© 2016 IJSRSET | Volume 2 | Issue 6 | Print ISSN: 2395-1990 | Online ISSN : 2394-4099
Themed Section: Engineering and Technology

Application of 2D Modeling for Design of Anti Erosion Works for a Braided River – A Case Study

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ABSTRACT

River bank erosion is inevitable part of natural geological cycle. However, the erosion results in loss of land, damage to the properties, communication systems, etc. River bank erosion is a process of detachment of soil particles due to different causes, like high-velocity flows, obliquity of flow, undermining, piping, sloughing etc on one hand and poor engineering properties of soil on the other hand.

The braided rivers are naturally unstable, causing frequent bank erosion in different reaches and at varying rate. If the bank is composed of finer non-cohesive material, the erosive activity could take a serious turn. Therefore, arresting the erosive activity is given high importance.

Anti-erosion works are normally costly. Therefore, such measures are executed mainly at critical locations. For providing dependable protection, scientific approach is required for the design. Hence, selection of suitable hydraulic design parameters is of prime importance.

Numbers of methods are available to determine the hydraulic design parameters. In this paper, the application of 2D mathematical modeling for deriving hydraulic parameters is presented. Considering the braided pattern and being an alluvial river, 2D modeling was felt absolutely necessary for the true representation of the flow conditions and velocity distribution in such a river. After studying alternative methods for the anti-erosion works, protection works in the form of revetment and launching apron using Geobags/ stones laid over Geo-synthetic filter was finalized.

Keywords: Bank protection, anti-erosion works, revetment, braided alluvial river, Geobags, Velocity distribution, Two-dimensional model, MIKE 21C, GIS.

I. INTRODUCTION

River bank erosion is a process of detachment of soil particles due to different causes, like high-velocity flows, obliquity of flow, undermining of toe due to eddies, piping because of movement of ground water towards the river, sloughing of the saturated slope due to floods of long duration and poor engineering properties of soil. The process of erosion is accelerated when slopes are steep and concentration of sediment in the river is high. Basically, the hydraulic forces, soil characteristic, ground water flows and water levels are the main factors which influence the bank erosion process.

The river undergoes morphological changes over a period of time. The rivers in alluvium tend to change its shape in plan. These are called as 'planforms' of a river. In the plan, rivers can be straight, meandering or braided [1]. Each planform has its own characteristics. The braided planform is attributed to heavy sediment load in river having shallow and wide cross sections. When there is a recession of flood, the carrying capacity of channel reduces and the sediment tends to deposit in the channel. The distribution of flow, sediment transport and sediment sizes across the channel are non-uniform which favors formation of islands resulting in a braided pattern. These islands travel downstream of the river. The channel alignment changes over the period of time owing to the varying discharge carrying capacity of the river. Such changes are responsible for bank erosion. To arrest the erosion as well as to prevent the outflanking of structures anti-erosion works/ river training works are essential. The anti-erosion works are complementary to river training works and are costly to execute [2]. Hence, these works are adopted for critical/important locations. For the design of anti-erosion works, the most important aspect is deriving the hydraulic design parameters. These include finding out water levels, flow patterns, velocities, depths, discharge, its distribution over vertical or horizontal, their extent of effects over the reach, afflux etc. These parameters can be evaluated using physical models as well as mathematical models.

A physical model is a representation of the prototype at a smaller scale. Generally, the river models are Freudian models, gravity being the predominant force acting on the river system [3]. The physical model is constructed according to the purpose of the study and the hydraulic parameters can be actually measured. The most important part in physical modeling is that the flow can be visualized. Before finalizing any design, necessary changes can be made in the system by visualizing the results.

A mathematical model can also be used to derive hydraulic parameters. It uses mathematical concepts and language. It can include dynamic systems, statistical models, differential equations, logical models etc. A numerical model can simulate time-dependent changes in velocity, water level, depth of flow, changes in bed level of a river, changes in bed material composition etc. An advanced hydraulic numerical model can also simulate water and sediment flow. In mathematical models, the system is simulated under known conditions. The time-dependent changes are to be simulated after imposing the man-made changes on the system. A number of mathematical models have been developed which can be selected based on different criteria and the requirement of the studies.

II. MATHEMATICAL MODELING

In nature, water flowing through a river is a three-dimensional phenomenon. The hydraulic parameters are unsteady and vary in all three directions. Such a flow phenomenon can be expressed in terms of Euler's partial differential equations in x,y,z coordinate system [4]. Though there has been rapid development in the field of computers the solution on which mathematical models are based, is not within economical limits because of the complexities involved. Hence, in numerical model technique, the original system of mathematical equations is more or less simplified according to the desired objectives. The terms which play minor role or contribute insignificantly to the flow phenomena are neglected. Thus a set of the formulation is made suitable only for the desired flow phenomena. Hence, the application is also restricted which incorporates few assumptions resulting in the introduction of approximations in the results. On the positive side, such modifications make the model cost effective and suitable for the speed and capacity of the computers. A number of software have been developed and are in vogue.

