AN INTEGRATED APPROACH FOR CIRCULAR SEDIMENT MANAGEMENT (CSM) IN RESERVOIRS

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ABSTRACT

Reservoir sedimentation is a challenge that escalates with the ageing of dams. The storage loss due to sedimentation increases annually by 0.8%, which implies 57 km^3 annual storage loss. Sediment management has become vital to mitigate such a growing problem. In this study, we developed a pilot application of an integrated approach to circular sediment management in Dakpathar barrage in India. The approach includes an assessment of flow and morphology of the reservoir and downstream reach using ground data and mathematical modelling (as non-structural measure), environmentally friendly sediment handing techniques (recurrent intervention) as well as innovative techniques and their application on re-using removed sediment. The barrage is located across the Yamuna River in the Uttarakhand State of India. In addition to the sedimentation problem at the barrage, recently bank erosion has occurred at the downstream area of the barrage. The approach is expected to be applied to provide a circular solution to the sedimentation problem that includes reuse of dredged material, filled in geotextile tubes, to protect the bank. The modelling study provides impact assessment of sediment removal and bank protection activities and their optimization. The study demonstrates that sediment in a reservoir shall be treated as a resource and not the waste to be used for various purposes.

1. INTRODUCTION

Dam and barrage construction reached its peak in the mid of last century. Around 60,000 large dams have been built globally (ICLOD,2009). Due to sedimentation, many dams are losing their storage capacity. It is estimated that the worldwide annual rate of storage loss is around 0.8%. This can be interpreted as around 57 km^3 of water storage that is replaced annually by sediment. Since dams are one of the main sources of water and energy for many countries, the problem related to sedimentation has become a big threat to sustainability and future water and energy security. India has more than 5,000 large dams, more than 2,300 dams have been built before 1980. Reservoir sedimentation has become a big challenge in India. The impact will be severe given the fact that the demand will be increased due to the population and economic growth in India. Providing proper attention to sediment management is one of the key aspects to minimize the loss of storage. There is a need for more innovative solutions and attention to reduce the risk of storage loss as well as the impact of sediment management. In this paper, we demonstrate a circular sediment management approach that helps to address not only the sediment related problems but also to get benefit from it by reusing the sediment providing sustainability of the measures and services.

1.1 *Objective and tasks*

The objective of this work is to carry out and demonstrate a real-world pilot application of circular sediment management approach (CSMA). The approach contains three major components: (i) morphological study, (ii) sediment handling (dredging and dumping), and (iii) sediment reuse. The three components have been applied in Dakpathar Barrage in India as a pilot study to prove its efficiency.

2. MORPHOLOGICAL STUDY

The morphological study component includes exploration and verification stages. The exploration stage includes a thorough analysis of all relevant hydraulic, morphological and sediment related aspects at the pilot area based on available historical (and measured within the scope of this study) data and information. Subsequently, this enables to screen all the possible options of the dredging and dumping considering all the aspects, constraints and the requirements of the stakeholders. Based on the exploration and analysis, some possible options are selected that are further investigated and verified using morphological modelling study, which we refer to as verification stage.

2.1 Pilot study area

Dakpathar Barrage lies across the Yamuna River at the Dakpathar village of Uttarakhand province in India. It is located about 2.3 km downstream of the confluence of Tons River and Yamuna River. Its main purpose is to divert the river flow towards a power channel for hydroelectricity generation. An overview of the study area is illustrated in Figure 1.

