of the tidal flow. Float tracks show how the location of the concentrated flow is different for the ebb and flood tide (Figure 16). If the top blocked spurs are placed on the right bank of the Lower Bhadra, possibly more spurs could be orientated to redirect the outgoing tide, which attacks the right bank more than the incoming tide.

Table 4: Effectiveness of the different spurs compared to the simulation with no spurs

	No Spurs	Permeable Spurs		Top Blocked Spurs	
Model	Near Bank Velocity [m/s]	Near Bank Velocity [m/s]	Velocity Reduction	Near Bank Velocity [m/s]	Velocity Reduction
Mike21 (IWM)	2.75	1.5	45%	Not Modelled	-
	1.5	0.75	50%	Not Modelled	-
CFD*	1.6	1.1 (90° to bank)	31%	0.8	50%
		1.3 (45° to bank)	19%		

*Near bank velocity for the CFD model is measured 20 m from the bank line and 1.5 m from the surface of the water on Line A and E.

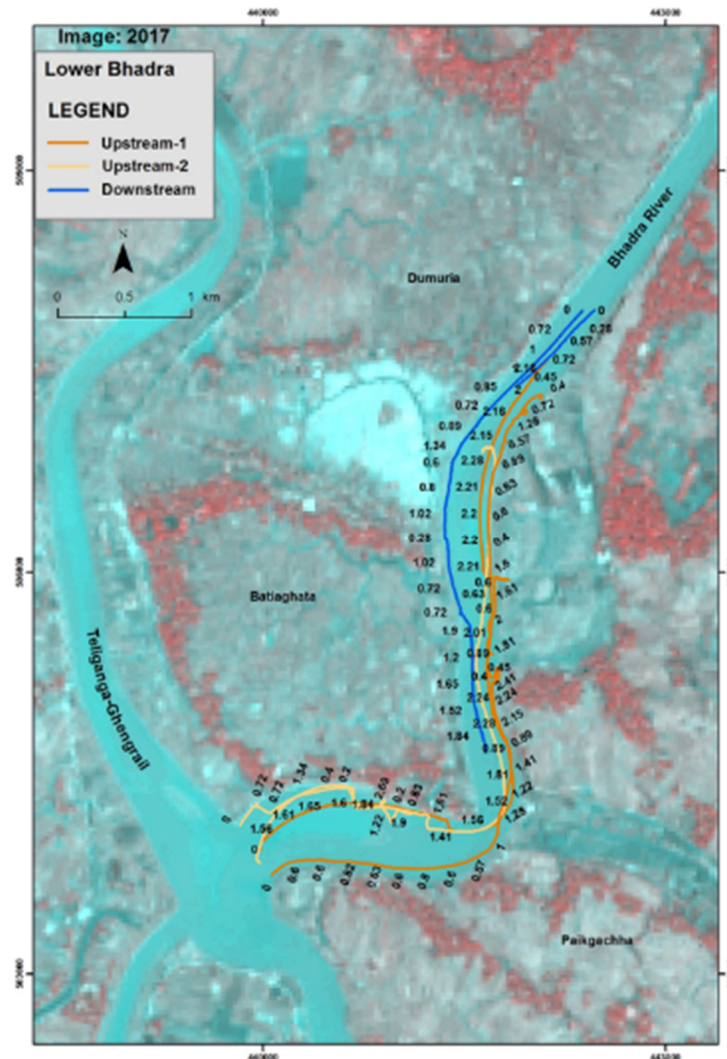


Figure 16: Float track along the Lower Bhadra showing how the tidal effects change the flow.

5 CONCLUSIONS AND RECOMMENDATIONS

Oblique top-blocked permeable spurs have been proposed by the Royal Netherlands Embassy (RNE) to be built as a pilot project for river training. They would combine the functionality of bandals and permeable spurs. Permeable spurs protect river banks. They are suited for environments with severe fluvial attack in terms of flow velocities and scouring. Bandals modify bed topography by redirecting sediment transport fluxes. They are suited for environments with mild flow attack. If bandals extend from the bank obliquely into the direction of the flow, they move sediment towards the bank. If they are placed obliquely against the flow, they move sediment away from the banks. The innovative idea behind the top-blocked permeable spurs was that alternating upstream and downstream oblique orientations would make them suitable for the two flow directions of tidal flows. However, the following reservations arise, partly from the present study:

- The alternating upstream and downstream oblique orientations do not produce a uniform distribution of sediment fluxes towards the bank, but an alternation of protruding accretion zones and intermediate erosion zones. This casts serious doubts on the suitability of oblique spurs; Flow tracks show that high flow velocities of flood flows and ebb flows occur on opposite banks, suggesting that for each bank a single constant oblique spur orientation would be more appropriate;
- The blocking screen might require adjustment to the water level several times a day, although possibly a placement suitable for average conditions might be sufficient.

The pilot design was prepared originally to protect an outer-bend bank of the Lower Bhadra river at Chandgar. As the design was insufficient for protecting this bank, it was decided to protect the bank by means of geobags, and to test top-blocked spurs on their performance in re-directing sediment fluxes to produce sedimentation near the bank.

This report presents numerical modelling as a preparation for implementation of the pilot. It does not show the potential scour or deposition in a direct manner, but the results do allow inferring initial erosion and deposition from the directions of bed shear stress. Building real test spurs in the river remains the most certain way to investigate how effectively the spurs protect the river bank. Given the reservations regarding the expected effectiveness and given the protection already provided by geobags, it is recommended to start with a pilot of only two spurs, in a similar configuration as studied in the present report. Along with this, the top-blocked screen should be adjustable in the height of submersion to add flexibility to the test, especially because of the changing water levels. As well, if the top-blocked method does not perform well in protecting the bank, permeable spurs will still be able to function as bank protection.

Ideally, the top-blocked permeable spurs should be built in a location where no other bank protection methods are applied. Emergency geobag revetments are being built over the critical reach of the Lower Bhadra before the 2017 flood season. If the spurs are built in this location too, their true performance will be difficult to gauge. If time permits, it is recommended to identify a more suitable location for testing that has milder environmental conditions and no interaction with any other bank protection or river training structures.

In order to proceed three alternatives can be considered:

- (i) Abandon the concept of top-blocked permeable spurs at this location because of their questionable potential as shown through 3D numerical modelling: This option indicates the need to find alternative locations for FRERMIP, specifically for less aggressive flow conditions. The critically eroding riverbank alongside the Polder 29 would require the upgrading of the emergency protection to full protection by BWDB.
- (ii) Implement one set of top-blocked permeable spurs: The modelling shows that this solution will incur additional riverbank erosion upstream and downstream of the pilot. This underscores the importance that BWDB upgrades the emergency protection to full protective level prior to conducting the pilot works. This approach creates a conflict because a test of a new way to protect banks against erosion would require protection of the banks by other means first.
- (iii) Implement three parallel, oblique permeable spurs with top-block option: This solution would be built at the downstream end of the upgraded emergency work and consist of

three permeable spurs equipped to test different top-blocked options. The screens would consist of movable bamboo mats, with the option to remove them if the testing fails. It is recommended to use steel instead of concrete piles. It does make individual spurs more expensive at their first implementation (250,000 USD instead of 175,000 USD), but steel piles would offer the possibility of re-using construction material in subsequent improved pilots.