Considering the predominant hydraulic phenomenon the mathematical models can simulate unsteady flow conditions, quasi-steady flow conditions and steady flow conditions. The unsteady flows can be simulated in the numerical model just like a river flows in nature. In unsteady flow model, flood routing studies can be conducted where discharge passing through the channel with reference to time can be observed. Estimation of water levels and other hydraulic parameters are also possible. In unsteady flow models, transport of pollutants, their distribution over the period, dissipation, dilution, etc can also be studied. When a mathematical model has to simulate quasi-steady flow conditions, the flow is assumed as constant for a given period and then it changes to next constant value. Simulations with sediment transport to reproduce changes in the bed level and bank alignment can be carried out in such type of models. For studies related to backwater profiles and related hydraulic parameters, the model can be simulated under steady flow conditions. Such models consider only one discharge value. Studies related to turbulence, initiation of turbulence, decay, area covered, intensity etc can be the type of studies conducted in such models.

Considering the dimensions of flow, the models can be one-dimensional (1D), two-dimensional (2D) or three-dimensional models (3D). Fig. 1 shows the applicability of numerical modeling under various conditions. The one-dimensional model involves modeling of a river along its length. All the hydraulic parameters are averaged. These models are good approximations for modeling situations where variation in the direction of flow is important; like flood propagations in the rivers. These models are appropriate when a situation where the complex changes in the flow distribution in different channels over the period of time is more important than the variation of parameters across the cross section. A two-dimensional model is more appropriate when the flow distribution across the cross section or in X-Y direction in general or over vertical is more important. In such models, flow phenomenon in the horizontal direction can be considered where vertically averaged values are worked out; like flows approaching a river bank, change in flow direction due to constriction of hydraulic structure, etc. Flow phenomenon in the vertical direction can also be considered where variation along the vertical section is calculated; like flow conditions downstream of barrage/intakes etc. Three-dimensional model is used when to flow phenomenon around a structure at a specific location or reach are to be studied in detail like scour around bridge piers/abutments etc. In such cases, model covering all the dimensions around a structure is to be set up. The computational effort in 3D modeling is very large. It is worth to go for 3D modeling only if the poor design has significant consequences or has considerable risk involved.

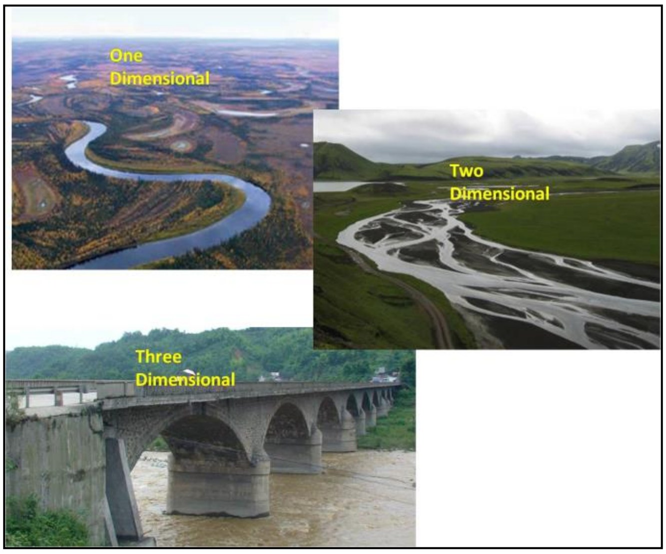

Figure 1: Applicability of numerical modeling under various conditions

A. Past Studies

Deriving hydraulic parameters is of extreme importance while designing anti-erosion works. Study of literature indicates the use of mathematical models to simulate hydraulic conditions in the river and finding parameters involved. In the case of braided alluvial rivers, the flow conditions, as well as velocity distribution can be simulated using 2D mathematical model. Many such models have been developed and applied to simulate dynamic flow conditions in rivers. A detailed description of the application of ArcGIS, CCHE-MESH, and CCHE 2D model to simulate the flow conditions in River Rib was presented by Muluken Shiferaw [5]. The author suggested structural measures such as construction dike along the river which would prevent the flooding caused by over banking. Suresh Maurya et al. [6] highlighted the flow regime and unique soil erosion characteristics of the Brahmaputra River and described the case studies where Geosynthetic are used as erosion control measures. The authors described their effectiveness at two different reaches. They recommended the use of Geosynthetics materials. Maminul Haque Sarker et al. [7] studied the hydro-morphological characteristics of Jamuna River in Bangladesh. The authors feel that Jamuna being a braided river, assessment of the performance of bank protection structures is difficult. They suggested the use of revetment type structures rather than groin type for better stability. Zorkeflee Abu Hasan et al. [8] compared 1D and 2D numerical models for flood management of Sg. Muda river, Kedah. They explained how 2D models are advantageous over 1D models in studies where local details of velocity and depth distributions are important. They stated that it is possible to use CCHE 2D to analyze flow behavior both in the river channel and flood plains by using only the hydraulic component. When using the sediment transport component, CCHE 2D can be used to analyze the behavior of River Muda after undergoing training works and its stability due to sand mining activities.

