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Multiple analysis approach for the design of the labyrinth spillway on the Nam Teng river, Myanmar: Concept design – CFD – physical model

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Abstract. This paper presents the results of a combined approach - concept design, Computational Fluid Dynamics (CFD) simulations and physical model test - to design a spillway on the Nam Teng River in Myanmar. The spillway includes a 140 m wide labyrinth weir which ensures that the PMF flow Q_{PMF}=6800 m^3/s passes with a maximum head of 5.5 m. The width required to pass PMF flow for a conventional ogee shaped weir is ca. 200m. The design of the spillway is based on design recommendations for labyrinth weirs from Tullis [1] and USBR guidelines to design the chute, stilling basin and outfall channel that leads the flood flow back to the river. The CFD simulations helped to improve the flow condition at the entrance and towards the labyrinth weir by altering the approach channel. The physical model tests confirmed the capacity of the labyrinth weir, investigated blockage risk due to floating debris. The design modifications made based on the physical model tests have increased the hydraulic performance and safety of the spillway and made the construction cheaper and simpler (less excavation and civil work).

1. Introduction and background

The paper presents the results of a design approach for a spillway in southern Shan state in Myanmar. The project is part of the construction of the Upper Keng Tawng (UKT) hydropower plant which will capture the water from the Nam Teng River basin (5200 km^2). The project consists of a 58 m high embankment dam that will dam the river and create a reservoir of about 120 mill. m^3 and a 52 MW powerhouse. Fig. 1 gives the project overview. The mean average flow is 269 m^3/s, the 1000-year flood flow is Q_{1000}=3055 m^3/s and the PMF is Q_{PMF}=6800 m^3/s. Flood flows are high due to the monsoon climate in the region. During the flood, the excess water is evacuated over a spillway. An alternative study which compared a broad-, an ogee- and a labyrinth-weir concluded that the labyrinth weir was the cheapest and best alternative given the technical constraints of the project (hydrology, deep overburden of soil and weathered rock, weak zones in the bedrock with presence of faults). Labyrinth weirs are of particular value when the site topography limits spillway width. When compared to a conventional ogee shaped weir, a labyrinth weir provides an efficient means

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of increasing spillway capacity without increasing the spillway width or raising the dam crest (less excavation and civil work).

The labyrinth weir overflows into a creek on the north side of the reservoir and it is necessary to include further civils works to safely pass the flood flow downstream the dam:

- An approach channel that leads the flow from the reservoir to the labyrinth weir.
- A chute approximately 50 m long, 140 m wide and with a vertical drop of 12.5 m terminating in a stilling basin. At the end of the stilling basin, the channel width is reduced from 140 m to 70 m.
- An outfall channel 70 m wide and 1100 m long which includes 3 check dams, all about 15 m high with a USBR Type III stilling basin downstream. The design of the outfall channel is not described in this paper.

The spillway was designed in three steps as presented in the following sections: the concept design (section 2), a numerical model of the spillway (section 3) and a physical model of the spillway (section 4).