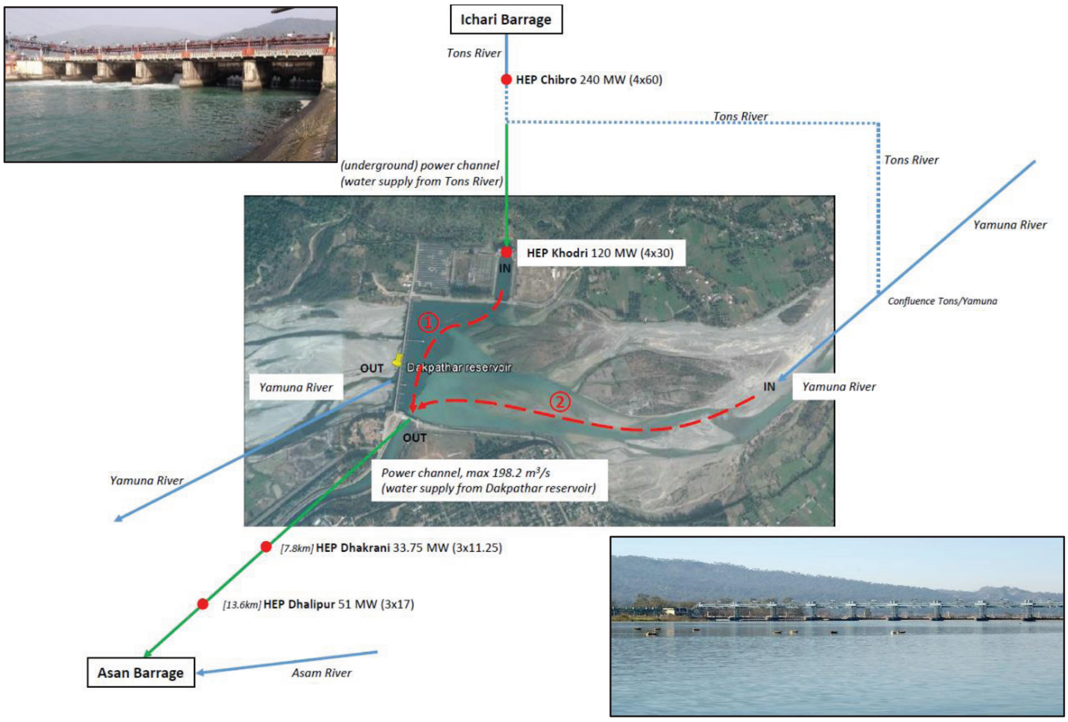


Figure 1 : Overview of Dakpathar Dam. The figure includes two pictures. The upper one shows the downstream of the channel inlet while the lower picture shows Dakpathar Barrage and the upstream reservoir.

2.2 Hydraulic data

The discharge data is available as a daily time series of the outflow from the barrage for a period from April 2004 to March 2013. The available data is the outflow from the barrage, and it may be affected by the storage in the reservoir. As there is no data for the inflow to the reservoir, it is estimated from the same barrage outflow data assuming no significant effect of storage and release from the reservoir. This is based on the fact that the barrage is operated as a run-off river barrage type. The annual hydrograph of the year 2005 to 2013 are shown in Figure 2. The average annual hydrograph is plotted in the same graph, indicated by the dotted line. The maximum inflow of 2013 is used in morphological modelling (in addition to 200 m^3/s inflow of HEP-Khodri).

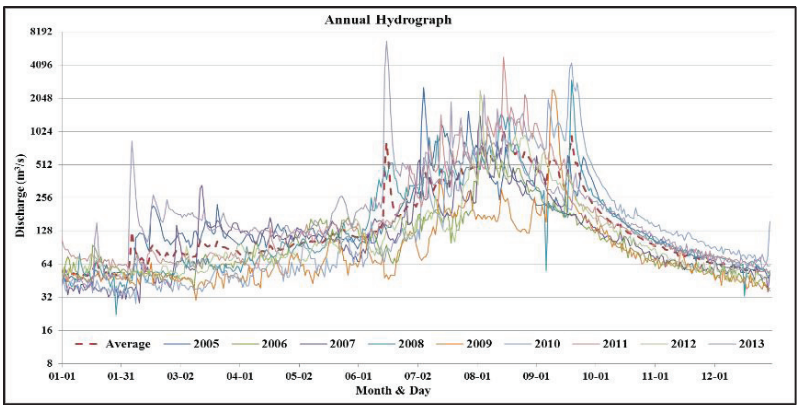


Figure 2 : Hydrograph of the Yamuna River at the Dakpathar Barrage (2005 to 2013).

2.3 Reservoir bed and sediment condition

A bathymetric survey is conducted for the reservoir bed as part of this study. Additionally, sediment sampling is carried out at various locations in the reservoir. This is necessary to identify a suitable location for dredging, firstly not to have any impact on hydropower operation, and secondly, the dredging efficiency depends on the type of sediment. Figure 3 shows the location of different sediment samples collected during the survey. The type of sediment collected at these locations is also indicated in the same figure. The grain size distribution data of all the samples are combined to get an average sediment grain size distribution. This can be used to represent all the sediment in the reservoir. The grain size distribution of all the samples is shown in Figure 4. The average grain size distribution is shown in the same figure as a dashed line.