B. Present Studies

In this paper, 2D numerical model based on MIKE 21C used to simulate the dynamic flow conditions and velocity distribution of a braided river, is presented. The river is alluvial river having highly erodible silty and clayey banks as well as high sediment load. Based on the results of the 2D model, anti-erosion works in the form of revetment and launching apron using Geobags/ stones laid over Geo-synthetic filter are finalized.

C. 2D Numerical Model

The flow pattern and velocity distribution in a braided river are extremely complex phenomena and can be simulated using numerical models. The 3D numerical model can have a better representation of the hydraulic conditions in braided river. However, 2D models are comparatively simpler and give a proper approximation of the situation where the overbank flows need to be simulated and hydraulic parameters need to be evaluated in the cross section. A number of 2D models are reported in the literature which can simulate such flows in a river like MIKE 21C, TELEMAC 2D, TIDEWAY 2D, CCHE 2D, etc. These models are based on the solution of the equation of continuity and momentum/energy. Selection of model can be done by using different criteria such as the purpose of the study, data availability, computational resources, time for study and financial resources. Based on the above criteria, two-dimensional model MIKE 21C developed by Danish Hydraulic Institute (DHI), Denmark was selected for the present study to simulate complex flow pattern in the braided river.

D. MIKE 21C

MIKE 21C is a special module of the MIKE 21 software package. It is a depth-integrated river and reservoir morphology modeling tool. It is based on a curvilinear grid adjusted to river and reservoir applications. For the areas of special interest, a grid of higher density can be used. This makes the software suitable for detailed simulation of rivers, where the blank lines are required to be described accurately. The model can be used to simulate changes in the river bed and planform, including scouring, bank erosion, shoaling associated with changes in the hydraulic regime. The model takes into account the vertical distribution of flow (both main and helical flow) as well as the vertical distribution of suspended sediment through assumed equilibrium profiles. MIKE 21C is particularly suited for river morphological studies and includes various modules which work in interaction with each other. The modules incorporate feedback from variations in bed topography, bank line geometry and alluvial resistance to sediment transport as well as flow hydrodynamics. In the present study hydrodynamic module has been used.

The hydrodynamic module simulates the water level variation and flows in rivers, channels, and estuaries. Model simulations are based on a curvilinear computational grid covering the area of interest. The hydrodynamic model solves the full dynamic and vertically integrated equations of continuity and conservation of momentum (Saint Venant equations) in two directions. [9]

III. STUDY AREA DESCRIPTION

A. Study Area Description

The study area is part of a highly braided river. The right bank of the river is more prone to erosion and is about 80 km in length. The study area is shown in Fig. 2, which is satellite imagery of the year 2015 taken from Google Earth. In this region, the climate is sub-tropical with an average rainfall of 1500 mm per year. Floods are very common. During flood season, the river carries a high discharge and flows from bank to bank. The average bank full width is 9.4 km with a maximum width of 13.9 km and a minimum of 5km. The area surrounding the river has been facing major problems like flood inundation and bank erosion.

Figure 2: Study area

The study area has been subjected to floods number of times since 1931 till recently. The area has also faced earthquakes quite a few times. Owing to these reasons, the problem of bank erosion has aggravated and is one of the major problems faced by this area. The erosion along the right bank of the river has caused a drastic reduction in the area of the adjoining land. Fig. 3 shows the Google imagery of study area of the year 2016. The extent of erosion at the right bank is clearly visible as compared to the conditions in the year 2015. Moreover, there is the formation of the new channel along the right bank. A number of villages and farms of the residents are located in this area. If this channel continues to develop, there is a threat that the whole area on the left side of the developing channel will slide into the river.

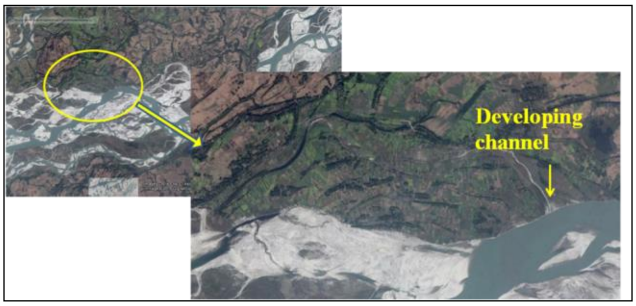

Figure 3: Development of channel

B. Model Setup

Grid and Bathymetry data

Two-dimensional numerical model of the study area covering a length of about 42 km was developed using MIKE 21C. A 2D grid of the study reach was developed using MIKE 21C grid generator. The total length of the river was divided into 500 grid cells along the longitudinal direction. The average width of the river was about 15 km which was divided into 120 grid cells in the transverse direction. Hence, the total number of cells works out to be around 60000 (500 x 120). The grid cell sizes were adjusted for orthogonality. The average grid size was about 30 m X 30 m. The final grid used in model studies is as shown in Fig. 4.