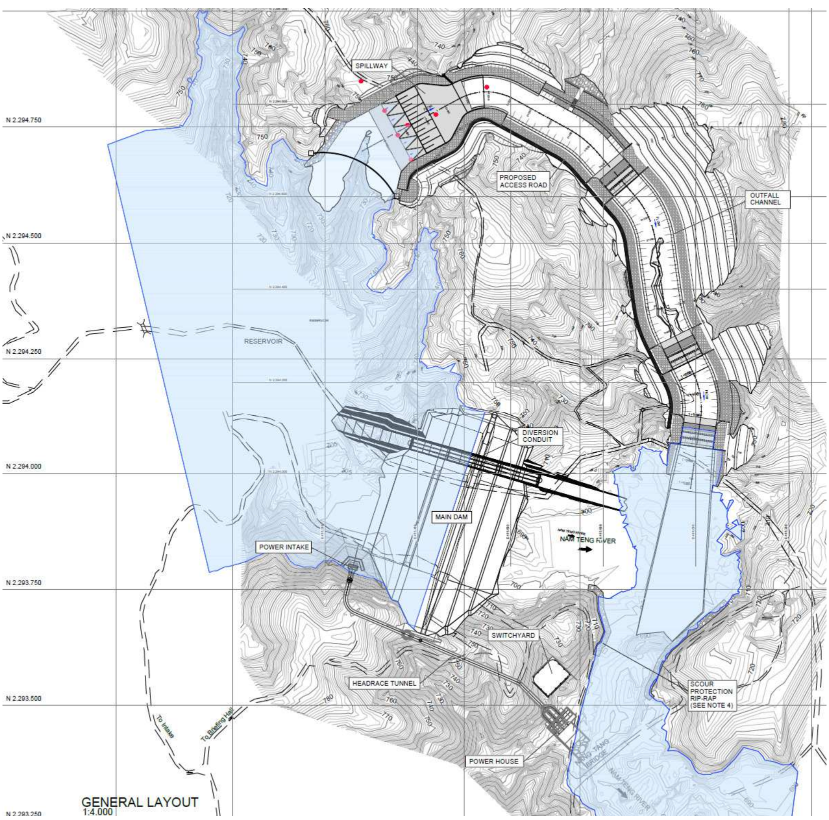

Fig. 1. Project overview displaying HRWL (742.0 masl.).

2. Concept design

2.1. Approach channel

The design requirements for the approach channel are that (i) it limits flow separation and velocity, thus minimizing head losses and potential for erosion of the bed and side slope of

the channel; (ii) the flow approaching the labyrinth weir is distributed uniformly to create satisfactory flow condition over the weir crest, in the chute and into the energy dissipater.
The channel is kept straight with a base width equal to the weir crest, W=140 m, to have a uniform flow. The length of the approach channel is approximately 350 m. The channel is trapezoidal with a bank slope of 1:1.5 (V:H). The banks are protected by rip rap (0.5-1 m). For the last 30 m where the velocity is about 4 m/s, the approach channel is concrete lined with vertical walls. The estimated head losses in the approach channel are reasonably low (0.2 m at PMF flow).

2.2. Labyrinth weir

A labyrinth weir is a linear weir that is ‘folded’ in plan-view to increase the crest length for a given channel or spillway width. Due to the increase in crest length, a labyrinth weir provides an increase in discharge capacity for a given upstream driving head (or energy level), relative to traditional linear weir structures. In addition, labyrinth weirs are effective drop structures, energy dissipaters, and flow aeration control structures. The labyrinth weir is particularly well suited to the UKT site where a large flood flow must be passed and where the available space for a spillway is limited.
The concept design of the labyrinth weir is based on design recommendations for labyrinth weirs from Tullis [1]. The labyrinth weir is designed to pass the PMF flow (Q_{PMF}=6800 m^3/s) with a H_r =5.5 m head on the crest (Fig. 7). The weir is 140 m wide with a total crest length of 379 m.
Fig. 2 shows the geometric variables (sidewall angle, total crest length, crest shape, number of cycles, configuration of the labyrinth cycles, and orientation of the labyrinth weir) to be determined for the labyrinth weir. There is some flexibility in the geometric design but optimizing the hydraulic design is challenging as there is limited design data for the many geometric design variables. The concept design for the labyrinth weir uses the layout shown in Fig. 2, where the weir is located inside a rectangular channel with the 5 bays normal to the flow direction [2]. It considers a quarter round crest shape which is preferred when it comes to the stability and aeration condition of the nappe [2].

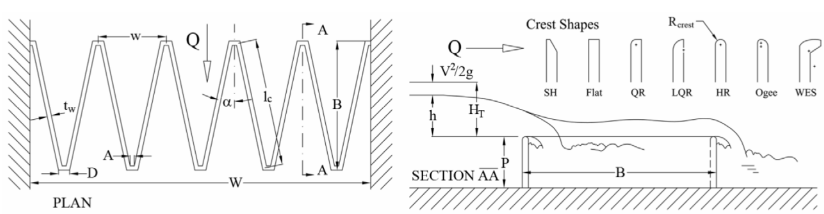

Fig. 2. Base design adopted for the labyrinth weir: normal orientation with straight inlet and quarter rounded (QR) crest shape.

The capacity and performance of the labyrinth weir depends strongly on the weir geometry (especially the weir height), the flow conditions, aeration condition of the nappe and the tailwater submergence of the weir. At, UKT, the flood flow is outside of the flow range for which the design criteria have been tested. Therefore, Computational Fluid Dynamics (CFD) simulations (Section 3) and physical model tests (Section 4) were performed to verify the capacity and performance of the labyrinth weir at UKT and to optimize the design.. The physical model can evaluate factors not included in the design procedure, like aeration and instability effects of the nappe at low heads, unusual flow conditions in the approach channel, and flow conditions in the chute. Floating debris were also modelled in the physical model tests as that can be a challenge for the UKT spillway.

