

Optimisation of Stilling Basin for an Ogee Spillway for Enhanced Energy Dissipation

V.V. Samet¹ Vankayalapati. S. Ramarao² V.S. Chavan³ P.B. Nangare⁴ A.T. Lokhande⁵

^{1&5}Graduate Student, Department of Civil Engineering, AISSMS College of Engineering, Pune, Maharashtra

² External Guide, Scientist-D, Central Water & Power Research Station, Pune, Maharashtra

³ Guide, Professor, Department of Civil Engineering, AISSMS College of Engineering, Pune, Maharashtra

⁴ Head of the Department, Department of Civil Engineering, AISSMS College of Engineering, Pune, Maharashtra

ABSTRACT

Spillways are meant for disposing of the excess flood safely to the downstream without causing any damage to its upstream, the structure itself and its downstream. Energy dissipator is essential component of spillway which dissipates the incoming excess energy. The most common energy dissipators are ski jump buckets, roller buckets, hydraulic jump type stilling basins, etc. Among these, stilling basins are very popular type of energy dissipators provided for high head / low head spillways, spillways, culverts and channels. Energy dissipation by stilling basins is governed by various factors like intensity of discharge, head causing flow, Froude number and tail water depth. When the tail water levels are sufficient to cope up with the sequent depth of hydraulic jump, stilling basins with horizontal apron are provided. If the tail water levels are higher than the required for sequent depth, sloping aprons are provided to contain the jump within the spillway glacis to avoid encroachment of jump further upstream. The design of horizontal basin involves fixing of length of basin, appurtenant structures like chute blocks, baffle blocks and end sill, whereas design of sloping apron involves fixing of slope of apron in addition to other components for horizontal apron. The slope of the apron must be determined from economic considerations and the length must be judged by the type and soundness of the riverbed downstream. The end sill is constructed at the downstream end of the stilling basin, whether solid or dentate and has function of reducing the length of the hydraulic jump and controlling scour. The performance of spillway depends upon the efficiency of its energy dissipator. In this paper, three different layouts of stilling basins, namely horizontal, sloping and curved aprons were studied, to achieve maximum energy dissipation. The study was carried out using both physical and numerical modelling techniques. Numerical modelling was done by using FLOW 3D HYDRO software. From the simulations, it can be concluded that a curved stilling basin would provide more energy dissipation than sloping or horizontal layouts.

Key Words: Spillway, crest, Sloping apron, tailwater level, initial depth, sequent depth, end sill, crest elevation.

1.0 INTRODUCTION

Spillway is a very essential structure of the dam safety. The main function of spillway is not only to release flood but to release it safely. In this context the role of energy dissipator is very crucial. Energy Dissipators for spillways are required to dissipate the excessive energy generated by impounding water when gets released down. The huge amount of potential energy is converted into kinetic energy due to steep slope of glacis of spillway. This energy may cause serious erosion which depends largely on the rate of discharge, head causing flow and the river bed material and surrounding geological area on the proximity of the dam and cause problems to the downstream of spillways and sometimes create threat to the dam complex itself. The energy of released flows can cause problems like erosion of banks and spillway undermining, sedimentation problems and submergence of downstream areas. To avoid such problems, the excess energy is to be dissipated to an allowable limit. The various structures which are required for this are called energy dissipators. The design of energy dissipator plays an important role in the dam safety issue. The common

types of energy dissipators are stilling basin with horizontal and sloping aprons, ski jump type buckets and solid/ slotted roller buckets.

2.0 STILLING BASINS WITH HORIZONTAL AND SLOPING APRONS

2.1. Horizontal Apron

When the tail-water rating curve approximately follows the hydraulic jump curve or is only slightly above or below it, then hydraulic jump type stilling basin with horizontal apron provides the best solution for energy dissipation. In this case the requisite depth may be obtained on a proper apron near or at the ground level so that it is quite economical. For spillways on weak bed rock conditions and spillways and barrages on sand or loose gravel, hydraulic jump type stilling basins are recommended. Hydraulic jump type stilling basin with horizontal apron may be classified into two categories: a) Stilling basins in which the Froude number of the incoming flow is less than 4.5, generally on spillways and barrages (Basin -I) and when the Froude number of the incoming flow is greater than 4.5, for dams (Basin -II) (IS 4997).

2.2 Sloping Apron

When Tail water is too high as compared to the sequent depth, the jet left at the natural ground level would continue to go as a strong current near the bed forming a drowned jump which is harmful to river bed. In such a case, a hydraulic jump type stilling basin with sloping apron should be preferred as it would allow an efficient jump to be formed at suitable level on sloping apron (IS 4997). Hager (1992) and Peterka (1984) worked on the hydraulic design of stilling basins, with Peterka's Bureau of Reclamation monograph providing standardized design rules, and Hager's later work (1992) offering improvements in the designs.

The hydraulic jump may occur in different ways on sloping apron as shown in Fig. 2. Type B jump forms at toe of slope and ends on horizontal apron, type C forms on slope and ends at junction of slope and horizontal apron, and type D forms entirely on slope. The length of apron required may range from 40 – 80 % of length of jump. Fig. 3 and 4 show length of jump in terms of conjugate depth D_2 and ratio of conjugate depth D_2 to D_1 (IS: 4997- 1968). Fig. 1 shows a typical horizontal and sloping stilling basins.

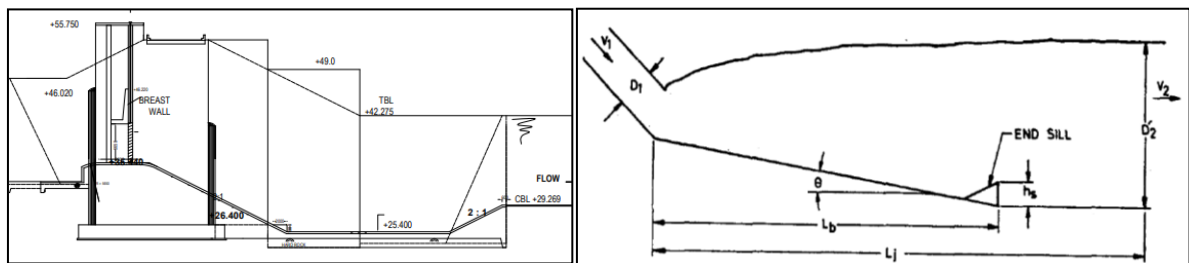


Fig 1. Spillways with horizontal and sloping stilling basins

3.0 OPTIMISATION OF STILLING BASIN FOR ENHANCING THE ENERGY DISSIPATION

One the major contributors in the energy dissipation downstream of spillways is the tailwater. In order to enhance the energy dissipation, three layouts of the stilling basin were studied.