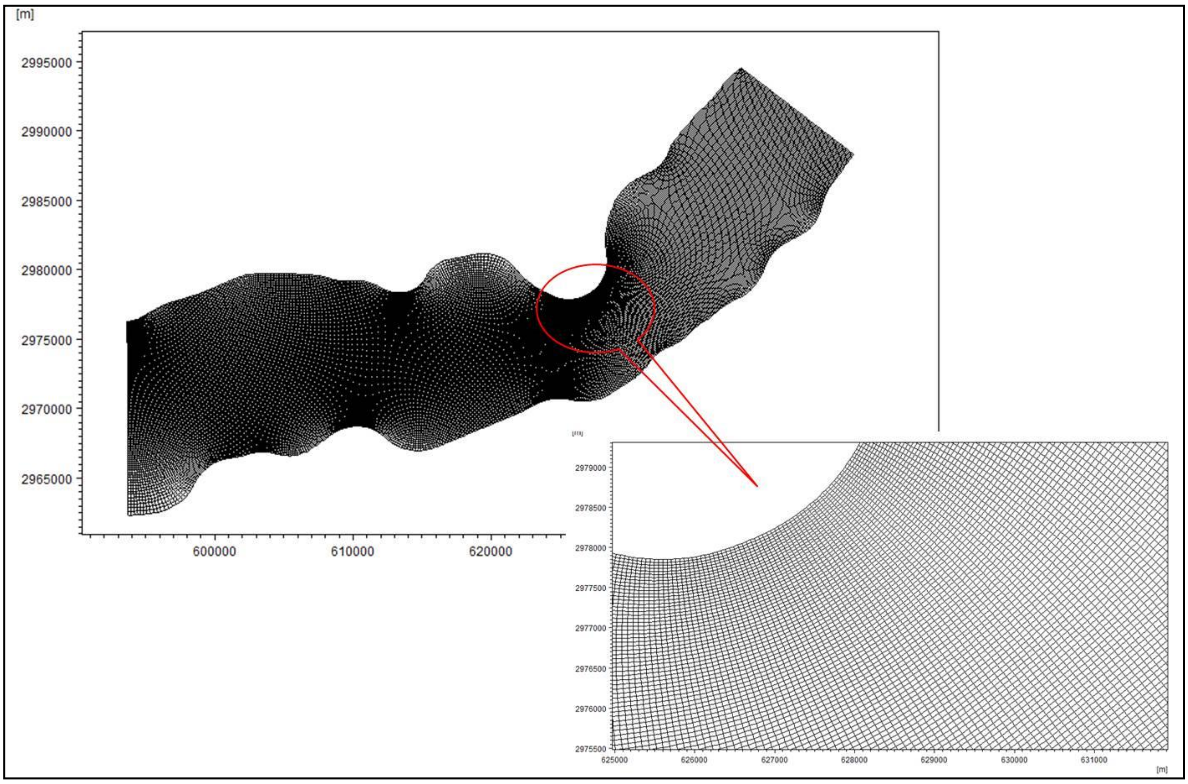

Figure 4: Grid used in MIKE 21C model

The grid points were updated with bed levels which are nothing but the elevations corresponding to the grid points. The actual survey data available for the study reach was in the form of cross sections at 2 km interval. Since the cross sections were spaced at a greater interval; Shuttle Radar Topography Mission (SRTM) and Bhuvan Digital Elevation Model (DEM) were tried at first to represent the river bathymetry. After processing the DEM data using Geographic Information System (GIS) software, it was found that both the DEM had different errors in representing the bathymetry accurately. Hence, DEM was prepared from the available cross sections using GIS software and elevation data were imported into the established grids of the river. Since the cross section grid was very coarse, interpolations were carried out using the usual procedure for model setup. The bathymetry of study reach created in MIKE 21C model is shown in Fig. 5.

