HYDRAULIC DESIGN ASPECTS OF DIVERSION OF OPEN CHANNEL FLOW INTO CLOSED CONDUIT

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ABSTRACT

There are many hydraulic design situations, when open channel flow is passed through closed conduits. The closed conduit generally is in the form of a circular or modified horse shoe shaped tunnel. In case of rivers having mild slope, diversion of flows into the diversion tunnel, the flow would be subcritical throughout, from open channel flow to the flow in the tunnel and at the exit portion of the diversion tunnel. However, in case of steeply sloping rivers, the flow may be supercritical throughout. For such diversion structures the flow may be subcritical or supercritical in the intermediate stages of flow due to the dimension of the structure.

This paper will highlight the various situations that can be avoided by taking care, prior to the construction of the system, during the design stage. The adverse effects of flow conditions, at the intake of the diversion tunnel, during diversion of flow, through the tunnel and at the exit can be taken care of, by properly dimensioning the structure and alignment of the system. These aspects may be in the form of free board requirements, avoiding formations of hydraulic jump in the closed conduit and design of the exit portal of the tunnel, in such a way that scour depth in the river, be kept minimum by providing suitable form of energy dissipation arrangement. In case of hydropower projects, in the Himalayan region, river slopes in the order of 1:20 to 1:40 and even steeper are very common. In such situations, the layout require major considerations, such as deflection of supercritical flow through the system, including that of cavitation damage.

In case of hydropower projects, there are instances that, the head race tunnel starts at a lower invert elevation, than that of the open channel, which brings water from the river. In such a situation, the transition flow between the open channel and head race tunnel may become near about supercritical thereby drawing more discharge intermittently and formation of vortex in the open channel. Sometimes anti-vortex devices in the form of baffle piers, baffle walls or horizontal beams near the free water surface are necessary. The above mentioned aspects will be presented in the paper by various prototype experiences and results of physical model studies.

Keywords: *Hydraulic Design, Diversion Tunnel, Closed Conduits.*

1. INTRODUCTION:

Diversion of open channel flow from the river into the closed conduit flow, present many hydraulic situations and scenarios. These situations and scenarios, if not predicted or understood well for a study, then the designers will not be able to predict the consequences of such design in terms of say, scour, damage potential of flow to the concrete lining, severity of flow conditions in terms of circulating currents, formation of vortices and scour into the bed rock. In broad view, there are typically two flow conditions in the river channel flow, that is subcritical flow and supercritical flow. As the flow of the river changes from subcritical to near about supercritical, the average velocities may increase substantially, with the corresponding river flows. It was observed that as the slope of the river becomes steep, more than 1:200 or so, supercritical flow or transitional flow starts in the river depending on the frictional characteristics of the regime and further becomes supercritical as the slope of the river increases from 1:100 and beyond. Photo 1 and Photo 2 shows supercritical flow through bouldery rivers having steep slopes.

Photo 1. River flow with slope of 1:30

Photo 2. River flow with slope of 1:20

In situations where, turbulent supercritical flow is to be diverted the adverse effects on the flow conditions near the intake of the diversion tunnel, and at the exit, has to be well thought of by properly dimensioning of the structure and alignment of the system. Figure 1 shows the typical layout of the diversion tunnel, intake and alternate layout of the arrangement, so as to have proper entry flow conditions and as far as possible uniform flow conditions throughout the intake and along the length of the tunnel.