3.1. STILLING BASIN WITH SLOPING APRON

3.1.1. Sloping Apron- Physical model study

Initially, stilling basin with the sloping apron was tested. To assess the energy dissipation, model studies are essential. Hence, hydraulic model studies were carried out on a 1:55 scale 2-D sectional model (Geometrically Similar, G.S) in Central Water and Power Research Station (CWPRS), Pune (CWPRS T.R.5027). The spillway was 609 m wide, about 98 m long. The crest level is at El. 31.75 m. The sloping basin has an end sill with its top elevation at El. 15.5 m. The basin has a curve with 7.64 m radius at the heel a slope of 11.11 m (H) to 1 (V). The cross section of the spillway is shown as Fig 2. The model and prototype quantities are given in Table 1.

Studies indicated that the discharge of $15,700 \text{ m}^3/\text{s}$ could be passed at Reservoir Water Level (RWL) at El. 37.5 m. The tail water level for the corresponding discharge was at El. 26.5 m. The velocity observed at the downstream was 1.51 m/s. Fig 3 shows the flow conditions in the performance of the sloping stilling basin, while passing $15700 \text{ m}^3/\text{s}$ (Ramarao et al, 2014).

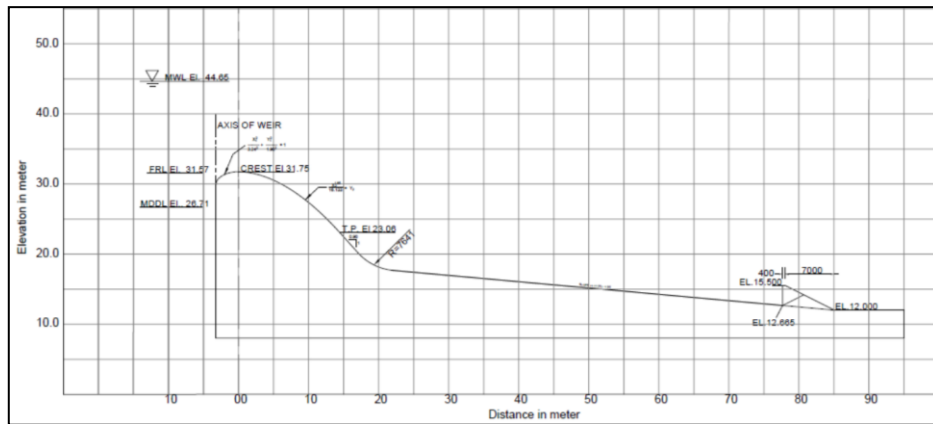


Fig. 2 Cross section of ogee spillway with sloping stilling basin

Table 1. Quantities of model and prototypes

Dimensions	Scale Relation
Length	1: 55
Area	1: 3025
Velocity	1: 7.42
Discharge	1: 22434
Time	1:7.42
Pressure in m of water head	1: 55
Manning's 'n'	1: 1.95



Fig 3. Performance of stilling basin while passing $15700 \text{ m}^3/\text{s}$ (Sloping apron)

3.1.2. Sloping apron- Numerical model study

The commercial software FLOW3D HYDRO, developed by Flow Science, was used for the numerical modeling of the flow. The FLOW3D uses finite-volume method to solve the Reynolds-averaged Navier – Stokes (RANS) equations over computational domain (Amorim et al, 2004). Tracking of free surface is performed using Volume-of-Fluid method. The numerical modelling of the flow inside the stilling basin is much complex due to the high intensity of the turbulence and the recirculation that is associated with the hydraulic jump. To represent these characteristics of the flow, Re-normalized Group (RNG) turbulence model was used. Total calculated cells for all blocks are 66,12,936, Mesh plane position step size was 0.01. The bottom most elevation of the geometry was set El. 8 m. Total number of probes were 75 in three rows (Right, Centre, Left). During simulation, both upstream and downstream boundaries were set as Pressure

Outlet. The extent of the mesh in the upstream X-direction was adjusted until any further increases had negligible effect on the water levels, while the downstream boundary was placed past the energy dissipator to cover tail water level conditions. The all simulations were run for 100 seconds which was found to be enough for the hydraulic jump stabilisation. During the simulation, flow starts from the rest and is settled by water level difference between upstream and downstream. There is an initial time gap, for which the hydraulic jump, still is not stabilised and characteristics flow parameters presents a great time fluctuation. When the jump becomes stable, these values have a small fluctuation around an average value. Simulation was carried out for 15,700 m³/s. Fig. 4 shows geometry of numerical simulation. Tables 2 and 3 shows the mesh details and boundary conditions.

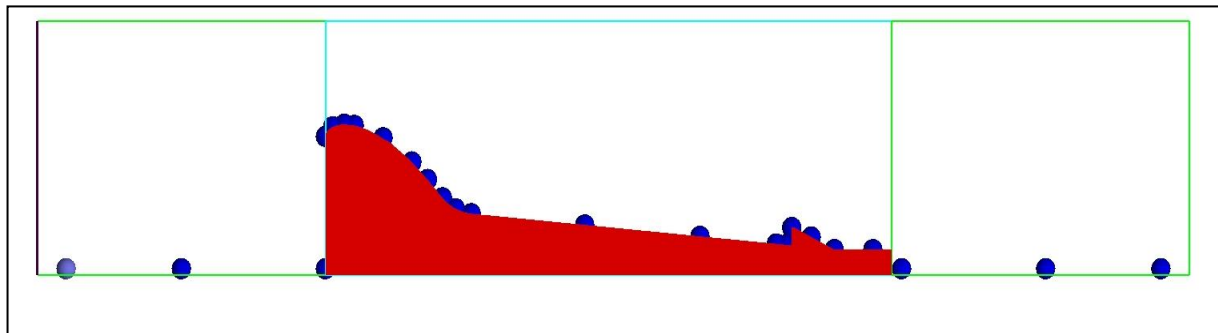


Fig 4. Geometry of stilling basin with sloping apron with probes location

Table 2. Details of the mesh blocks of the geometry

Mesh Block	X _{min}	X _{max}	Y _{min}	Y _{max}	Z _{min}	Z _{max}	Size of cell/ total cells	Total calculated cells mesh block
1	-50	0	0	609	0	40	0.9	16,68,128
2	0	98.27559	0	609	0	40	0.9	32,46,892
3	98.27599	150	0	609	0	40	0.9	16,97,916