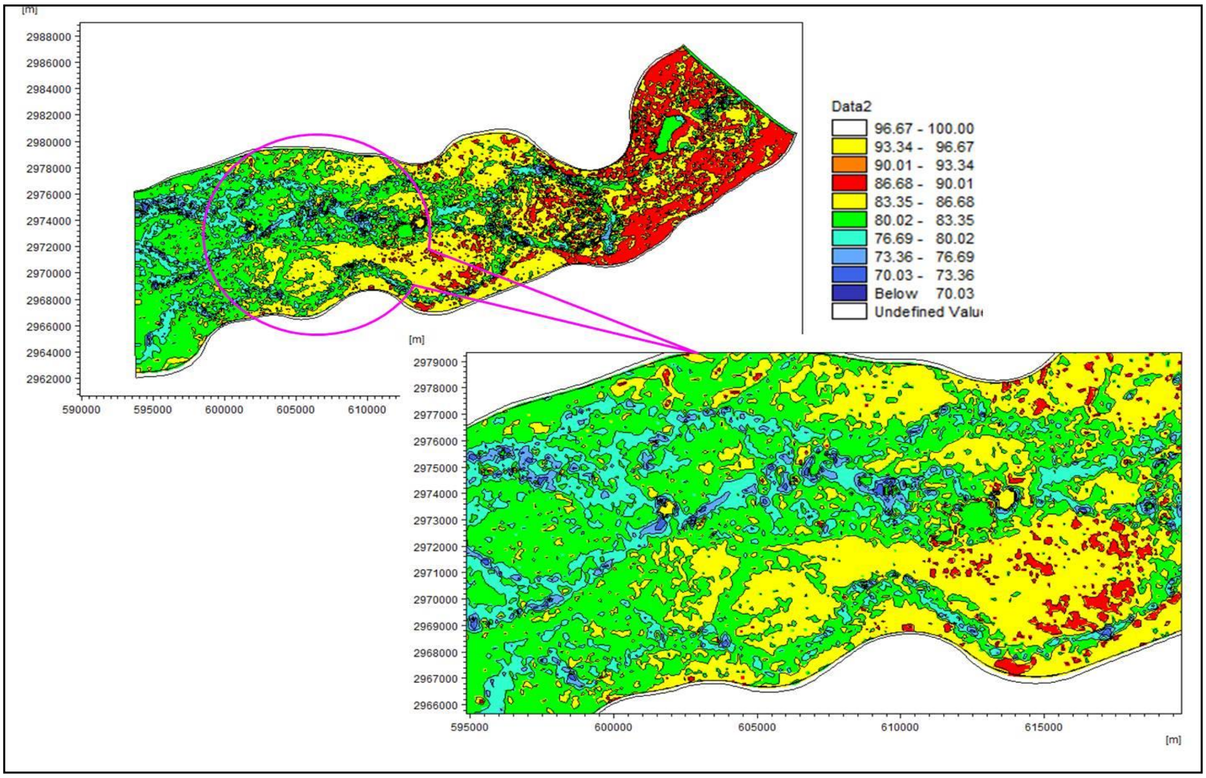

Figure 5: River Bathymetry reproduced in MIKE 21C

Boundary Conditions

The inflow discharge was specified as an upstream boundary condition for the simulations in the hydrodynamic module. The Gauge Discharge (GQ) curve for downstream boundary was developed using available water level and corresponding discharge data. It is as shown in Fig. 6. The model was run for discharges of 10,000 m^3/s, 20,000 m^3/s, 30,000 m^3/s, 40,000 m^3/s, 50,000 m^3/s and 60,000 m^3/s, with no inflow sediment load.

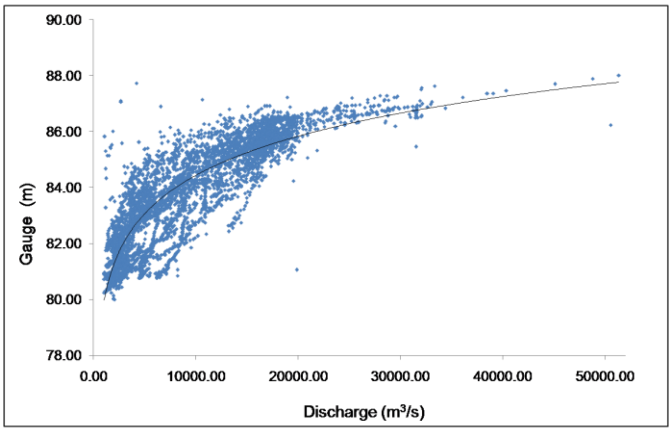

Figure 6 : Gauge Discharge curve used for downstream boundary

Calibration

The calibration process for MIKE 21C hydrodynamic module involves tuning of calibration factors like bed resistance (Manning's or Chezy's number) and the Eddy viscosity. The Manning's M = 40 $m^{1/3}/s$ (or n=0.025 $s/m^{1/3}$) was adopted in present 2D model simulations. The eddy viscosity (E), representing the level of turbulence and therefore the lateral exchange of momentum across the width of the river, was specified as 1.00 m^2/s.