2.3. Chute and stilling basin

The water passing over the labyrinth weir flows down a 140 m wide chute with a vertical drop of more than 20 m from the labyrinth crest to the stilling basin. This eliminate the risk of submergence of the weir. The drop and slope of the chute was chosen to reduce excavation and concrete works and to ensure good flow conditions in the stilling basin. The hydraulic conditions at the end of the chute were estimated using the energy and continuity equation. For Q_{1000}, the flow depth at the toe of the chute is estimated to 1.3 m, the velocity to 17 m/s, and the Froude number to 5. Given the hydraulic conditions at the entrance of the stilling basin, a USBR type III basin at elevation 719.0 masl was selected. At the end of the stilling basin the width of the channel reduces linearly from 140 m to 70 m.

3. Numerical approach: CFD

CFD simulations of the spillway were performed using ANSYS CFX (v.17.0) and ANSYS ICEM for meshing. To speed up the analysis, three separate simulation models were created. First, the flow from the reservoir through the approach channel to the weir was analysed in isolation. Then, a model was run for the labyrinth weir and chute in isolation. Finally, a full model from the reservoir to the end of the chute was run to check the validity of the results obtained from the two previous modelling steps.

The first simulation model aimed at analysing the flow pattern in the approach channel to check the homogeneity of the flow reaching the weir. The region was simulated for a geometry incorporating both the bathymetry of the reservoir and geometry of the approach channel. A simplified one-phase (i.e. water only) simulation was then run with the water surface represented by a rigid, frictionless, horizontal surface. This methodology is valid if the effect of the dynamic head on the water surface topography is small compared to the local depth. The advantage of the method is that it enables using much larger numerical time steps than a (two-phase) free surface simulation. Pressure boundary conditions were set along vertical surfaces, ca. 400 m upstream in the reservoir and along the top of the weir.

Fig. 3 shows the velocity along the surface from the simulations of the initial and final layouts of the approach channel. In the initial design a separation zone was identified along one sidewall. This separation zone has a large influence on the flow conditions towards the weir segment lying directly downstream, and thus on the weir capacity. This flow inhomogeneity was removed by angling the wall in two steps to create a "bell-mouth" inlet towards the weir. On the opposite side of the channel the sidewall was shortened to lower construction cost with no significant reduction in the quality of flow conditions at the weir. Results from this simulation was also used for checking head losses in the approach channel and served as the basis for the design of the approach channel in the physical model.

An unstructured numerical mesh consisting of tetrahedral cells and prismatic layers was used for the approach channel. This facilitated the representation of the complex bathymetry. To simulate the flow past the labyrinth weir efficiently, on the other hand, a structured hexahedral mesh was created that closely followed the geometry. The structure and resolution of the mesh is illustrated in Fig. 4. Much effort was put into designing a mesh with high resolution perpendicular to the local weir orientation, and in the nappe region directly downstream from the weir.

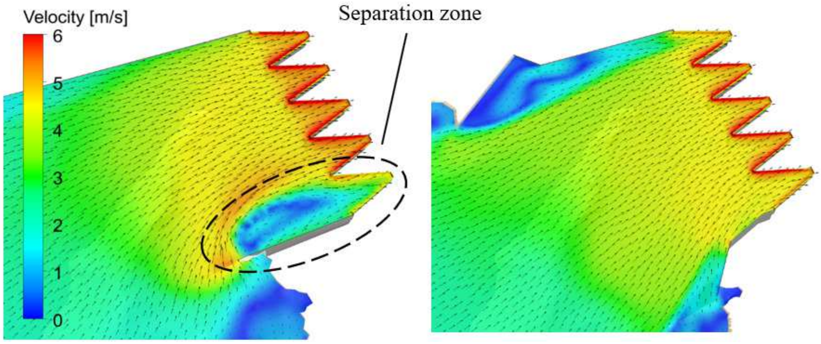

Fig. 3. Flow in Approach Channel, respectively initial (left) and final (right) design.