Table 3. Details of the boundary conditions of the mesh blocks of the geometry

Mesh Block	X _{min}	X _{max}	Y _{min}	Y _{max}	Z _{min}	Z _{max}	Fluid elevation
1	Pressure	Symmetry	Wall	Wall	Wall	Pressure	37.5 m
2	Symmetry	Symmetry	Symmetry	Symmetry	Symmetry	Symmetry	-
3	Symmetry	Pressure	Wall	Wall	Wall	Pressure	26.5 M

Studies indicated that the discharge of 15,700 m³/s could be passed at Reservoir Water Level (RWL) at El. 37.5 m. The tail water level for the corresponding discharge was kept at El. 26.5 m. Hydraulic jump was forming in the stilling basin. The velocities observed at the downstream were 1.27 m/s, 1.34 m/s and 1.36 m/s respectively on left, centre and right side of the downstream of the stilling basin. Figures 5 and 6 show the comparison of the water surface and pressure profiles, while passing 15700 m³/s, for both physical and numerical studies and it was found that these were in good agreement with each other. Figures 7,8 and 9 shows the simulation results of water surface profiles, pressure profiles and velocity profiles along the spillway and stilling basin respectively.

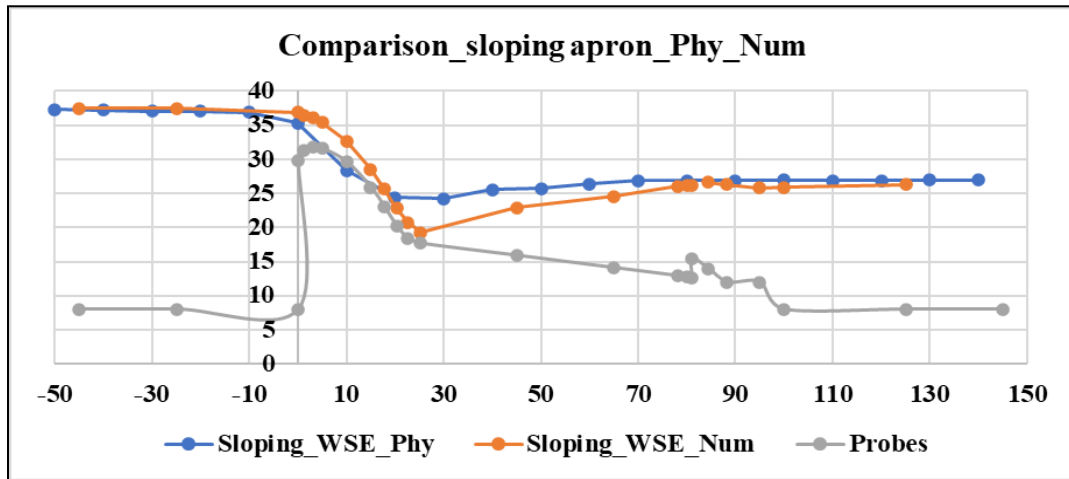


Fig 5. Water surface elevations for sloping stilling basin for discharge of 15,700 m³/s (Physical and Numerical model studies)

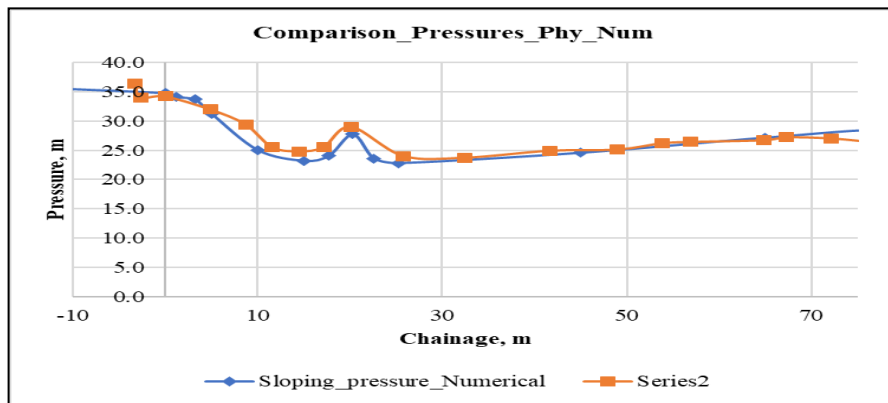


Fig 6. Pressure profiles for sloping stilling basin for discharge of 15,700 m³/s (Physical and Numerical model studies)

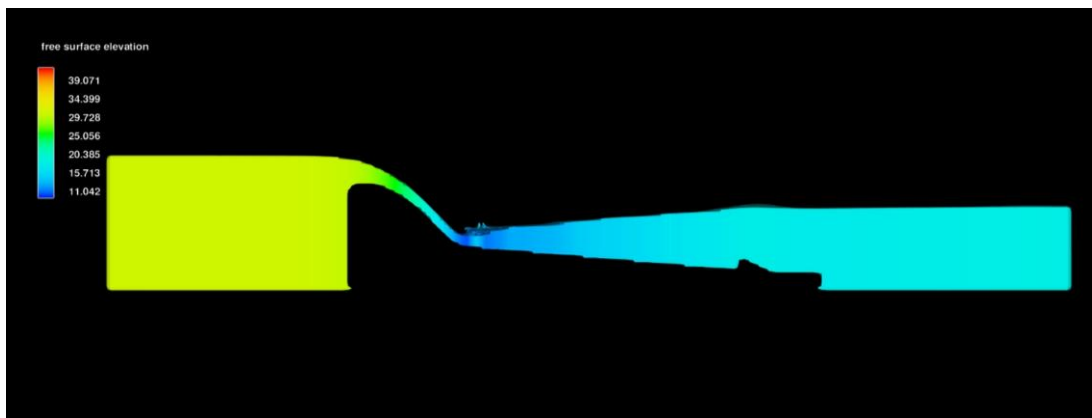


Fig. 7. Water surface profile from Numerical Simulation for discharge of 15,700 m³/s (Sloping apron)