Hydrodynamic simulations

Initial conditions in terms of water level and discharges were defined at the beginning of the hydrodynamic simulation. Due to the dynamic nature of the flow in the river, the simulations were performed in fully dynamic mode to simulate the flow conditions in the braided river.

C. RESULTS

Simulations were carried out in the hydrodynamic mode to compute the water surface profile and velocity distribution in the study area. Simulations were carried out for the discharges 10,000 m^3/s, 20,000 m^3/s, 30,000 m^3/s, 40,000 m^3/s, 50,000 m^3/s and 60,000 m^3/s. The water surface and velocity profiles for discharge of

50,000 m^3/s are presented in Fig. 7 and Fig. 8 respectively

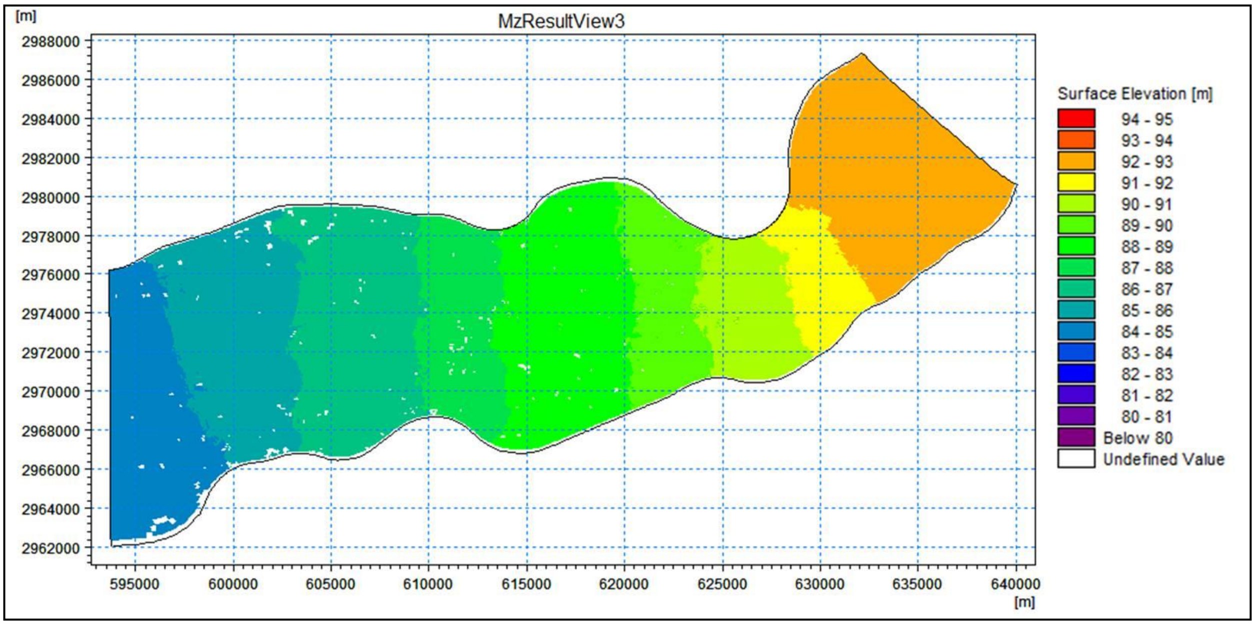

Figure 7: Water Surface Profile for a discharge of 50,000 m^3/s

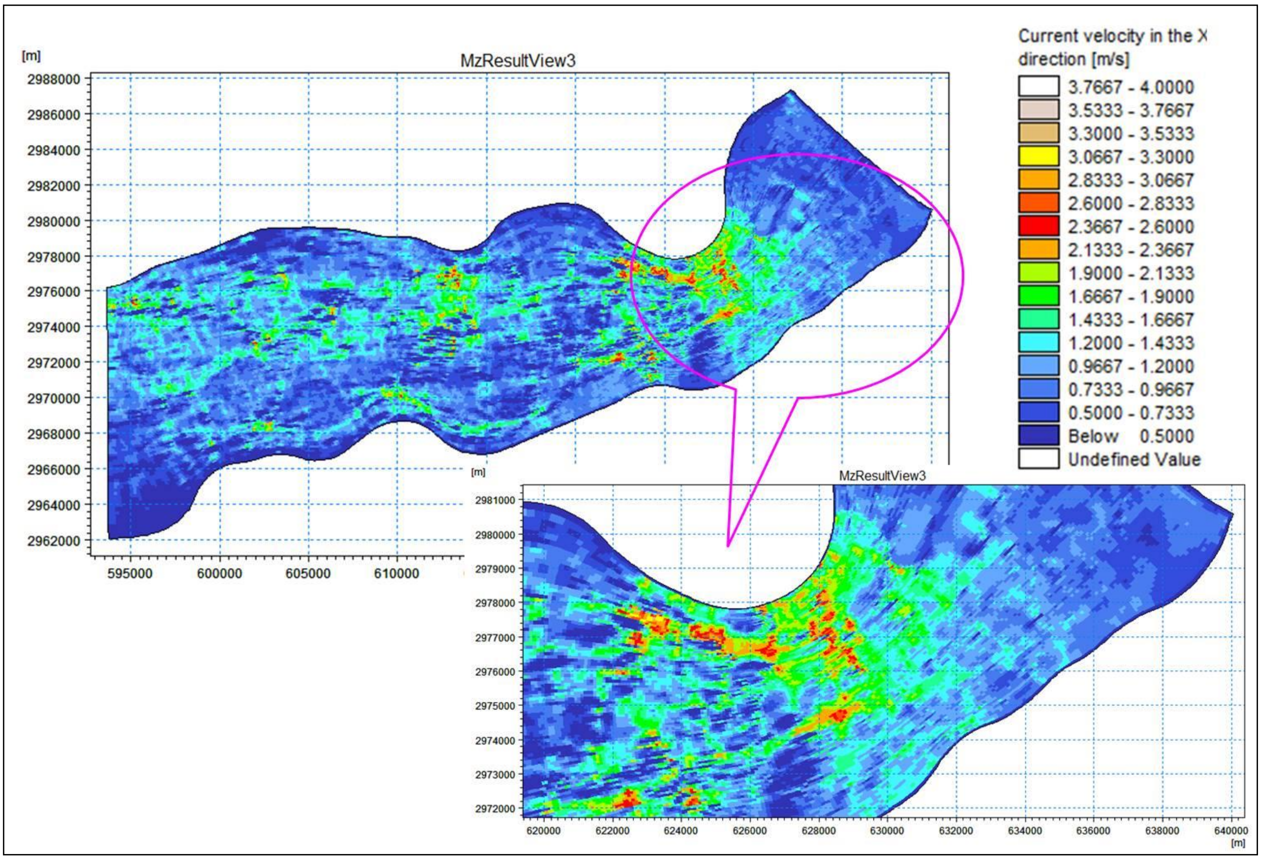

Figure 8: Velocity Profile for a discharge of 50,000 m^3/s

It was observed from the velocity profile that the flow velocities of the order of 2.5 to 3.2 m/s prevail along the right bank of the river in the longitudinal direction. The velocities in lateral direction were less than 1 m/s. The maximum magnitude of velocity within the reach is 3.4

m/s. Hence, anti-erosion works were decided to be designed to withstand the velocity of 3.5 m/s.

IV. DESIGN OF ANTI-EROSION WORKS

After studying alternative methods for the anti-erosion works, protection work in the form of revetment and launching apron using Geobags/ stones laid over Geo-synthetic filter was finalized for the study area. The design of revetment was done for the velocity of 3.5 m/s and discharge of 50,000 m^3/s following IRC: 