Sample No.	Sediment Type
S01	Sand
S02	Rock
S03	Rock with Sand
S04	Sand
S05	Rock with Silty Clay
S06	Rock
S07	Rock
S08	Clay with Sand
S09	Clay with Sand
S10	Clay with Sand
S11	Clay
S12	Clay with Sand
S13	Clay
S15	Sand with Clay
S16	Rock
S17	Sand with Clay
S18	Sand with Clay
S19	Sand with Rock
S20	Clay
S22	Clay

Figure 3 : Location of sediment samples in the Dakpathar Reservoir (the placemarks with dark brown colour indicate rocky areas).

2.4 Sediment handling options

Based on the sediment sampling, a map indicator for sediment type is generated (as shown in Figure 5). In the figure, some dredging locations are proposed based on technical, operational, morphological and environmental aspects that are explained further in this paper. Three options for dredging are identified in different locations in the reservoir. These are named as Dredge-I, Dredge-II and Dredge-III. Dredge-I is located about 100 m upstream of the barrage and extends along the central part of the reservoir section. It is expected to deepen the right and left part of the reservoir creating a smooth flow towards the canal intake. Dredge-II is located about 300 m upstream of the barrage in the left side channel. Dredge-III is located in the far-right side of the reservoir just upstream of the barrage. These options of dredging location are shown in Figure 5. Similarly, the locations for dumping are identified to serve some valuable purpose like check dams, bank protection, island filling, etc. One suitable use of the dredged sediment is to use it for filling the geotextile tubes which can be used for various purposes (described in the next section).

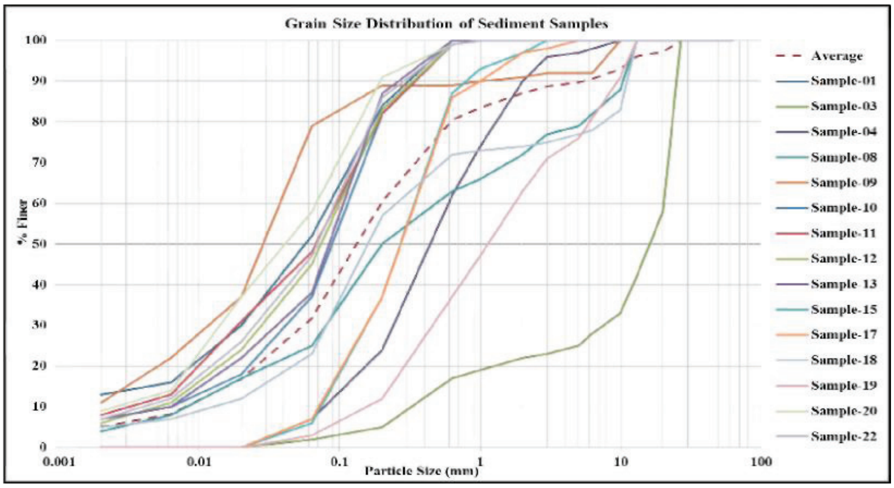


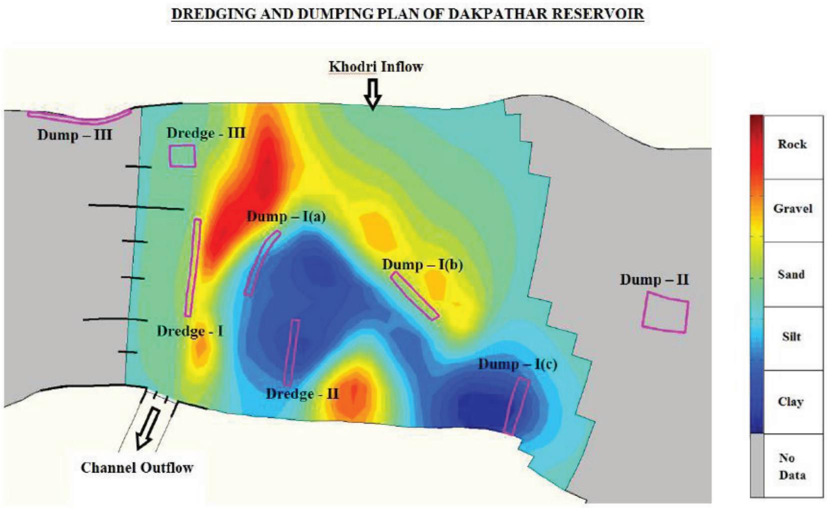
Figure 4 : Grain Size Distribution Curve of the sediment samples.