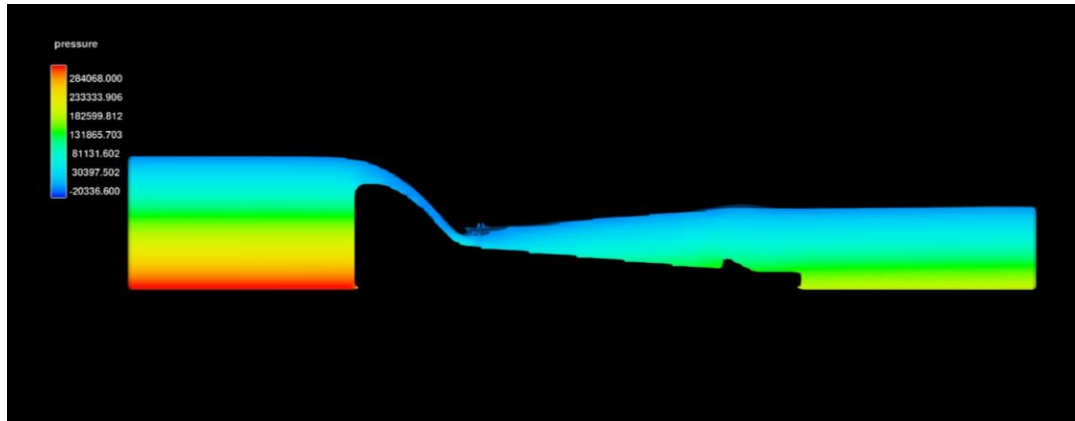


Fig. 8. Pressure profile from Numerical Simulation for discharge of 15,700 m³/s (sloping apron)

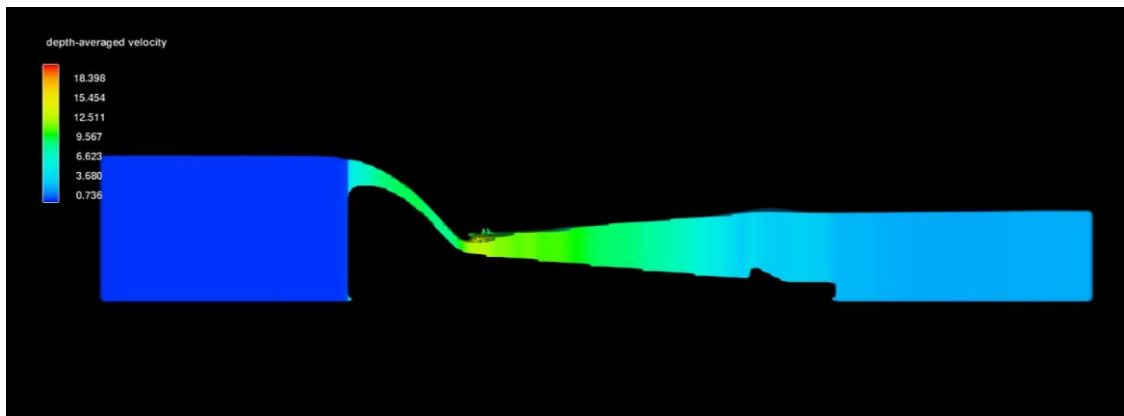


Fig. 9. Velocity profile from Numerical Simulation for discharge of 15,700 m³/s (Sloping apron)

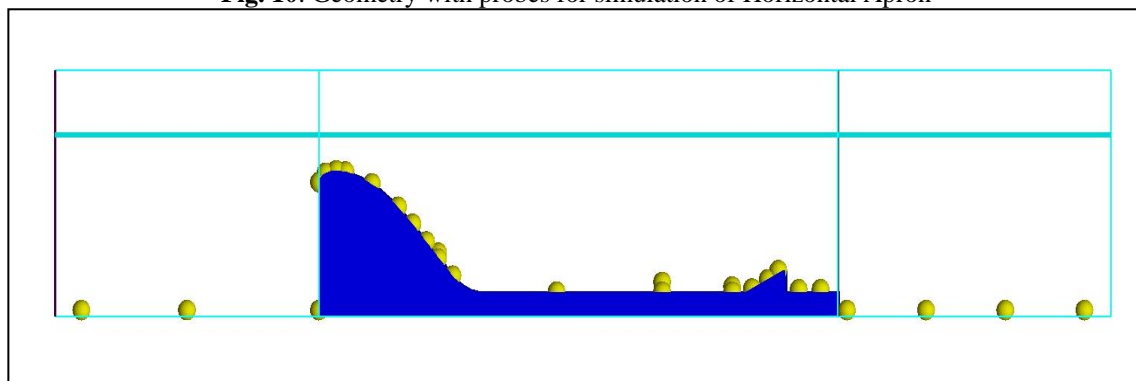
3.2. STILLING BASIN WITH HORIZONTAL APRON

3.2.1 Horizontal Apron- Numerical model study

The geometry for this numerical simulation comprises of the spillway and horizontal stilling basin, with a total length of about 98 m long with end sill sloping upstream and its top elevation is at El. 15.5 m. The basin has a curve with 7.64 m radius at the heel and then after the basin remains horizontal. 75 probes were installed along the profile in three rows of left, centre and right side of the spillway, as shown in Fig 10.