89-1997, IS 13195: 1991 and IS 14262: 1995 [10, 11, 12]. To protect the slope against the computed velocity, pitching was designed using i) stones, ii) stones in the crate, iii) concrete blocks and iv) Geobags along with launching apron at the base. The slope of the existing bank at the study area is 1(V):3(H) as the sub-soil is clayey silt. For this slope, the angle is 18.43^0 which is less than the angle of internal friction for all the materials tried for pitching. Hence, the slope is stable to any height. Toe wall was provided at the base of pitching to prevent sliding and failure of revetment on a slope. A layer of Geo-fabric filter below the layer of pitching was provided. To reduce the chances of clogging, woven textile filter with mesh size (D_{50}) greater than 0.149 mm should be used. Below the Geo-textile filter, a mixture of fine and medium sand was provided to avoid damage during construction. The revetment should also be properly anchored to the adjoining bank.

The details of pitching using different materials and launching apron are given in Table 1. The final design is shown in Fig. 9.

TABLE I

DETAILS OF PITCHING AND LAUNCHING APRON

Sr. No.	Material used for pitching	Size	Thickness of Pitching	Apron dimensions
1	Stones	0.35 m cubical	0.7m = 0.35m in 2 layers	30m x 1.2 m with 2 layers of stones
2	Stones in crates	0.7m	1.4m = 0.7m in 2 layers	30m x 2.1 m with 3 layers
3	Concrete blocks	0.4 m cubes	0.5m (computed) = 2 layers of 0.4m cubes (0.8m in practical)	30m x 1.7 m with 5 layers of concrete cubes
4	Geobags	1.3 m x 0.73 m x 0.23 m	2 layers of Geobags in staggered manner	30m x 1.0 m with 5 layers of Geobags