Five options for dumping are identified, named as Dump-I(a), Dump-I(b), Dump-I(c), Dump-II and Dump-III. Dump-I(a), I(b) and I(c) are defined as the dumping alternatives as Geotextile tubes for the dredged material from Dredge-I. Dump-II is an option for dumping in the island just upstream of the reservoir. Dump-III is an option for providing Geotextile tubes at the downstream right side (or left side) of the barrage, which can serve for bank protection. The options of dumping are also shown in Figure 5. Furthermore, the dredging and dumping options should have some other favourable conditions such as appropriate water depth for workability, reachable distance from dumping location to dredging location, less turbidity, more sand, etc. The average depths of water from the reservoir level of 455.07 m at different locations are shown in Figure 5.

The distance from dredging locations to dumping locations is shown in Figure 5. According to the proposed locations, multicriteria analysis is conducted between the dredging locations and dumping locations as shown in Figure 6. The multicriteria analysis is considering the multi-aspects related. It helps very much to create the best scenarios that can be investigated using numerical modelling to assess the expected dredging and dumping impact on the reservoir morphological bed changes. According to the scoring shown in Figure 6, some dredging and dumping locations are eliminated. The selected locations to be tested are shown in Table 1. The combination of the dredging and dumping locations are based on technical aspects like the distance between them compare to the 1 km pipe that will be used to transport the dredged slurry.

2.5 Morphological modelling

According to the sediment handling scenarios, a numerical model is built using the open-source Delft3D software. Quasi 3D morphological model is developed and coupled with the real-time control (RTC) toolbox. The morphological model is simulating the water and sediment while the RTC-toolbox is online coupled with the model to mimic the dam gates operation (Omer et al, 2017). Three fractions of sediment are defined in the model: silt (d_{50} = 0,017 mm), sand (d_{50} = 0.19 mm), and gravel (d_{50} = 11.0 mm).



Average water depth

Location	Water Depth (m)
Dredge-I	2.8
Dredge-II	1.42
Dredge-III	3.45
Dump-I(a)	1.62
Dump-I(b)	1.64
Dump-I(c)	1.55
Dump-II	0.00
Dump-III	1.00

Distances between Dredging and Dumping areas

From / To	Dump - I(a)	Dump - I(b)	Dump - I(c)	Dump - II	Dump - III
Dredge - I	120 m	425 m	650 m	890 m	350 m
Dredge - II	180 m	255 m	435 m	710 m	585 m
Dredge - III	250 m	510 m	780 m	950 m	215 m

Figure 5 : Dredging and dumping options in the Dakpathar Reservoir. The figure includes water depths at these locations and the distances from dredging to dumping locations.

Criteria	Dredge-I	Dredge-II	Dredge-III
distance to the dumping locations	5	4	3
water depth	4	2	4
Turbidity	3	3	4
availability of Sand	4	1	4
less suspended sediment to the power channel	3	3	4
increase total storage	4	4	4
increase live storage	1	1	1
Total	24	18	24
Total rating	**3.4**	**2.6**	**3.4**

Legend

Legend
0
1
2
3
4
5

Criteria	Dump-1a	Dump-1b	Dump-1c	Dump-II	Dump-III
Not creating island	4	2	2	5	5
hampering navigation	4	3	1	5	5
trap sediment	5	3	5	0	0
visibility	0	1	4	5	5
sand mining	0	0	0	4	2
Siberian bird	0	1	2	4	2
Not required permission	5	5	5	2	1
total	18	15	19	25	20
Total rating	**2.6**	**2.1**	**2.7**	**3.6**	**2.9**

Legend

0
1
2
3
4
5

Figure 6 : Multi-criteria analysis: The upper table refers to dredging options while the lower table states the dumping options

Silt is defined as “mud” which represents cohesive sediment. Sand is defined as “sand” which represents non-cohesive sediment that can be transported as both bedload and suspended load.

Gravel is defined as “bedload” representing non-cohesive sediment with its transport limited to bedload only.

Table 1 : Scenarios of dredging and dumping.