Studies indicated that the discharge of 15,700 m³/s could be passed at Reservoir Water Level (RWL) at El. 37.5 m. The tail water level for the corresponding discharge was kept at El. 26.5 m. It was seen that the hydraulic jump was seen submerging the heel of the stilling basin. The velocities observed were 1.55 m/s, 1.44 m and 2.82 m respectively on left, centre and right side of the downstream of the stilling basin. Figures 11,12 and 13 shows the simulation results of water surface profiles, pressure profiles and velocity profiles along the spillway and stilling basin respectively, while passing 15700 m³/s.

Fig. 10. Geometry with probes for simulation of Horizontal Apron



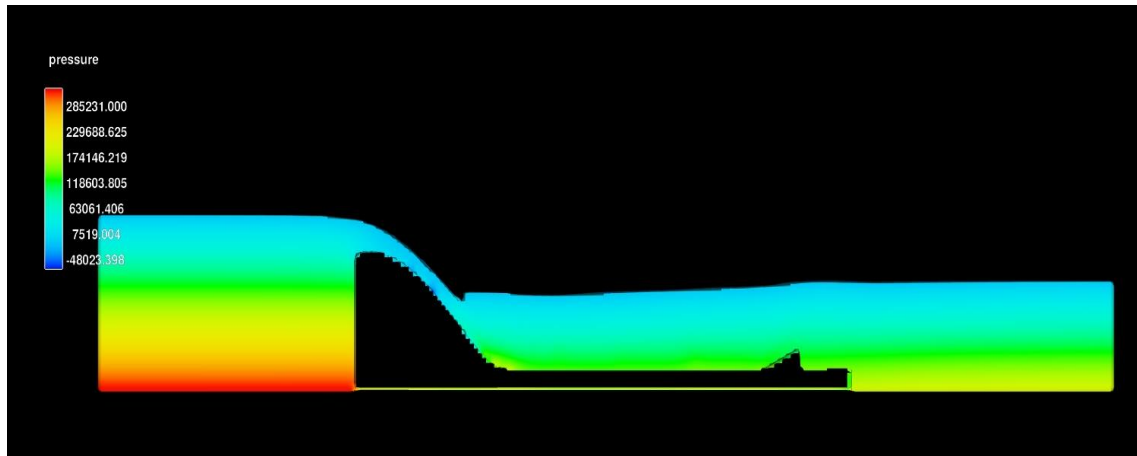


Fig 11. Pressure profile from Numerical Simulation for discharge of 15,700 m³/s (Horizontal apron).

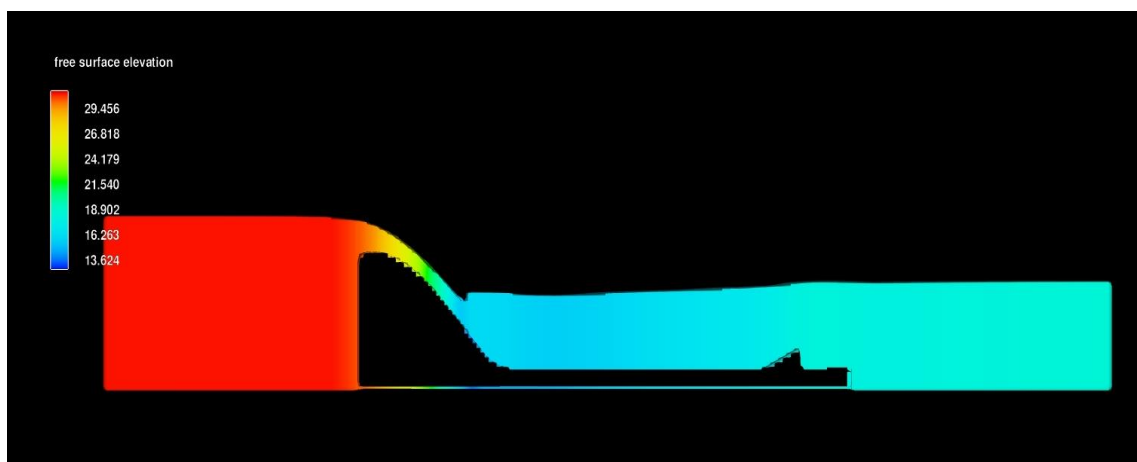
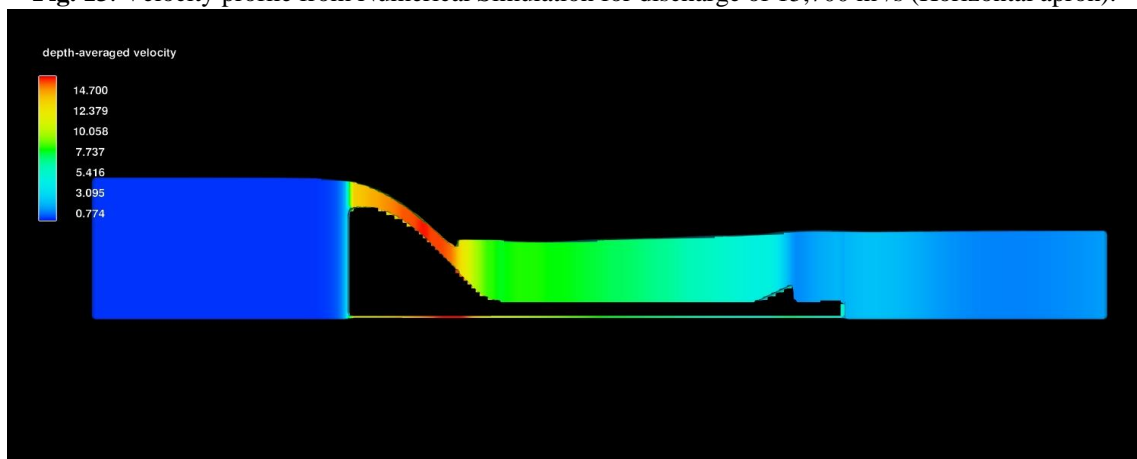


Fig. 12. Water surface profile from Numerical Simulation for discharge of 15,700 m³/s (Horizontal apron).

Fig. 13. Velocity profile from Numerical Simulation for discharge of 15,700 m³/s (Horizontal apron).