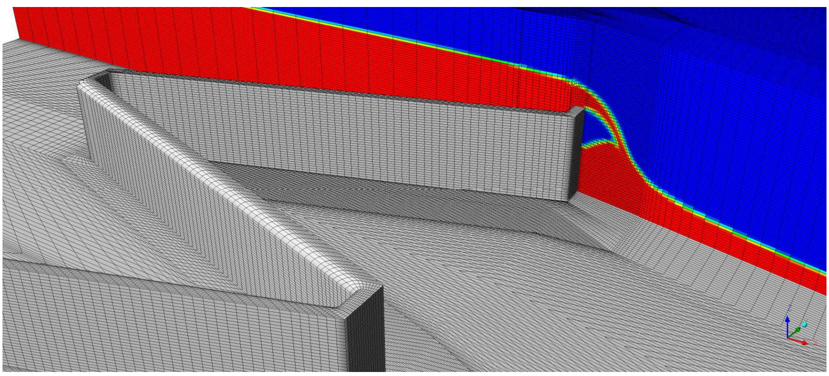

Fig. 4. Numerical mesh for labyrinth weir. Volume fraction of water (red) and air (blue) at Q_{1000}, shown along cut.

The inhomogeneous Eulerian-Eulerian solver in CFX was used to track the flow of both water and air through the domain. Fig. 5 shows the flow pattern for Q_{1000}, revealing how the flow turns toward the perpendicular to the local weir direction, passing over it. Further, one can see closed air pockets behind the nappe, and counter rotating downstream vortices with upwash in the wedge between the weir walls.

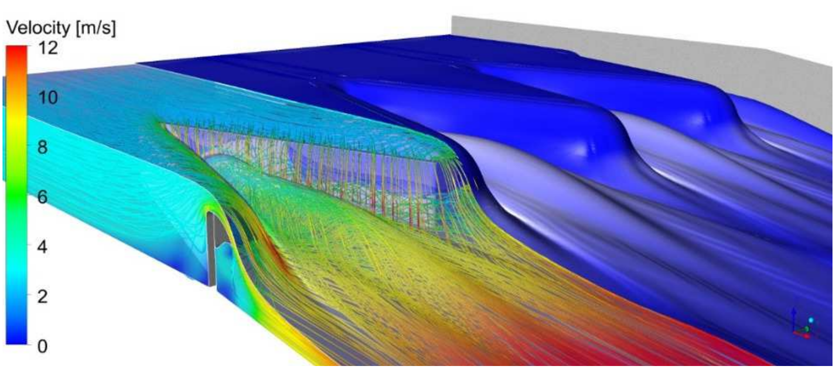

Fig. 5. Illustration of flow past weir and into the chute at Q_{1000}.

4. Physical model

A model study was performed at the Department of Hydro Power Implementation (DHPI) Hydraulic Laboratory at Paunglaung, Myanmar to check the hydraulic performance of the UKT spillway and outfall channel and to optimize the design for better hydraulic performance. Two models were built. One model at scale 1:50 (Fig. 6) that included the approach channel, labyrinth weir, chute, stilling basin, first part of the outfall channel and check dam No. 1. Test were performed for flows up to Q_{10000}=3839 m^3/s. Tests were also performed with floating debris and movable bed in the outfall channel.
A second model in scale 1:30 was built that included one of the 5 bays of the labyrinth weir. Results of this model test are not discussed in this paper.
The final design of the approach channel seen in Fig 3 was used for the physical model. No separation zone was observed during the tests which confirmed that the design of the "bell-mouth" inlet towards the weir, suggested by CFD, supressed the separation zone.

4.1. Labyrinth weir capacity

For the labyrinth weir the main purpose of model testing was to confirm its capacity and the upstream reservoir levels. In Fig. 6 the flow in the physical model is shown for a flow of Q_{1000}. The observed upwash in the wedge between the weir walls is similar to the CFD simulations shown in Fig. 5. Downstream from the weir the flow in the model is strongly affected by air entrainment.

Fig. 6. The labyrinth weir model in scale 1:50 with Q_{1000}=3055 m^3/s. Flow past the weir and into the chute.

In the physical model the labyrinth weir crest was fixed at elevation 742.0 masl. In order to investigate the effect of weir height on weir capacity two different approach channel invert levels were tested; at elevations 734.0 and 735.0 masl. The results are compared to the design and to the CFD simulation in Fig. 7. The design has an invert elevation of 734.5 masl. Fig. 7 shows that for the tested range the weir capacity is not sensitive to the invert level of the approach channel, and the results confirmed the weir capacity estimated from the concept design and CFD simulations.