Scenario	Dredging	Dumping
0	-	-
1	Dredge-I	Dump-Ia
2	Dredge-III	Dump-III or II
3	Dredge-I	Dump-Ic

The upstream boundary is the flow hydrograph of 2013 shown in Figure 2. Downstream outflow Boundary-I is defined at the downstream end of the Yamuna River within the model domain. There is data available for water level or discharges at that location. Therefore, a QH-relation between water level and discharge is generated and improved to provide a realistic flow condition at the downstream end of the model. An outflow boundary condition should be prescribed for the downstream end of the power channel as well (denoted as Downstream outflow Boundary-II). Also, in this location, no data is made available. Therefore, some model simulations are conducted for different flow condition to generate a QH-relation. The water level that gives a stable model result for a certain discharge is adopted. This is carried out for a range of discharge values to get a rating curve. The rating curve used for the Downstream Outflow Boundary-I and II is shown in Figure 8.

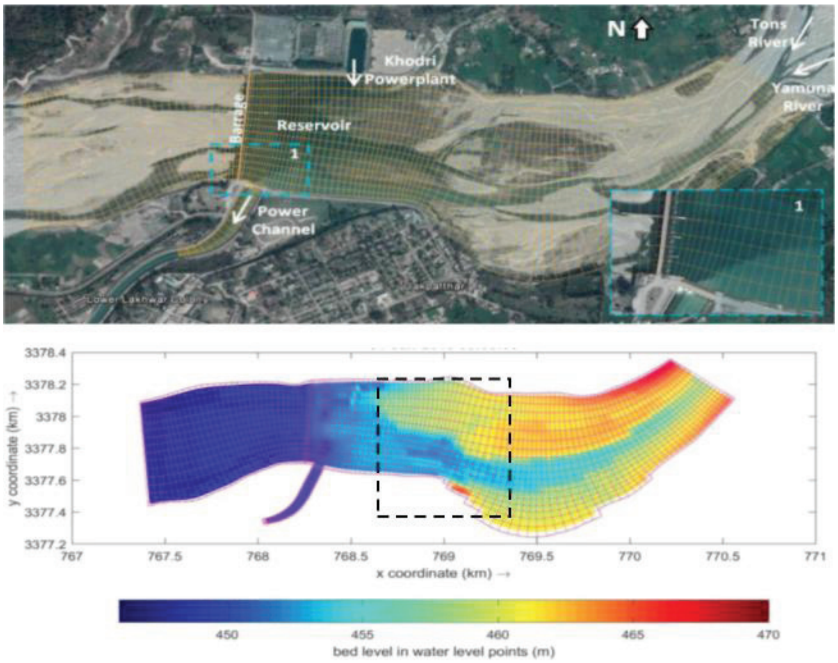


Figure 7 : The modelling domain. The upper plot shows the computational grid, while the lower plot shows the grid with projected bed topography of the study area.

The manning roughness used for reservoir-river bed and the concrete power channel are 0.035 s/m$^{1/3}$ and 0.025 s/m$^{1/3}$, respectively. As the three sediment fractions are of different characteristics, different sediment transport formula is used for each fraction (this functionality is available in Delft3D). The default formula of Partheniades-Krone for cohesive sediment is used for the silt fraction (Partheniades,1965). The Ashida-Michiue (1972) sediment transport formula is used for the sand and gravel fractions (total load transport) based on our previous experience in the region. Based on the modelling study, the following findings can be outlined:

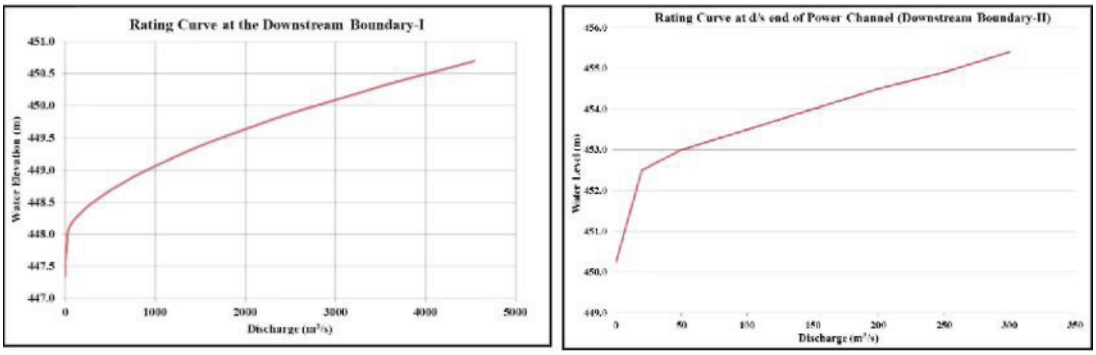


Figure 8 : Rating curve for downstream boundary condition (I -end of the model) and (II- end of the channel).