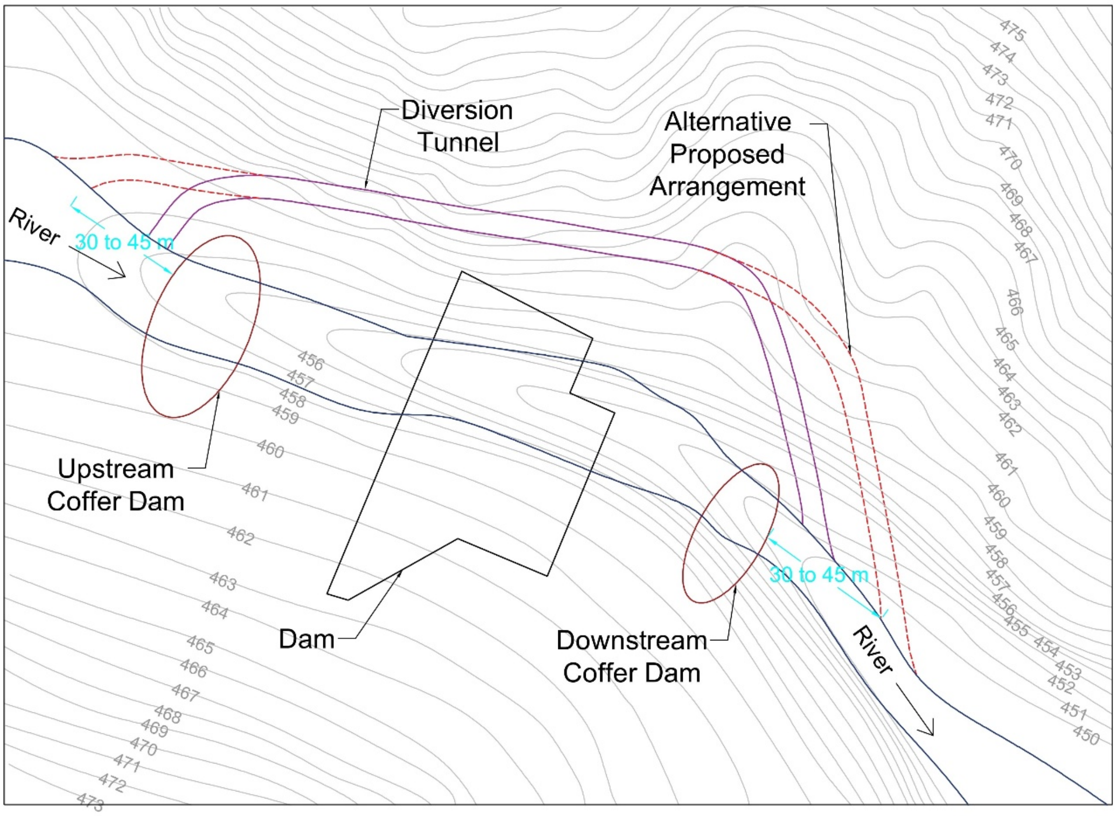

Figure 1. Typical layout of Diversion Tunnel

The aspects of flow conditions, such as avoiding formations of hydraulic jump in the closed conduit, flow conditions at the exit portal of the tunnel. In addition to this, the layout requires major considerations for diversion of supercritical flow through the system, including evaluation and estimation of cavitation potential and its effects on the structure. If the intake velocities are more than the average velocities in the river, then reservoir formation will not take place. Such a situation will be beneficial for flushing of sediments from reservoir.

The layout considerations are generally in the form of open channel flow, by cutting a separate channel along the bank or by diverting the flow through the closed conduit. The following paragraphs will highlight the diversion of flow through closed conduit for hydro power projects. The invert level of the tunnel generally starts, little lower than the average river bed level, in the nearby vicinity of the river. The flow is diverted through the tunnel for various depths of flow, during the flood season and non-monsoon periods. Sometimes, the tunnel may be pressurized right from intake and subsequently the open channel flow will prevail for part of the length of the tunnel, and vice versa, depending on the slope of the tunnel. At some intermediate river stage, formation of vortex and swirling flows in the open channel leading to the intake of the tunnel cannot be ruled out. These design aspects have been described in the following paragraphs. Only the hydraulic aspects of the studies have been considered. The dimensioning of the tunnel and its cost estimates, etc. have not been subject of the present study.

2. FLOW CONDITIONS FOR STEEP AND BOULDERY RIVERS

Many hydro power structures are designed as run-of-the-river schemes. These projects are located in the Himalayan or Shivalik ranges having perennial streams. Most of the sites having rivers with flatter slopes from 1:1000 to 1:400 have been developed, and projects are coming up on the river streams having steeper slopes than 1:200 and lesser. The supercritical flow prevails in such rivers. The supercritical flows have control upstream. It is very difficult to divert the flows by changing the direction of the supercritical flow, unlike the subcritical flows. The practical experiences during the last decade have indicated that, the slopes of much steeper and having average velocities in the range of 4 m/s to 8 m/s. the Photo 3 and Photo 4 shows bouldery rivers having velocities in the range of 5 m/s to 8 m/s.

Photo 3. River flows having average velocity of 5 m/s

Photo 4. River flows having average velocity of 8 m/s

There would be many intricacies for the intake structure. Most of the diversion tunnels are having inlet angle of near about 90o to the normal river flow. This introduces three dimensional swirling flows at the bell-mouth portion of the intake tunnel, which cannot be seen from the surface flow conditions. The swirling flows, damages to the concrete near the sill beam and also severe damages take place to the curved portion of the tunnel. Many prototype experiences indicated severe damage to the sill beam and downstream portion. Once such damage is initiated, it has a cascading effect throughout the length of the tunnel.

