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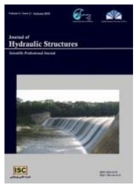

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Hydraulic performance evaluation of head works using FLOW 3D

Mukesh Raj Kafle [1]

Abstract

This paper evaluates the hydraulic performance of barrage and under-sluice of Sunkoshi-Marin diversion head works. The numerical simulation was carried out based on the conceptual design of hydraulic structures using FLOW 3D. Velocity vectors, pressure profiles, entrained air volume for barrage and under-sluice were assessed and evaluated. The average velocity over the barrage crest was observed more than 9 m/s at full gate opening. The maximum flow velocity at stilling basin and throughout the longitudinal profile were observed around 10 m/s was 16.90 m/s respectively. There was no sign of negative pressure formation throughout the profile. The minimum pressure observed was 101.356 KPa downstream from diversion axis, along the free surface elevation. Therefore, the structure would be free from cavitation phenomenon. The discharging capacity at FSL with simultaneous operation of barrage and under-sluice bays was assessed as 10,086 m3/s. The flood corresponding to 100 years return period equivalent to 9,241 m3/s easily passes with headwater level being lower than FSL. Further, the extreme discharging capacity of the head works for headwater level 479.5 masl was found 16,547 m3/s. Therefore, deck level adopted as 481.00 masl would be sufficient to release 10,000 years flood.

Keywords: CFD, FLOW 3D, FSL, Head Works, Under-Sluice, Sunkoshi-Marin.

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1. Introduction

Nepal is shifting to agricultural modernization. This needs for more diversified and efficient irrigation infrastructure. In addition to infrastructures, water deficiency is a key issue. In this background, Sunkoshi-Marin diversion scheme is proposed to enhance the agriculture modernization and address the water deficiency issue in Madhesh Province of Nepal.

For the multi-purpose project head works are critical hydraulic structures. They should be capable of diverting sufficient river water into conveyance system fulfiling the requirements of multi purpose schemes. These schemes may include irrigation, hydropower and water supply as well [1,2]. Besides, the hydraulic structures should ensure the smooth operation of the system preventing coarser sediment particles into conveyance system and safely bypassing the flood [3,4]. The upstream and downstream water level difference in region of hydraulic structure in the river may create high velocity flow and hydraulic jump resulting scouring downstream the structure. It may threaten the safety of such structures due to anticipated scouring of riverbed and dissipater deformation in the downstream [5]. In addition, the safety of hydraulic structures is a key concern in water resources management. Failing of such structures may invite downstream disasters. Understanding of flow characteristics and its consideration during construction of hydraulic structures is important. Recently, many researchers have been widely used computational fluid dynamic (CFD) techniques as an effective tool to simulate many complicated hydraulic phenomena [6].

In the past, several researchers have investigated the flow characteristics around hydraulic structures in the river. Chanson & Brattberg (2000) studied the energy dissipation associated with hydraulic jump phenomenon [7]. Dhamotharan et al. (1981) analyzed flow characteristics in different weir installation using a one-dimensional model [8]. Olsen (1999) used a three-dimensional (3D) model to simulate the Kaligandaki Reservoir flow velocity [9]. Kim (2004) elaborated how the shape of underwater structures influences hydraulic characteristics of river flow [10]. Saad and Fattouth (2017) and Bagheri et al. (2018) discussed hydrodynamic characteristics of flow over circular openings and streamlined weirs respectively [11,12]. Sharafati et al. (2021) developed computational models and empirical equations to evaluate the scour around hydraulic structures [11].

This study investigates the downstream flow characteristics of Sunkoshi-Marin diversion head works with a FLOW 3D model. Overall head works arrangement and capacity are assessed for flood evacuation. Moreover, the hydraulics of barrage and under-sluice structures is investigated and rating curve is generated.

2. Study area

Sunkoshi - Marin Diversion Multipurpose Project (SMDMP) is proposed as a run-of-river basin diversion scheme planned mainly to provide irrigation facilities in the command area of Madhesh Province covered by Bagamti irrigation scheme. The project aims to augment water at the head reaches of Bagmati Irrigation scheme by diverting water from Sunkoshi into Bagmati River through Marin Khola, a major tributary of the Bagmati River. The project covers the area between 490 m and 390 m above mean sea level geographically. The head works site is located in the Lesser Himalayan zone of eastern Nepal. Its location is at Khurkot VDC of Sindhuli district, Bagmati Province (Figure 1, Figure 2).

Figure 1. Sunkoshi - Marin headworks site at Khurkot

Figure 2. Weir axis at head works site

3. Methodology

A high-precision CFD model FLOW-3D was selected for numerical analysis. A model was then constructed for barrage and under-sluice. Flow characteristics downstream the head works were analysed based on the boundary and operating conditions of barrage and under-sluice. Methodology of the study incorporates the steps as discussed below.

3.1 FLOW 3D

Flow-3D is a powerful numerical modelling software, capable of solving a wide range of fluid flow problems. A good selection of different options across the entire Flow-3D graphical user interface allows the software to be applicable to such a wide variety of situations. Flow-3D allows either one or two fluid flow, with or without a free surface, and a multitude of available physics options to suit the specific application. Various meshing and geometry options are available including multi-block grids and the ability to draw simple objects in the software or import different forms of more complex geometry or topographic files.

Flow 3D has been designed for the treatment of time dependent (transient) problems in one, two and three dimensions. Steady state results are computed as the time limit of a transient. Because the program is based on the fundamental laws of mass, momentum, and energy. Conservation, it is capable to almost any type of flow process. For this reason, FLOW 3D often referred to as a general purpose CFD solver. The continuity and Renyolds averaged NavierStokes equations is presented as follows:

$$\frac{\partial U_i}{\partial X_i} = 0 \tag{1}$$

$$\frac{\partial U_i}{\partial_t} + U_j \frac{\partial U_i}{\partial_j} = \frac{1}{\rho}\frac{\partial}{\partial X_j}\left\{-P\partial_{ij} + \rho V_T\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right)\right\} \tag{2}$$

Where U is the Reynold's- averaged velocity over time t, x is the spatial geometrical scale, ρ is the water density, P is the Renyolds averaged pressure, δ is the Kronecker delta and is the turbulent eddy- viscosity. The turbulence is predicted by the RNG k- model (turbulent kinetic energy k and its dissipation) using the constant empirical values. The pressure is calculated according to SIMPLE method (Semi-Implicit Method for Pressure-Linked Equations)

3.2 Layout of head works

The overall layout of the head works is as shown in Figure 3. The sectional elevation is shown in Figure 4. The head works is a low-head diversion structure and consists of barrage and under-sluice bays and a fish passage in between. The barrage bay includes 6 number of 15 m wide and 14 m high openings, whereas the under-sluice bay includes 2 openings, each 10 m wide and 15 m high. The existing riverbed level is about 459.0 m reduced level, which is adopted as crest level of under-sluice bays. The crest level of barrage bay is adopted one meter higher than that of under-sluice. The full supply level at the head works is 474.0 m. The head works is designed to safely pass 1,000 years return period design flood equivalent to 12,328 m^3/s and checked for 10,000 years return period flood equivalent to 15,630 m^3/s.