- The study confirms that dredging will increase the storage, but also this will lead to an increase of trap efficiency because the recovered storage causes the velocities to decrease and to enhance sedimentation.
- The simulation result shows that the used artificial baffles and traps (e.g. using filled geotextile tubes) in the reservoir would hamper the flushing efficiency of the barrage given apparently adverse effect on flow field due to resistance exerted by geotextile tubes.
- The simulation result shows that the measures of scenarios S1 and S3 could cause less suspended sediment during the low flow season. During high flood season, the sediment concentration cannot be controlled by any measures. However, it appears that the dumping options of S1 and S3 (dumping inside the reservoir using filled geotextile tubes) cause a negative impact (like a reduction of flushing efficiency during high flows). If dredge-I is combined with Dump-II or III, the effectivity of scenarios S1 and S3 might be improved.
- Based on the analysis of the simulations results, the scenario S2 seems to be the best scenario that would fulfil the dam authority's requirement and ensure safer dredging operation. The dredging operation can be carried out at the location (indicated as Dredge-III**)** without much increase of turbidity. However, Dredge-I is also preferable, since it would help to increase the water depth along the deeper channel that connects the tailrace of the Khodri-HP and the intake of the HP-channel.
- The dredging option of the scenario 1 (i.e. Dredge-I) also appears to be an effective option with respect to decreasing the suspended sediment during the low flow season as well as deepening the reservoir channel, connecting Khodri to power channel. Only the dumping option of S1 (Dump-1a, i.e. filling the geotextile tubes and put in the reservoir to trap sediment) could be not very effective since it decreases the flushing efficiency due to resistance of the geotextile tubes.

A comparison made between the scenarios based on their efficiency to transport sediment to the downs stream, through the hydropower channel, increase of storage and better morphological patterns. Consequently, S2 is the best with respect to its negative impact and then S3 and S1. The morphological study concludes that: (i)The dredging is preferable to be implemented at two locations (i.e. Dredge-I and Dredge-III), and, (ii) the dumping is preferable to be applied at two locations (i.e. Dump-II and Dump-III). Eventually, the intention is to select one dredging location and one dumping location. However, the unselected locations of both dredging and dumping shall be considered as backup plans. After discussion with the client, Dredge-I (main source) and Dredge-III (Backup source) are selected and Dump-III, but the client preferred to protect downstream the left bank instead of the right bank. Because the flood of 2019 creates an erosion to the bank lead to demolition to the fence of a solar panels field located there.

3 SEDIMENT HANDLING

The removal of sediment from the Dakpathar reservoir is conducted by means of hydraulic dredging with a submerged dredge pump. The system exists of a simple design, where a pump is operated from a floating pontoon with A-frame in which the pump (IHC TT pump) can be hoisted and lowered accordingly (see Figure 9). The grid at the suction inlet is made to prevent large material entering the pump and subsequently being pumped to the disposal location. the IHC TT-pump is equipped with jet nozzles, through which water is pumped with a high velocity. This water-jet is used to fluidize the sediment were after it can be sucked. 700 m length of HDPE-pipeline is used to transport the dredged material and pump it into the geotextile tubes. Before the slurry is pumped into the geotextile tubes, it is first dumped on a designated dumping location (using a Y-piece pipe fitting). Here it is first checked if the slurry contains a concentration which is high enough to pump into the tubes. This dump location is also used when it is required to connect the pipeline to another inlet of the tube (because each tube has five inlets). This approach of sediment removal, transport and direct pumping into the geotextile tubes is one of the projects' unique and innovative features.

Figure 9 : The sediment handling. The left image shows the pontoon on the reservoir, the middle image shows the pump used to suck the slurry; while the right image illustrates the downstream left bank erosion and fence destruction occurred during the 2019 flood.

The total volume of sediment dredged for filling the tube is around 3,500 m^3. This volume is dredged from location "dredge-I" and dumped downstream of the dam to protect the left bank where the erosion occurred. Dredge-I location increases the water depth along the deeper channel that connects the tailrace of the Khodri-HP and the intake of the HP-channel. This may reduce the turbidity of water goes to the HP-channel as most of its inflow comes from Khodri-HP during the dry season. The dumping will be in geotextile tubes and will be placed on the left bank to protect the bank. The right picture in Figure 9 shows the left bank erosion that was occurred during 2019 flood.