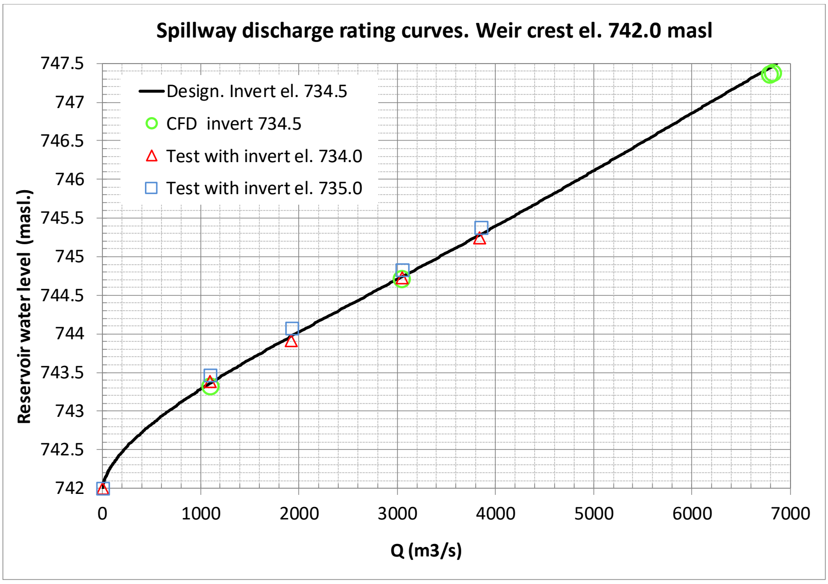

Fig. 7. Discharge rating curve for the labyrinth weir. Physical model scale 1:50.

4.2. Floating debris

Physical model tests were run with floating debris as seen in Fig. 8 as the watershed is largely covered with forest. The forest is exploited for timber and is also exposed to illegal logging. Trees heights in the watershed vary from 5 m to 25 m with trunk diameters varying from 0.35 m to 1.65 m. Larger debris are expected during larger floods, although the distribution of the debris both in time and size is hard to predict. The number and percentage of tree trunks stopped at the weir for the different floods are shown in table 1. Most of the tree trunks pass over the weir for both the Q_{10000} and Q_{1000} floods. For lower floods, Q_{30} and Q_2, much of the debris will stop at the weir. This will remain at the labyrinth weir and possibly stop other debris coming with later floods if not removed.

Fig. 8. Floating debris tests for Q_{1000} (left), Q_{30} (centre) and Q_2 (right) at the labyrinth weir.

Table 1. Nos of tree trunks stuck at the weir during tests.

Flood	No. of trunks stopped	% stopped at the labyrinth weir
$Q_{10\,000}$	6* and 0	7.5* and 0%
$Q_{1\,000}$	12	15%
Q_{30}	25	31%
Q_2	44	55%

**Test with all floating debris arriving at the same time.*

One test was performed to test the effect of the distribution of the trees in time. The test shows that if the trees arrive in larger quantities some can get stuck for the Q_{10000} flood. The effect of the trapped debris in the model is a water surface rise of about 0.1 m for the Q_2, 0.2 m for Q_{30}, 0.05 m for the Q_{1000} and 0 m for the Q_{10000}. This is not significant, but this result raises the question of if and how it is possible to manage the debris at the weir to avoid large accumulation and a more significant effect on the labyrinth weir capacity. Debris that passes over the labyrinth weir can also cause problems in the outfall channel. It was observed that several trees got stuck in the stilling basins due to the chute- and baffle blocks.
The recommended solution for management of blockage risk is a floating debris barrier at the entrance of the approach channel which leads the debris to either side of the weir abutments and includes an arrangement for removal of the debris that accumulate in front of the floating barrier. The floating debris barrier is located about 150 m upstream from the labyrinth weir and it is not expected to affect the weir capacity.

4.3. Chute and stilling basin

The physical model tests showed that there is no need for chute blocks, baffle piers and a sill at the downstream end of the chute, and that the tailwater given by the downstream outfall channel and check dam No. 1 was high enough to ensure an efficient hydraulic jump. Therefore, blocks, piers or sill were removed from the design of the stilling basin and the invert lifted to el. 722.0 masl. The physical model tests showed flow separation and wave actions at the linear transition from the 140 m wide stilling basin to the 70 m wide outfall channel. The transition was changed to two curved sections with a radius r=30 m. This significantly reduced flow separation and wave run-up.

5. Concluding remarks

The multiple approach to the spillway design has proved very useful. The concept design gives the basis of the design. The CFD simulations helped to improve the flow condition at the entrance and towards the labyrinth weir by altering the approach channel. The physical model tests confirmed the design of the approach channel and the capacity of the labyrinth weir, and allowed risk og blockage due to floating debris to be investigated. The physical model tests contributed to further improve the design of the spillway and made the construction cheaper and simpler.

References

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