Figure 3. Project layout at head works Area

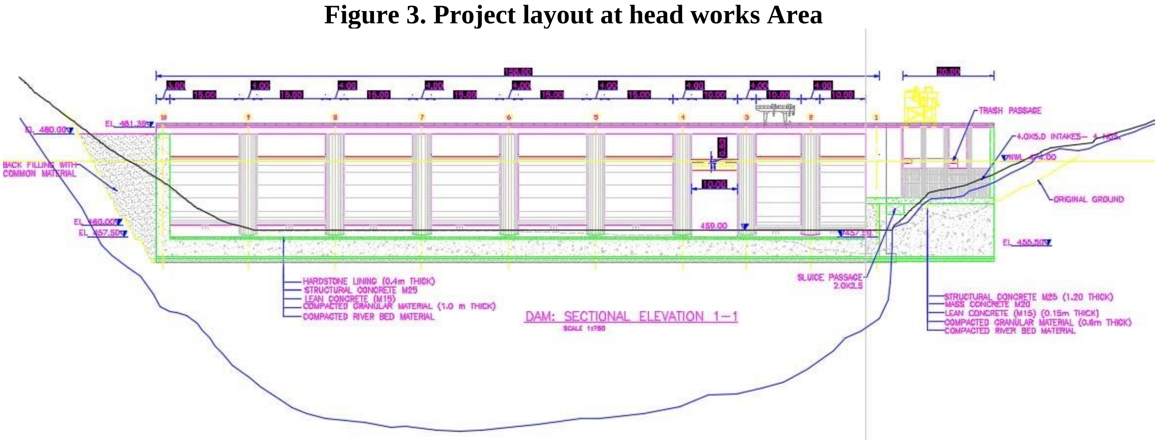


Figure 4. u/s view of dam

Both the openings barrage and under-sluices are equipped with radial gates. The arrangement of under-sluice and barrage is presented in Figure 5.

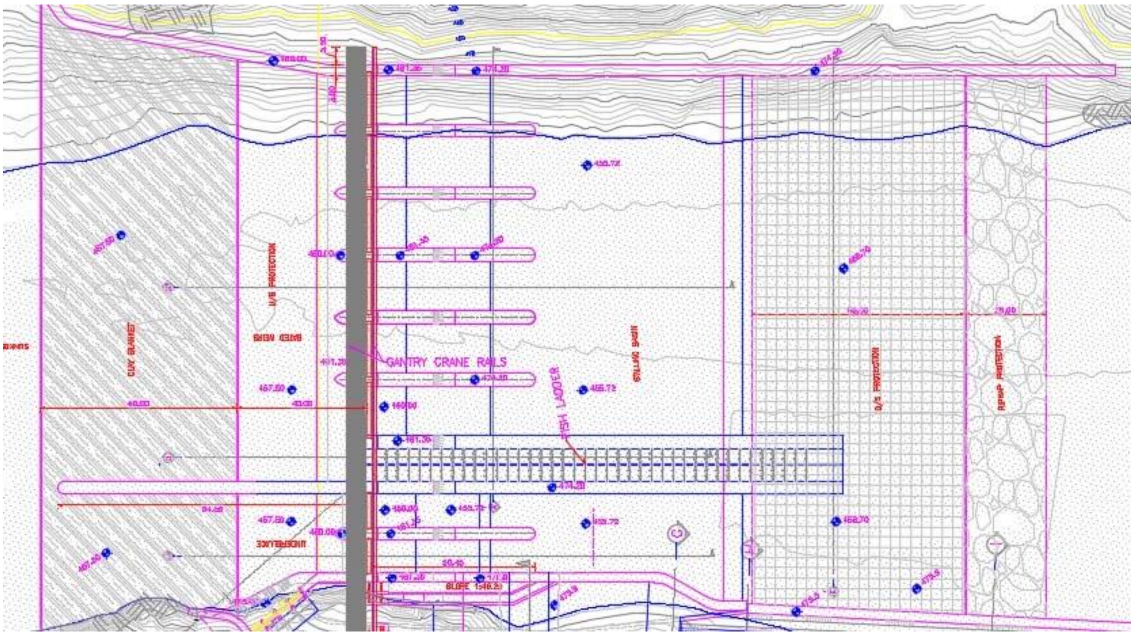


Figure 5. Plan of under-sluice and barrage

3.3 Model Setup

The 3D geometry of head works is prepared with under-sluice and barrage structure incorporating up to the stilling basin. The opening of each barrage and under-sluice is assigned with flux surface namely B1, B2, B3, B4, B5, B6 and U1, U2 respectively from right to left bank. Additional flux surface are defined at upstream face of weir axis and stilling basin. The probes are assigned along the under-sluice and barrage profile for velocity and pressure measurements (Figure 6).