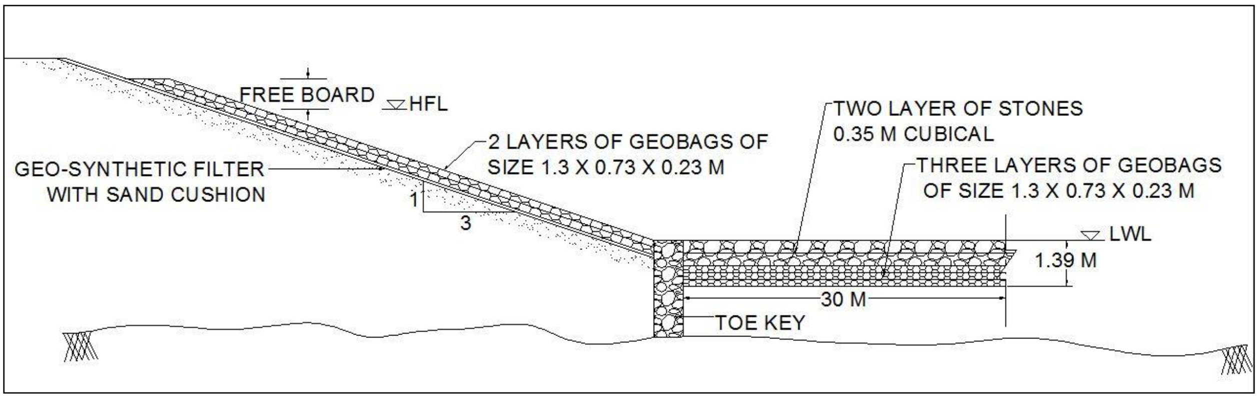

Figure 9: Final design adopted for the protection work of study area

V. CONCLUSION AND RECOMMENDATIONS

1) Owing to the availability of sand at the project site, the use of Geobags for slope protection is a better alternative in this case. Use of concrete blocks for pitching is a very costly alternative in terms of material as well as handling and transport. The location for the preparation of concrete cubes, space, and duration required for curing are the practical difficulties involved.

2) Geobags should be laid in a double layer for pitching. There is a tendency that voids or gaps develop in between Geobags due to local shifting, creep, loss of filled material etc. Hence, they should be laid in a staggered manner while laying in a double layer.
3) The study area is having clayey silt. While filling the Geobags, as far as possible local sand should be avoided and screened coarser sand should be used to restrict the presence of clayey material in Geobag. If not, sand should be washed and then filled, as the presence of clay loosens up the Geobags later. The clayey material can be too fine and gets watery to escape through the micro gaps during floods. After filling bags should be weighed to ensure weight as per requirement.
4) Generally, three sides of Geobags are stitched in the factory with proper quality control. However, the fourth side is stitched after locally filling the bags at the site. The quality of stitching at the site should be rigidly monitored to avoid loss of filled up material later.
5) Use of Geobags though recommended on a slope, apron designed by using only Geobags is not a better alternative. This is because when Geobags are laid under water, the specific gravity reduces due to voids. Moreover, they are narrower in width and have a large surface area as compared to stones. Therefore, there are chances of scattering as well as damage during dumping. Hence, the apron can be designed using half thickness of Geobags with overlaid half thickness of loose stones.
6) The design of apron, in this case, works out to be: Width of apron = 30 m, with 3 layers of Geobags and 2 layers of stones over it (Total thickness 1.39 m).
7) In this case, while laying Geobags under water aprons, winch/crane should be used to lower them to the river bed. This will ensure location as well as total number of Geobags in an apron. This will also prevent damage/rupture.
8) Launching apron must be laid at or below LWL.
9) The angle of repose is the most critical aspect of the design. The bank slopes must be flatter than the angle of repose of material. Hence, for the existing sub-soil in the study area, the slope of 1:3 must be maintained.
10) Toe wall should be made of stones in crates for proper drainage. Gabions of size 3 m x 2 m x 1 m can be used and laid vertically as 3 m in depth direction, 2 m along the length and 1 m along the width. The gabions should be packed properly by using stones of suitable size. The crates are laid in two rows so that the width of toe wall is 2 m. Toe wall should cover the whole length of protection works. The height of the toe wall should be kept twice the maximum thickness of apron. The top level of the toe wall has to be located at the LWL.
11) Though the material of Geobags acts as a filter, use of Geo-fabric filter is recommended to be on safer side. The surface of slopes should be dressed before putting the Geo-fabric filter and the bags. To avoid damage to the Geo-fabric filter during placement of bags, a mixture of fine and medium sand should be provided over the Geo-fabric filter.

VI. ACKNOWLEDGEMENT

The authors wish to express their deep sense of gratitude to Shri M K Sinha, Director, CWPRS, Pune for utilizing the infrastructure at CWPRS. The support and encouragement from Dr. Mrs. V V Bhosekar, Scientist ‘E’ CWPRS, Pune is also acknowledged with thanks.

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