3.3. STILLING BASIN WITH CURVED APRON

3.3.1. Curved apron- Numerical Study

In addition to horizontal and sloping aprons, an innovative curved apron was also simulated. In this type, a curve of large radius was introduced along the slope of the sloping apron. This profile has marginal variation against the sloping apron. The end sill also made sloping towards the upstream. All the other design components remain unchanged. Fig. 14. Shows the geometry with probes for simulation of curved apron stilling basin.

Studies indicated that the provision of the curve improved the flow conditions and the energy dissipation. The discharge of $15,700 \text{ m}^3/\text{s}$ could be passed at Reservoir Water Level (RWL) at El. 37.5 m. The tail water level for the corresponding discharge was kept at El. 26.5 m. The velocity observed at the downstream was 1.23 m/s, 1.23 m and 1.36 m respectively on left, centre and right side of the downstream of the stilling basin, while passing $15700 \text{ m}^3/\text{s}$. Figures 15,16 and 17 shows the simulation results of water surface profiles, pressure profiles and velocity profiles along the spillway and stilling basin respectively.

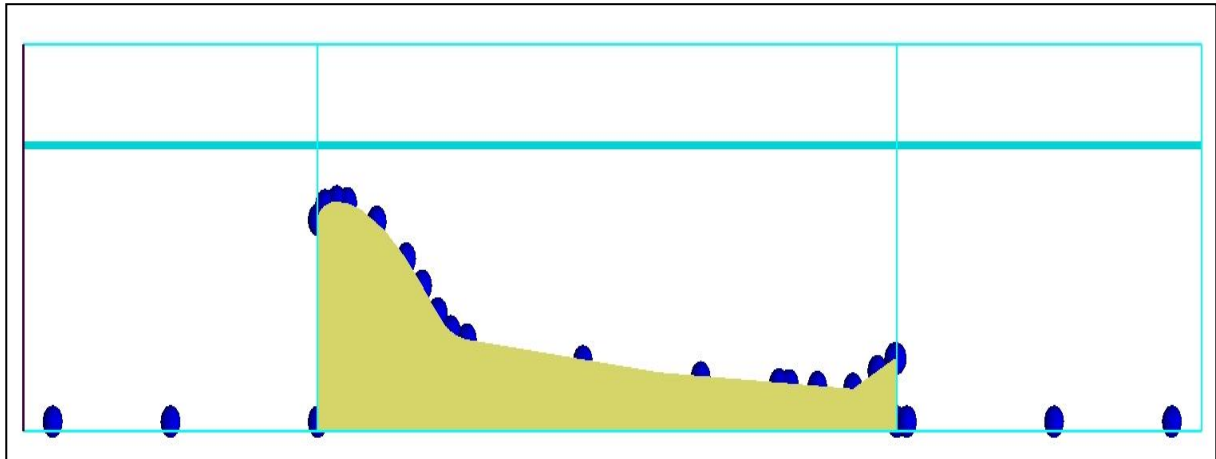


Fig. 14. Geometry with probes for simulation of curved apron stilling basin

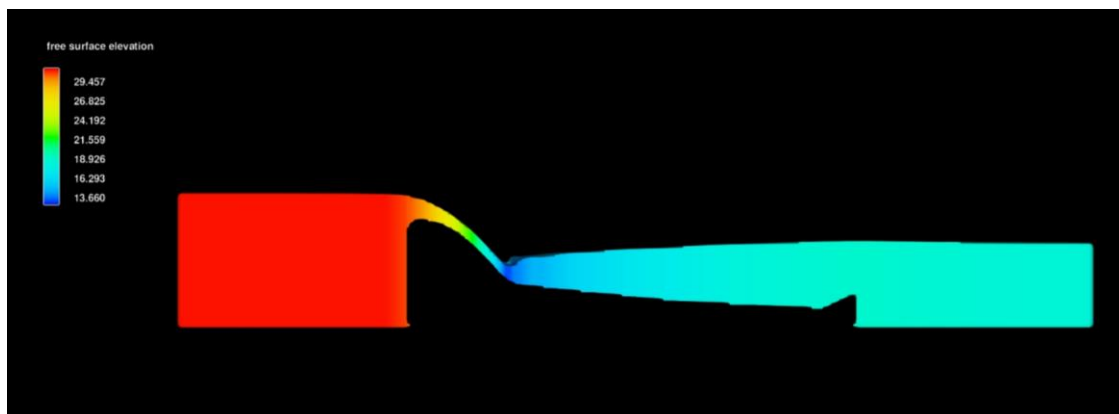


Fig. 15. Water surface profile from Numerical Simulation for discharge of $15,700 \text{ m}^3/\text{s}$ (Curved apron)

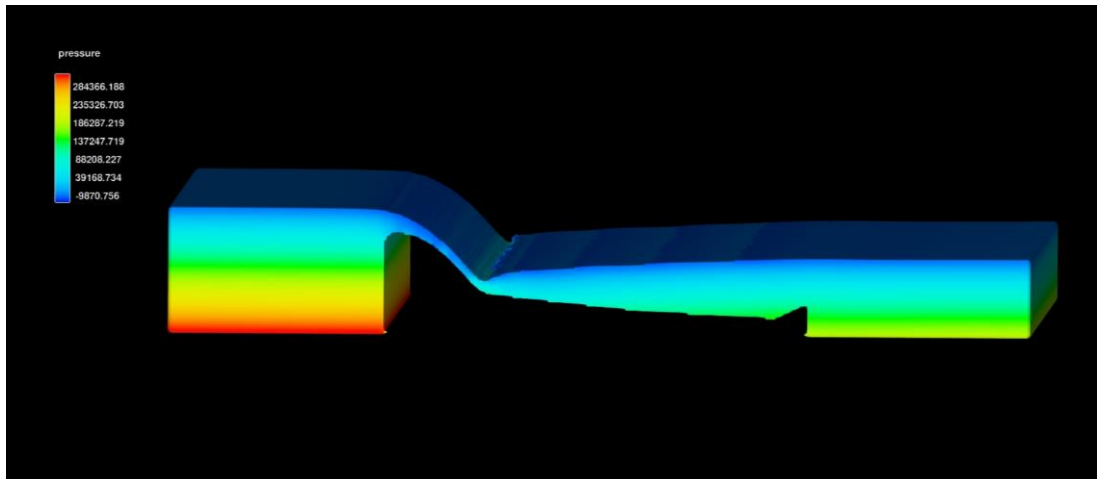


Fig 16. Pressure profile from Numerical Simulation for discharge of 15,700 m³/s (Curved apron).