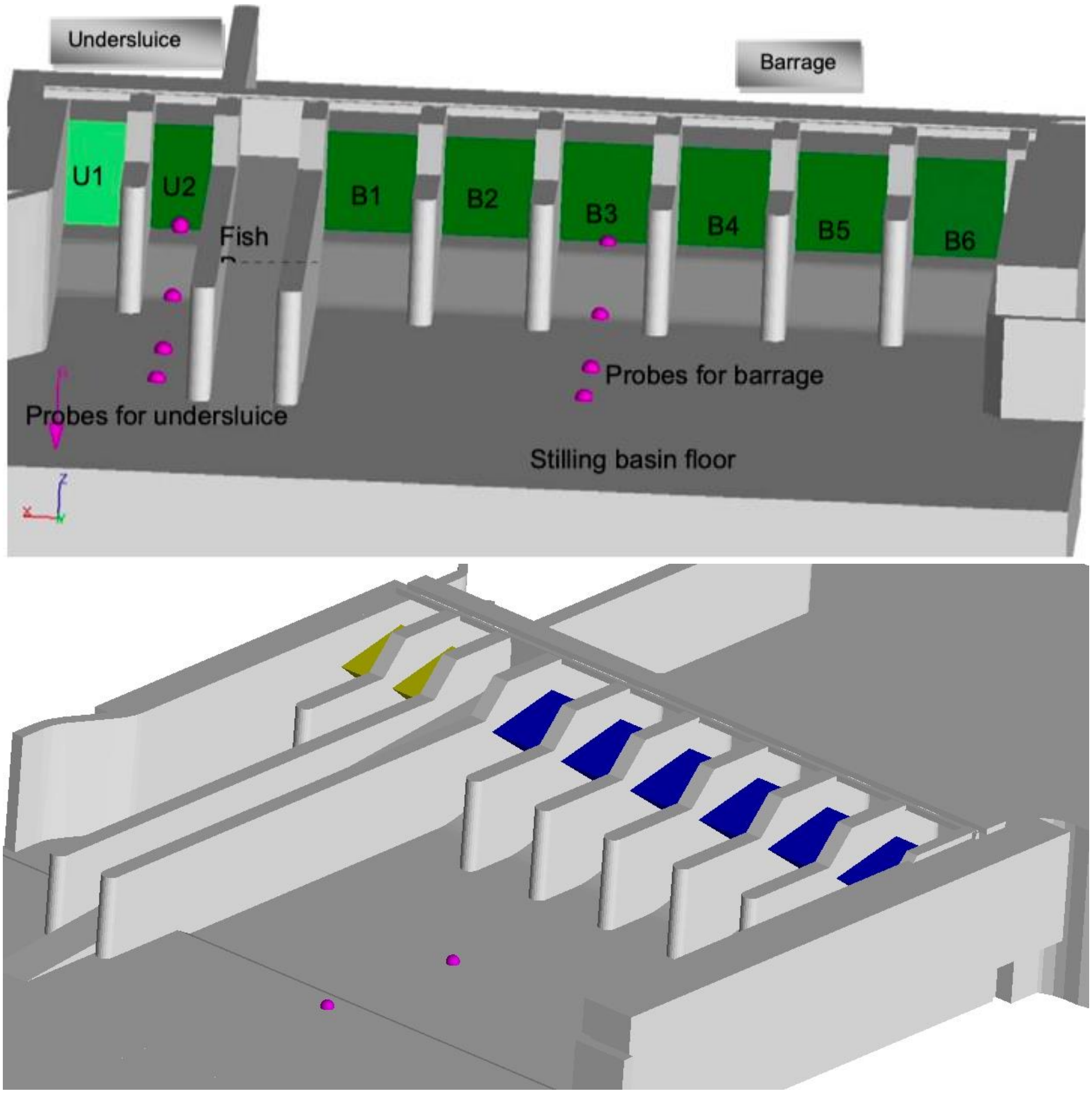


Figure 6. 3D model setup of barrage and under-sluice

Rectangular (2D) and hexahedral cells (3D) for structured and orthogonal grid are used. The non-adaptive grid is immovable during calculation. The geometry and water border is defined by Fractional Area Volume Obstacle Representation (FAVOR) method. The number of cell is adopted according to the objective of simulation (Figure 7).