Dredging IHC TT-pump (the TT pump) is environmentally friendly equipment that is compact, versatile, easy to use and transport. The TT-pump series from IHC is specifically designed for these types of (small) dredging works and can reach great depths. In addition, the dredging will be a slow dredging process (low environmental impact) which makes it very suitable to use for geotextile tubes due to the low filling capacity of the tubes. The dredging arrangement and transport is shown in Figure 10.

4. SEDIMENT RESUE: BANK PROTECTION USING GEOTEXTILE TUBES

4.1 Geotextile tube technology

In the past geotextile tubes were used for dewatering wet sediments. In the last decade, knowledge is developed to include geotextile tubes filled with dredged sediment in the design of civil structures. With unique developed models these ingenious hydraulic structures are engineered and designed. Dozens of projects have been carried out with the use of geotextile tubes filled with (dredged) soft sediment. Many geotextile tube applications are possible. With local dredged sediments embankments, dykes, dams, breakwaters and harbours can be made. For each specific (hydraulic) structure the failure mechanisms, geotechnical influences, morphological situations and hydrodynamic forces are determined. All these aspects are combined into a number design and engineering models such as the tube strength model, consolidation model, settlements model, construction models, loads model, design model, textile specs and test model (e.g. NETICS models).

Figure 10 : Dredging, transport and dumping arrangement.

4.2 Design of geotextile tube bank protection structure

After selection of the most suited location to build with the geotextile tubes, the structure was engineered in detail. The most important elements for the engineering were the properties of the dredged material, the specifications of the geotextile tubes, the geometry of the building site, water levels and hydrodynamic conditions and the final design of the bank structure. Each element was engineered and design with the NETICS design tools and specific software which resulted in an integrated approach where all design aspects like dimensions, strength, durability and functionality were optimized. A sketch of the bank protection structure is depicted in Figure 11, which provides an illustrative impression of the design approach.

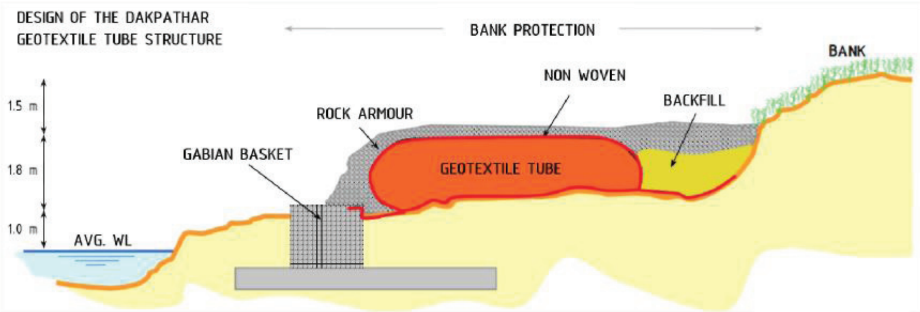


Figure 11 : Design of bank protection structure using geotextile tube.

4.3 Monitoring during the execution of the works

For the evaluation of the technical design, the theoretical predictions were compared with the field measurements. It was found that the sediment was evenly distributed within the tubes which meant that the pump had enough power to pump the sediment sideways after entering the tube. The designed configuration of selected materials, geotextile tubes, pipelines, hydraulic pump and sediment dredging location resulted in a successful and evenly distributed filling of the tubes. The crest height of the tubes was based on the requirements of the client. The first tube has a height of approximately 1,8 m while the second tube has a height of 0.8 m. During and after filling the height of the tubes decreased according to calculations and design. After reaching the required height the tubes were covered with the non-woven geotextile. Figure 12 provides some impression about the filled tubes and their placement at the site. Monitoring of the performance of the geotextile tubes used to protect the bank will be continued.

Figure 12 : Geotextile tube along the eroded bank, downstream of the barrage.

5 CONCLUSION

The CSM approach is applied in Dakpathar Barrage. The pilot project demonstrated an integrated approach that includes knowledge-based impact assessment using data analysis, numerical modelling and expert judgement, sediment handling technique using environmentally friendly equipment as well as engineering design and application of sediment reuse for bank protection. The CSM approach can be applied in many reservoirs depending on their hydraulic and morphological characteristics as well as the applicability of sediment handling and reuse techniques and options. The approach can be useful for both a short- and long-term sediment management depending on the reservoir characteristics and magnitude of the sediment related problem.

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