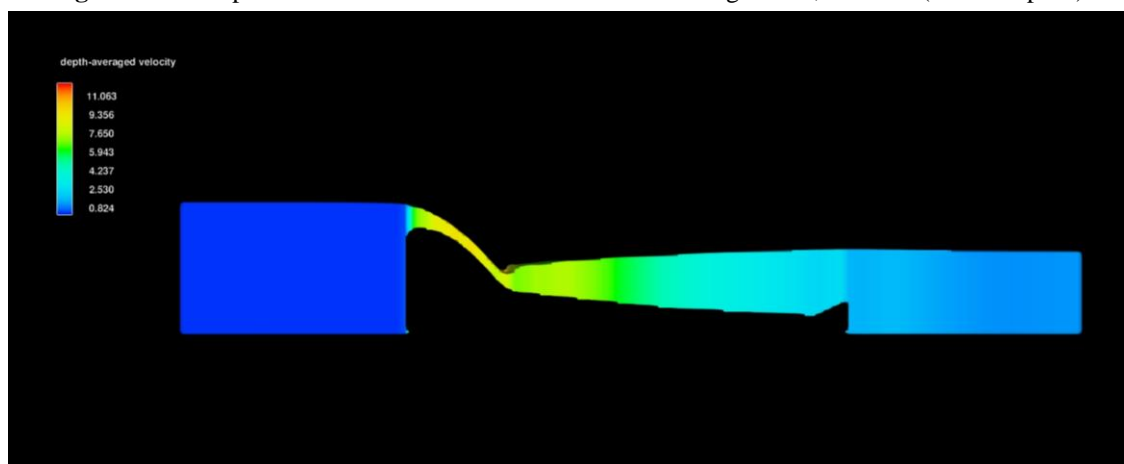


Fig. 17. Velocity profile from Numerical Simulation for discharge of 15,700 m³/s (Curved apron)

4.0 COMPARISON OF THE RESULTS OF THREE LAYOUTS

The results obtained from numerical simulation of three layouts were compared in respect of water surface elevations, pressures, velocities and energy dissipation.

4.1 WATER SURFACE PROFILES

The studies on water surface profile over surface of spillway indicated that the jump was seen encroaching upwards on the glacis of the spillway for horizontal apron. There was no variation water surface profiles in the three layouts except in the stilling basin zone. Fig. 18 show results from numerical simulation and comparison of results for water surface elevations obtained from numerical simulation with a discharge of 15,700 m³/s, respectively.

4.2 PRESSURE PROFILES

Pressure at probes points were measured from numerical simulation at 100 seconds, corresponds to occurrence of stable hydraulic jump. Fig.19 shows the results from numerical simulation and comparison of results for pressures obtained from numerical simulation and experimental studies for discharge of 15,700 m³/s, respectively. The results showed variation in the pressures along the spillway profile and the stilling basin but there was no variation along the upstream of the spillway.

4.3 VELOCITY PROFILES

Velocities at probe points were measured, corresponds to occurrence of stable hydraulic jump. Fig.20 shows results from numerical simulation and comparison of results for pressures obtained from numerical

simulation and experimental studies for discharge of 15,700 m³/s, respectively. Curved profile has lesser velocities observed downstream of stilling basin. These velocities were 4-8% lesser than sloping layout and 20-50% lesser than horizontal layout. Table 5 shows the comparison of velocity profiles for three layouts of stilling basin.

4.4. ENERGY DISSIPATION

In stilling basins, turbulence dissipation is a direct indicator of how effectively the basin reduces the energy of high-velocity flows coming from spillways or outlets. Turbulent energy dissipation downstream of stilling basins is primarily achieved through hydraulic jumps, where high-energy water transitions from supercritical to subcritical flow. High turbulence dissipation correlates with reduced velocity at the basin exit, minimized cavitation risk, and controlled hydraulic jumps. High turbulence levels mean energy is being broken down into smaller eddies and eventually converted into heat. Effective dissipation prevents downstream erosion, scouring, and structural damage. A well-designed basin spreads turbulence evenly, avoiding localized high-energy zones that can undermine the basin floor or sidewalls. The maximum difference in energy dissipation 157% on right side, 18.5 % on the centre and 134 % on the left side, when compared with horizontal apron. Table 6 shows the comparison of turbulence dissipation for three layouts of stilling basin

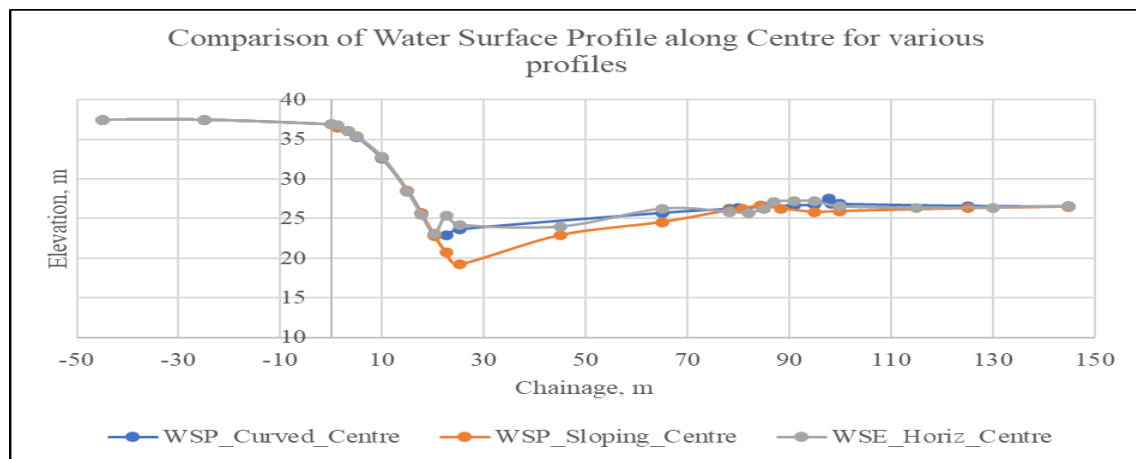


Fig. 18. Comparison of water surface profiles for three layouts for discharge of 15,700 m³/s.