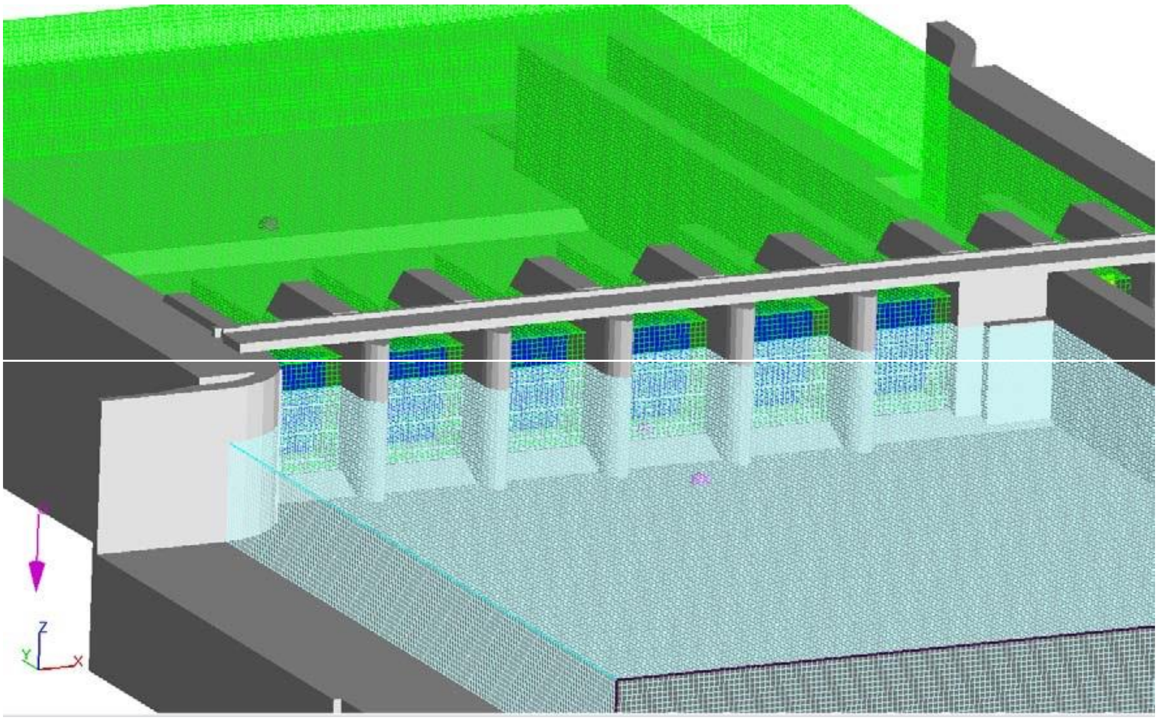


Figure 7. Meshing for Under-sluice and Barrage Modelling

3.4 Boundary and Initial Conditions

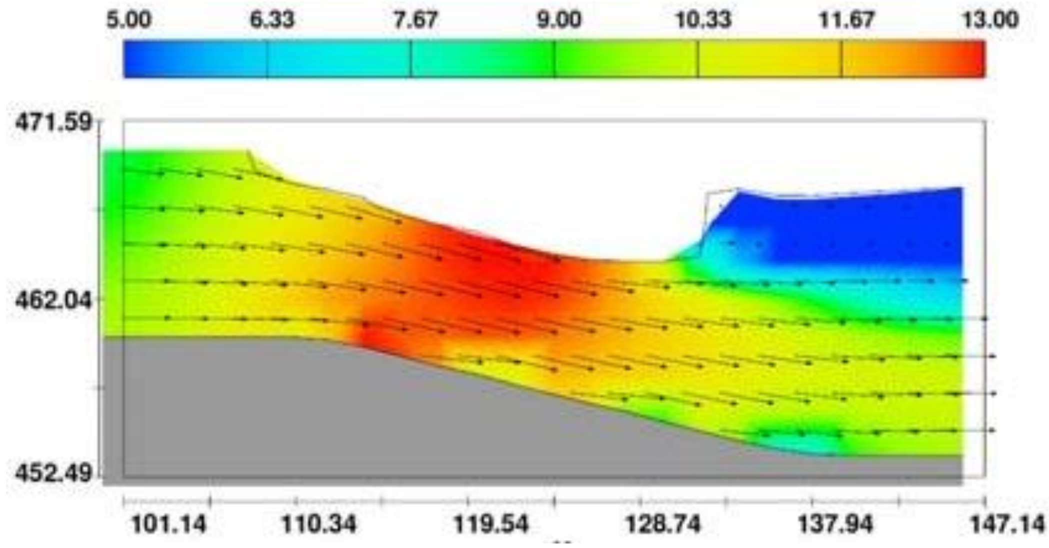
Computational domain with different mesh size is divided into two zones. These zones are sequential having overlapping boundaries. This enables faster computation avoiding the time step limitation. Specified pressure is set as inlet condition. Outflow is set as the downstream boundary. Inlet and outlet boundary conditions are set as continuative to allow water infiltration. The modelled top surface is assigned a specified pressure and rest of the boundary is set as symmetry.

4. Results and discussions

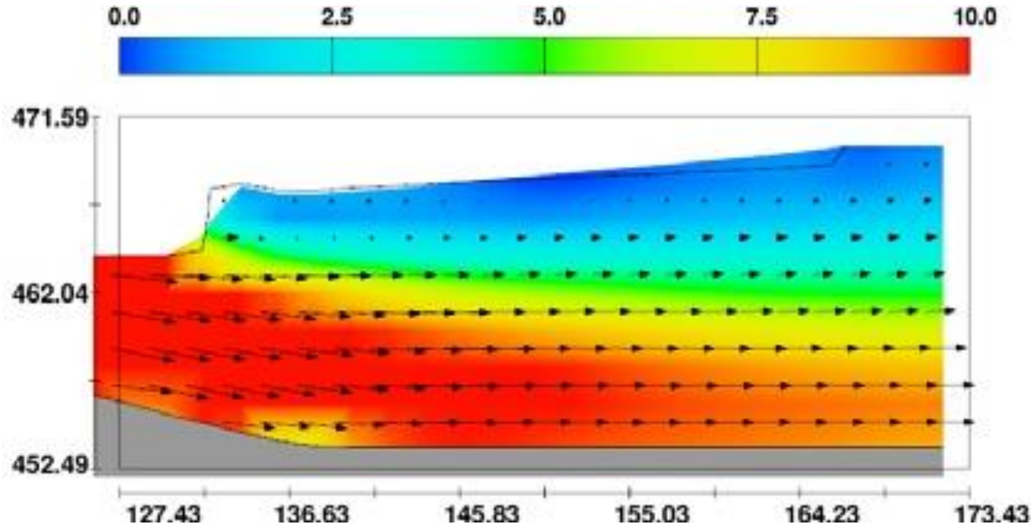
The results of the analysis for each barrage and under-sluice bay are presented below.

4.1 Velocity profiles

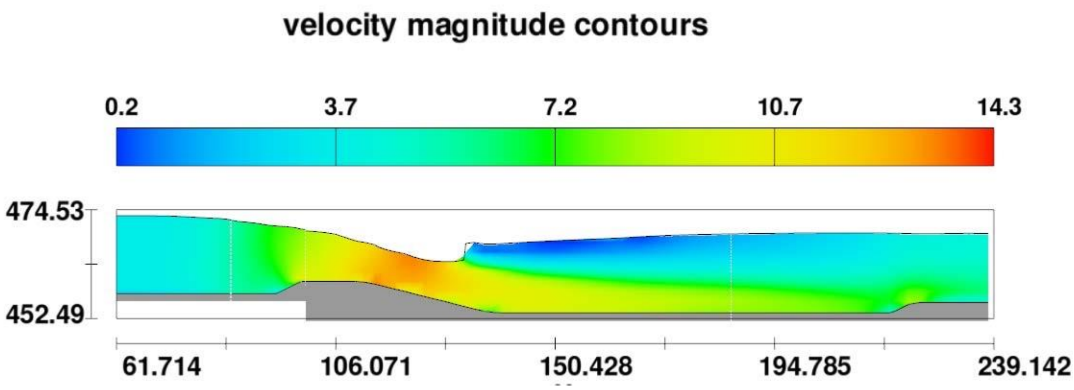
The proposed barrage assumes to regulate the reservoir level mostly at FSL and to release excess water including hazard floods. The velocity profile across the barrage bay at crest level is provided in Figure 8 (a). The average velocity over the crest is observed more than 9 m/s at full gate opening. The maximum flow velocity at stilling basin is around 10 m/s as shown in Figure 8 (b). The velocity magnitude contours along the barrage profile is presented in figure 8 (c).



(a)



(b)



(c)

Figure 8. Velocity Vector a) at crest b) at start of stilling basin c) along barrage Profile

The velocity contour for headwater elevation at 479.50 m is presented in Figure 9. The elevation of trunnion axis of radial gate is below the maximum water surface elevation for headwater elevation at 479.50 m. The maximum velocity observed throughout the longitudinal profile is 16.90 m/s.

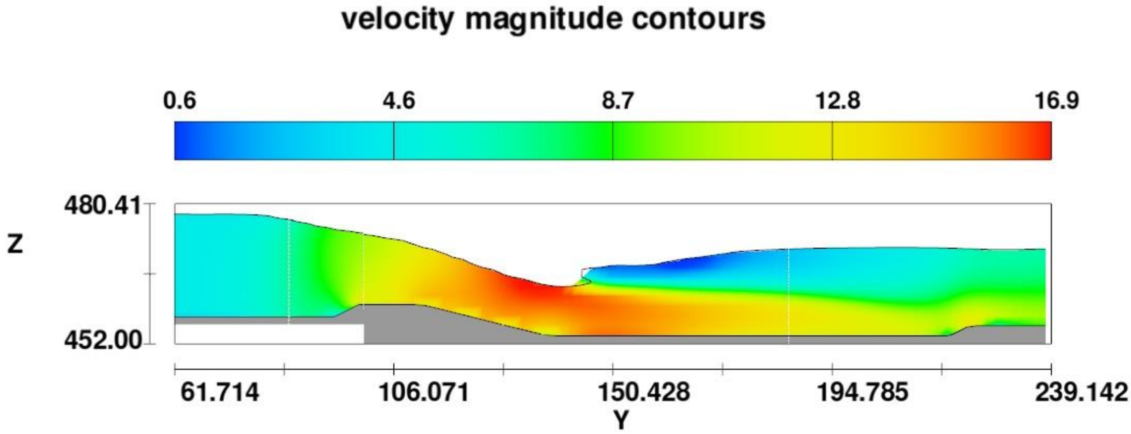


Figure 9- Velocity Magnitude (m/s) along the barrage profile at 479.5 m (Z- elevation, m and Y-distance, m)

The crest level of the double bay under-sluice is lower by 1.0 m compared to that of the barrage bay. The bays equipped with radial gates are designed to flush the sediment accumulated near the intake area and regulate the reservoir level at FSL. Like the barrage bays, they also release excess flow including hazard floods as well. The simulation is done to determine the velocity profile along the under-sluice profile. The average velocity over crest is observed more than 9 m/s at full gate opening.

The velocity magnitude profiles along the flow direction are shown in figure 10 (a). The maximum velocity observed throughout the longitudinal profile is 13.3 m/s. The velocity vector at the crest level at the under-sluice is observed 13 m/s (Figure 10 b). The maximum flow velocity at stilling basin is around 10 m/s (Figure 10 c).

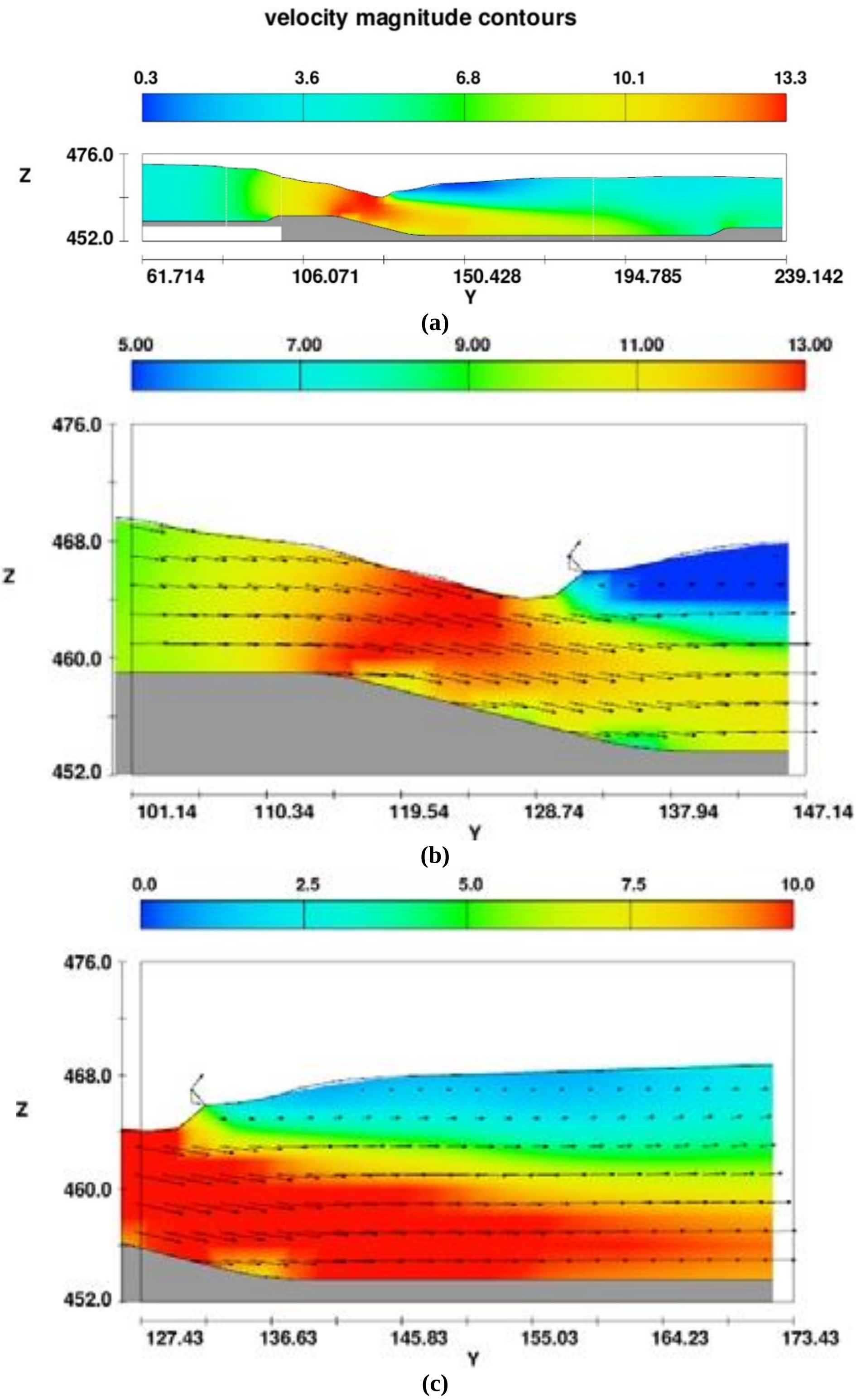


Figure 10. Velocity vector in under-sluice a) along the flow direction b) at crest c) at stilling basin

4.2 Pressure profiles

The pressure contours for FSL operation of barrage is presented in Figure 11. There is no sign of negative pressure formation throughout the profile. The minimum pressure observed is 101.356 KPa downstream from diversion axis, along the free surface elevation. Therefore, the structure will be free from cavitation phenomenon.

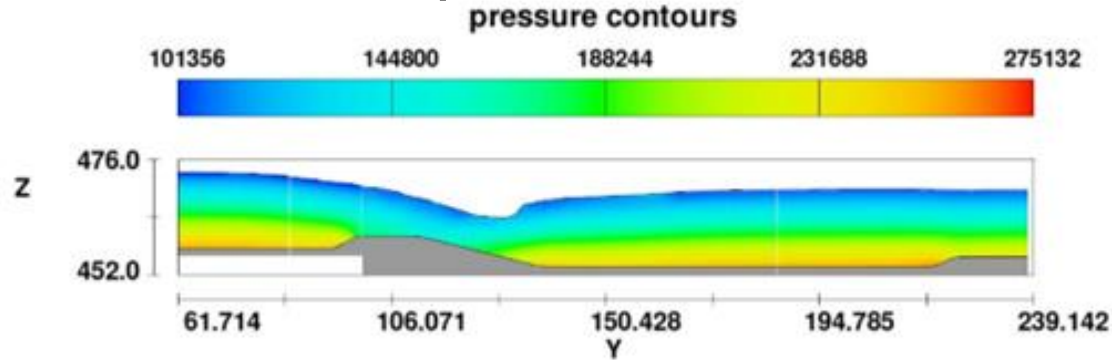


Figure 11. Pressure contours along the barrage profile for FSL operation

The pressure contours for FSL operation of under-sluice is presented in Figure 12. There is no issue with negative pressure formation throughout the under-sluice profile. The minimum pressure observed is 101.555 KPa throughout the free surface elevation.