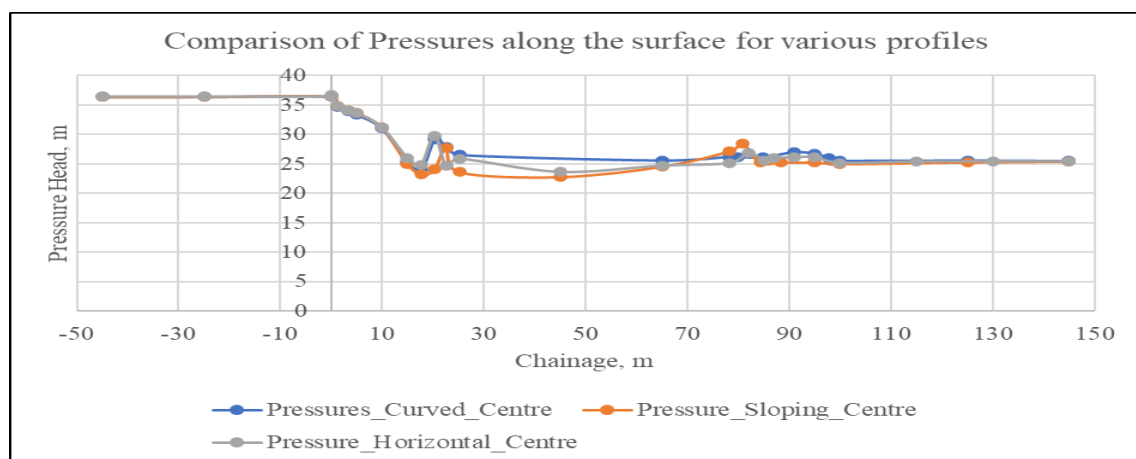


Fig. 19. Comparison of pressure profiles for three layouts for discharge of 15,700 m³/s

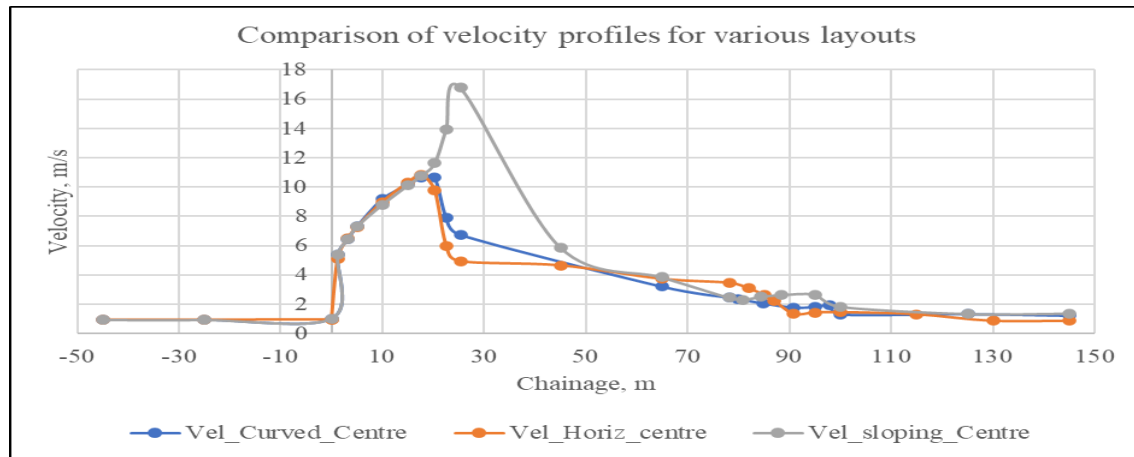


Fig. 20. Comparison of velocity profiles for three layouts for discharge of 15,700 m³/s.

Table 5. Comparison of velocity profiles for three layouts of stilling basin

Profile	Right side	Centre	Left side
Horizontal stilling basin	1.55	1.44	2.82
Sloping stilling basin	1.27	1.34	1.36
Curved stilling basin	1.23	1.23	1.36

Table 6. Comparison of Turbulence dissipation (m²/s²) for three layouts of stilling basin

Profile	Right side	Centre	Left side
Horizontal stilling basin	0.032919	0.049143	0.034935
Sloping stilling basin	0.022631	0.052503	0.022924
Curved stilling basin	0.058259	0.058259	0.053709

5.0 CONCLUSIONS

The provision of type of apron for a stilling basin, whether horizontal, sloping or curved depends upon the prevailing tail water levels and downstream geology. The objective is to achieve maximum amount of energy dissipation downstream of the stilling basin. The design involves finalisation of the invert level of the stilling basin and slope of stilling basin which suite to frequently disposable floods. Studies were carried out on three different layouts of stilling basins, horizontal apron, sloping apron and curved apron, using FLOW 3D HYDRO numerical modelling, to observe their performance while passing a specific discharge and maintaining corresponding tail water levels. From the results of simulations, it can be concluded that a sloping stilling basin or curved stilling basin would provide more energy dissipation than horizontal layout. The velocities were more along the sides than along the centre, for all the layouts. There was marginal variation in the water surface, pressure profiles among the three layouts. The studies indicated that the length of apron is sufficient for containing the jump for all the layouts. Thus, it is inferred that the numerical modelling can be used as a complementary tool to physical modelling for studying complex spillway problems.

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Nomenclature

- D_1 = Depth of flow at the beginning of the jump
 D_2 = Depth conjugate to D_1 for horizontal apron
 D'_2 = Depth conjugate to D_1 for sloping apron
 h_s = Height of endsill
 L_j = Length of hydraulic jump
 L_b = Length of basin
 V_1 = Velocity of flow at the beginning of the jump
 V_2 = Velocity of flow at the end of the jump
 θ = Angle of sloping apron with horizontal
 F_1 = Froude Number of flow at the beginning of the jump

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