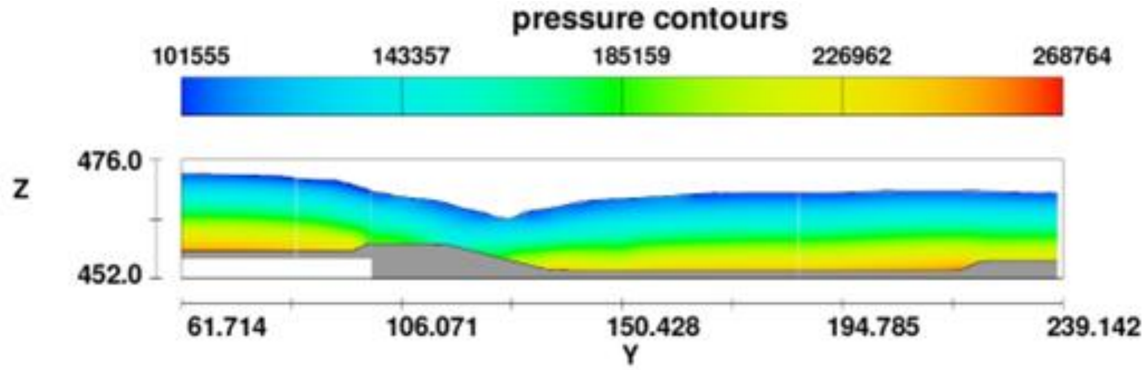


Figure 12. Pressure Contours along the under-sluice

4.3 Entrained air volume

The air entrainment starts at the start of stilling basin. The plot of entrained air volume fraction with fluid across the barrage bay with range from [0-0.05] is presented in Figure 13. The entrained air occupies stilling basin from the start to end.

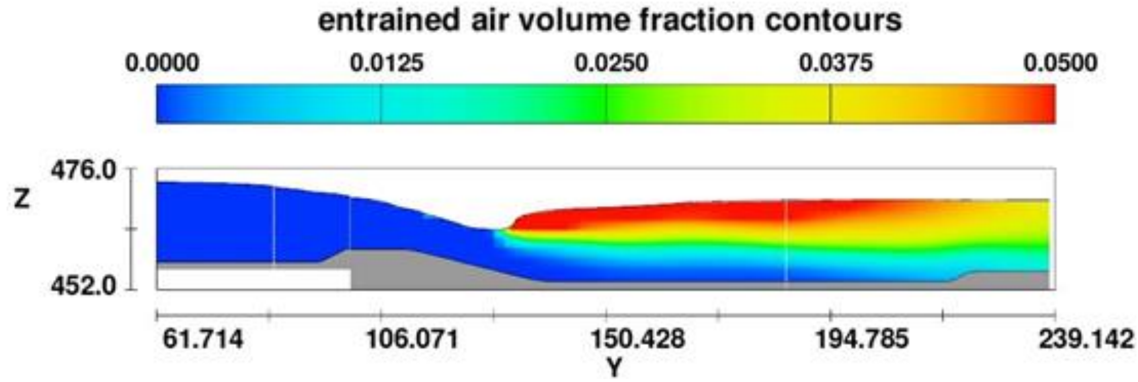


Figure 13. Entrained air volume fraction along the barrage profile

The air entrainment in under-sluice starts at the start of stilling basin. The plot of entrained air volume fraction with fluid along the longitudinal profile with range from [0-0.05] is presented in Figure 14. The entrained air occupies stilling basin from the start to end. Further downstream, air volume reduces to 50%.

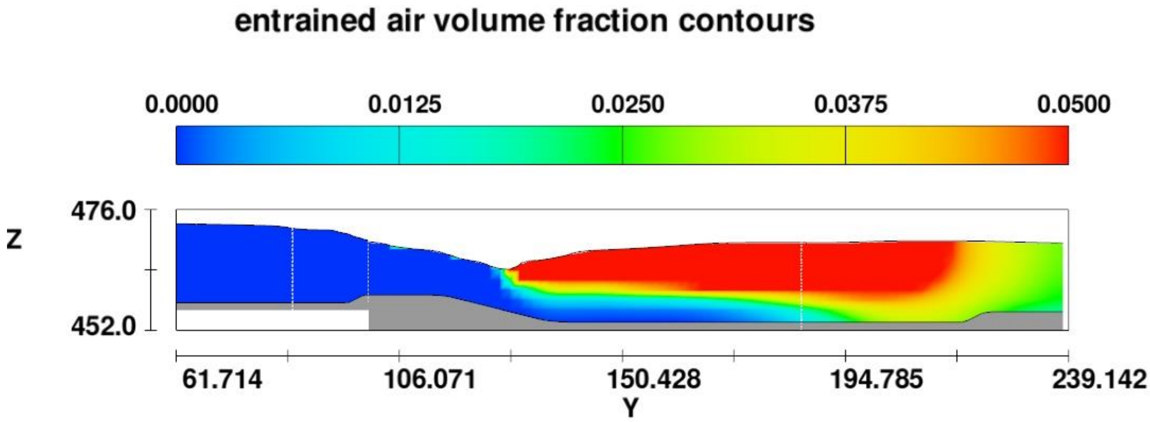


Figure 14. Entrained air volume fraction of under-sluice profile with FSL at 474.0 masl

4.4 Free surface profiles

The free surface profile with respect to bottom profile at different headwater elevation is presented in Figure 15. It can be observed that the hydraulic jump moves further upstream when the headwater is increased from 470.0 m to 474.0 m. In contrast, the hydraulic jump moves further downstream with the increase of headwater from 473.0 m to 478.0 m the jump moves downstream.

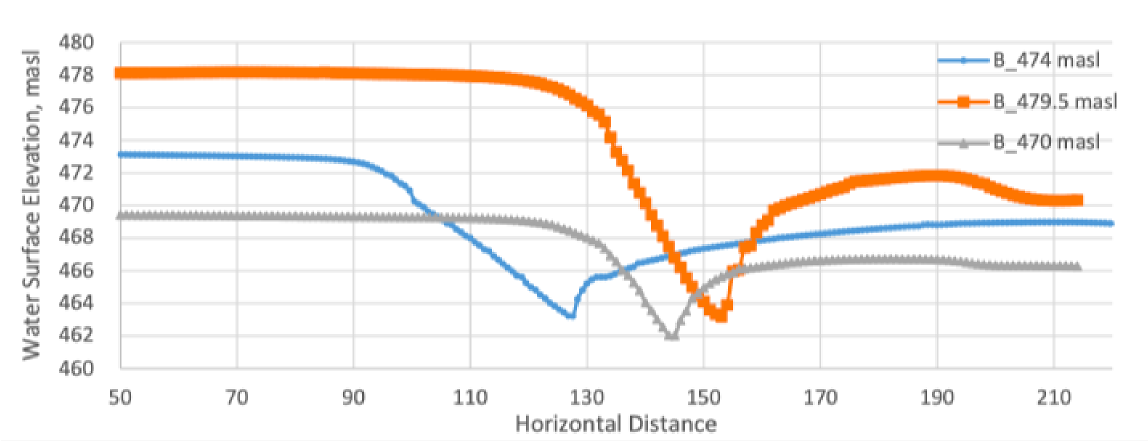


Figure 15. Free surface profile for different design head of barrage

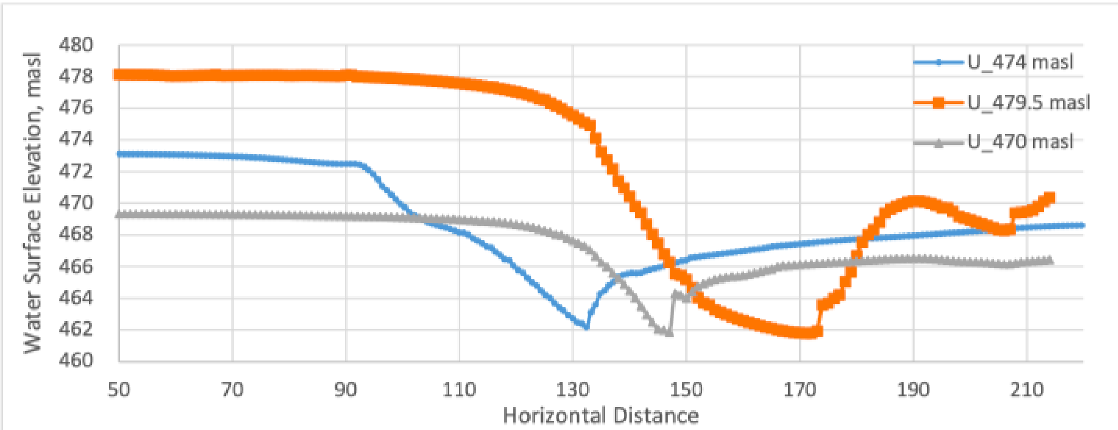


Figure 16. Free surface water profiles for under-sluice at different head water level

4.5 Rating curve

The rating curve for single barrage bay is generated simulating the bay for different head water elevation as presented in Figure 17.

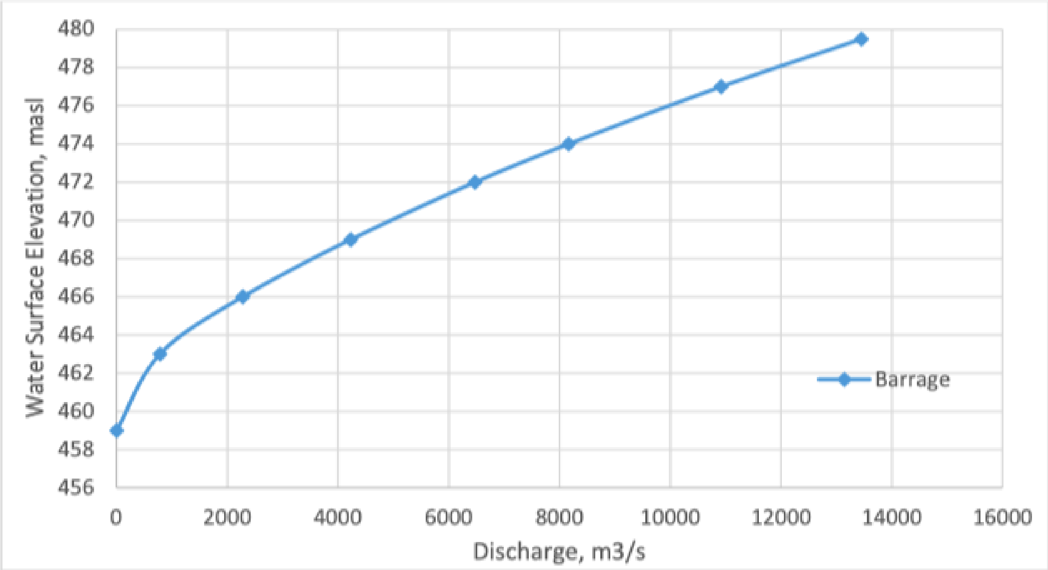


Figure 17. Rating curve of barrage bay under operation

The rating curve for under-sluice is generated and compared with the rating curve generated from 1D hydraulic equation (Continuity and Energy Equation) as shown in Figure 18.

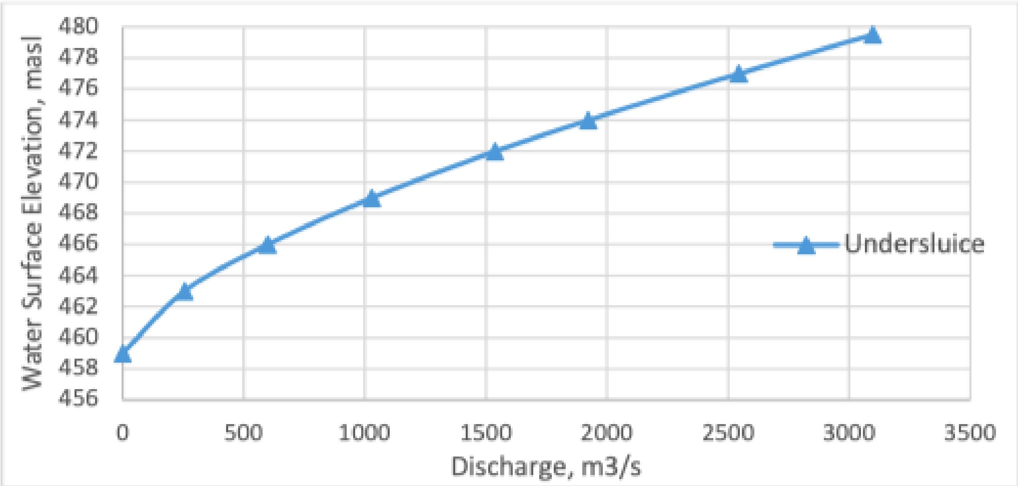


Figure 18. Rating Curve for Under-sluice operation

4.6 Combined operation of under-sluice and barrage

The simulation is used to determine the discharging capacity of head works for the given arrangement. The streamlines under operation are observed for both individual and combined bays. Small modification on the general geometry and arrangement are made to observe final simulation. Then, no local circulation and vortices are observed implying the hydraulic performance of the structure as satisfactory. The streamlines observed for combined operation is shown in Figure 19.

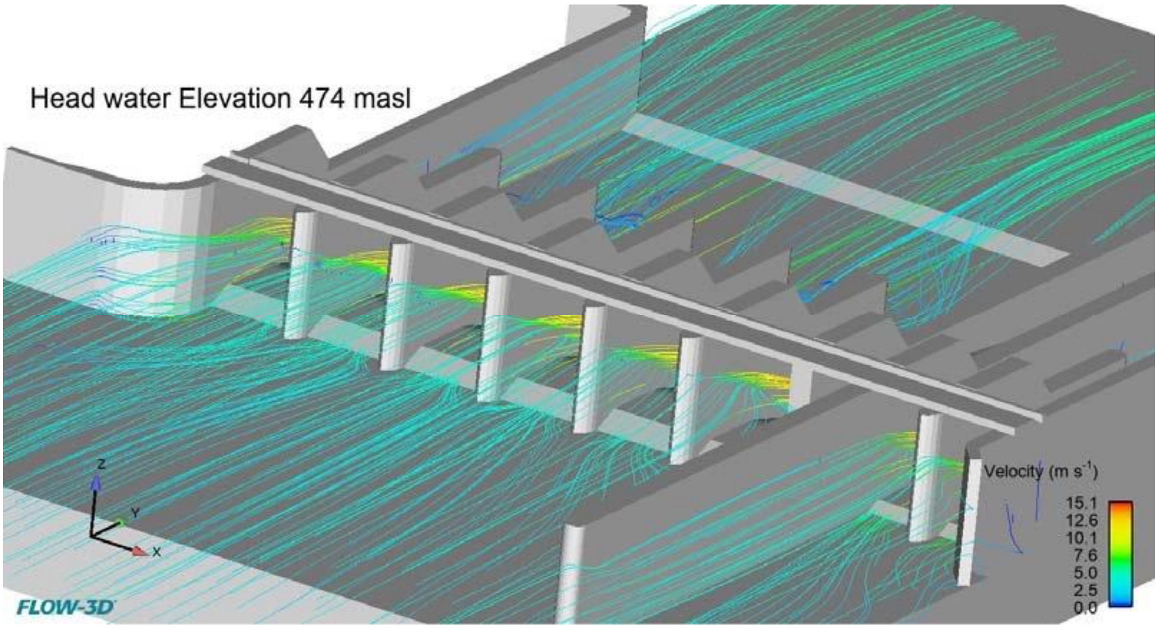


Figure 19. Streamlines from 3D model simulation for overall head works arrangement

The discharging capacity at FSL with simultaneous operation of barrage and under-sluice bays is assessed as 10,086 m^3/s. The flood corresponding to 100 years return period is 9,241 m^3/s and hence easily passes with headwater level being lower than FSL. Further, the extreme discharging capacity of the head works for headwater level as 479.5 masl is also assessed and found as 16,547 m^3/s. Therefore, deck level adopted as 481.00 masl will be sufficient to release 10,000 years flood.

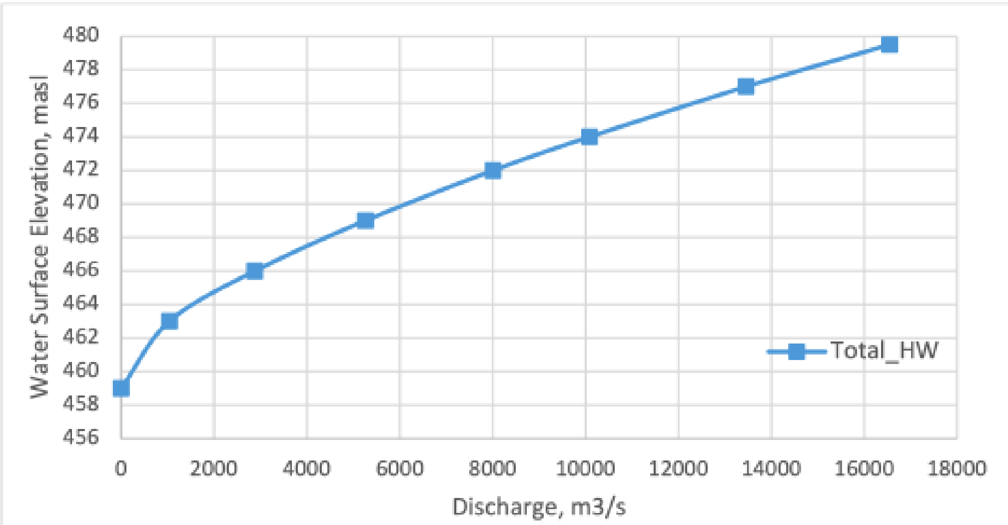


Figure 20. Rating Curve of Head works arrangement

5. Conclusions

FLOW 3D was capable of simulating and evaluating the hydraulic performance of barrage and under-sluice as well. The simulation was carried out based on the conceptual design of hydraulic structures. The proposed barrage assumes to regulate the reservoir level mostly at FSL and to release excess water including hazard floods. The average velocity over the barrage crest was observed more than 9 m/s at full gate opening. The maximum flow velocity at stilling basin was around 10 m/s. The maximum velocity observed throughout the longitudinal profile was 16.90 m/s. There is no sign of negative pressure formation throughout the profile. The minimum pressure observed was 101.356 KPa downstream from diversion axis, along the free surface elevation. Therefore, the structure would be free from cavitation phenomenon. It could be observed that the hydraulic jump moves further downstream with the increase of headwater. Further, deck level adopted as 481.0 masl would be sufficient to release 10,000 years return period flood. The produced rating curve for both barrage and under-sluice operation will be helpful in the operation and safety of barrage after placement.

This study simulates the barrage and under-sluice using FLOW 3D in the given environment and assess the performance of the structures. However, the real structures are often planned in a complex environment, where orientation of the structure, river morphology, hydraulic profiles of structures, upstream and downstream conditions play a vital role. Often flow streamlines are not witnessed as expected resulting in circulation and vorticity around the structures leading to sometimes instability of structures in some cases and lower capacity of the structures or both in other cases.

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Conflicts of Interest: The author declares no conflict of interest.

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