Therefore it is suggested that a wider intake structure, with an angle of much less than 45o would be more suitable from hydraulic considerations. The intake structure should be located at least 30 m to 50 m upstream of upstream coffer dam, because once the flow is diverted through intake, there is return flow around the toe of the coffer dam. If the intake velocities are of the order of 8 m/s to 10 m/s, then return velocities would be in the range of 3 m/s to 4 m/s, in case of the upstream coffer dam is located at a distance less than 30 m or so. Hence, the recommended arrangement would provide much relief to the coffer dam.

These experiences led to some numerical analysis for assessing the velocities and Froude numbers for various average slopes of the river and at different stages of river. Figure 2 shows the variation of the velocities for average river slopes ranging from 1:1000 to 1:20 for various stages of the river. It can be seen from the Figure 2, that the average velocities for the rivers, steeper than 1:200, the average velocities varies from 2 m/s to almost 10 m/s for various manning's roughness friction factors varying from 0.035 to 0.050. Corresponding Froude numbers, for the conditions mentioned in Figure 2 are plotted in Figure 3. It can be seen from the figure, for steeper rivers, the Froude numbers are much above the critical Froude number of 1.

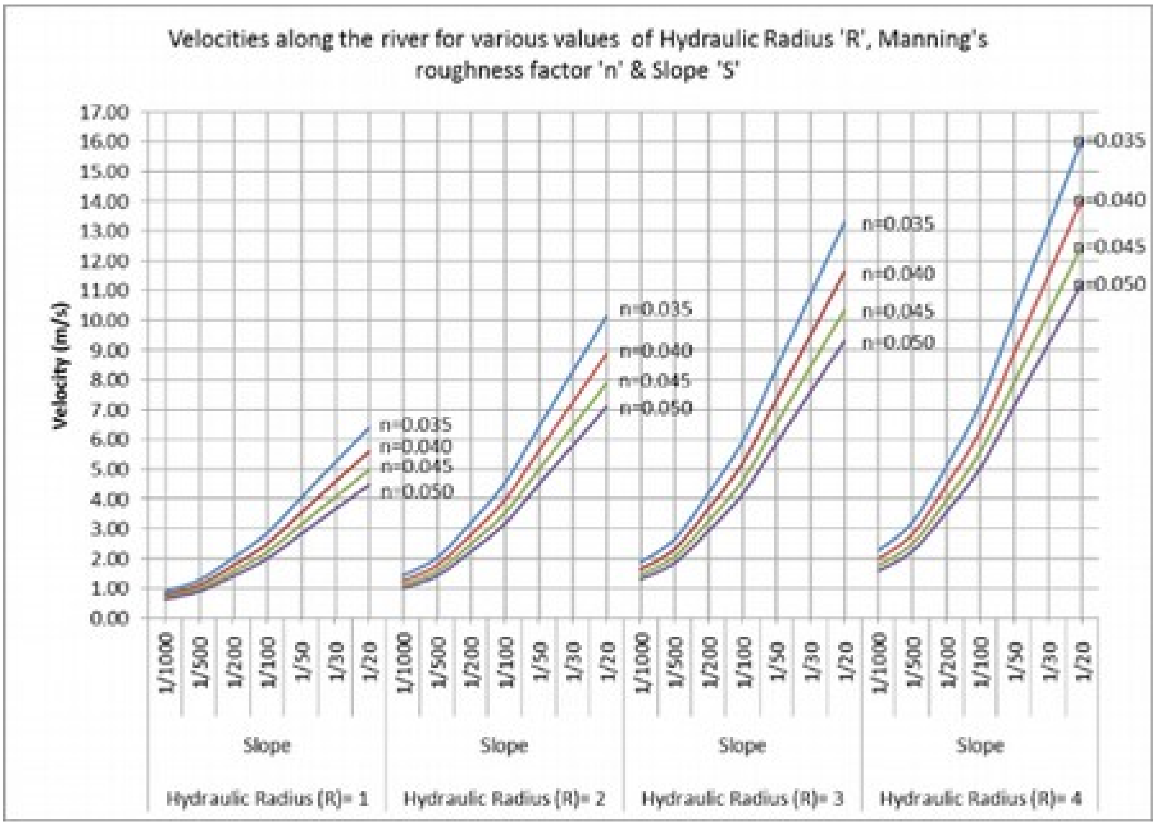

Figure 2. Velocities along the river for various values of Hydraulic Radius 'R', Manning's roughness factor 'n' & Slope 'S'

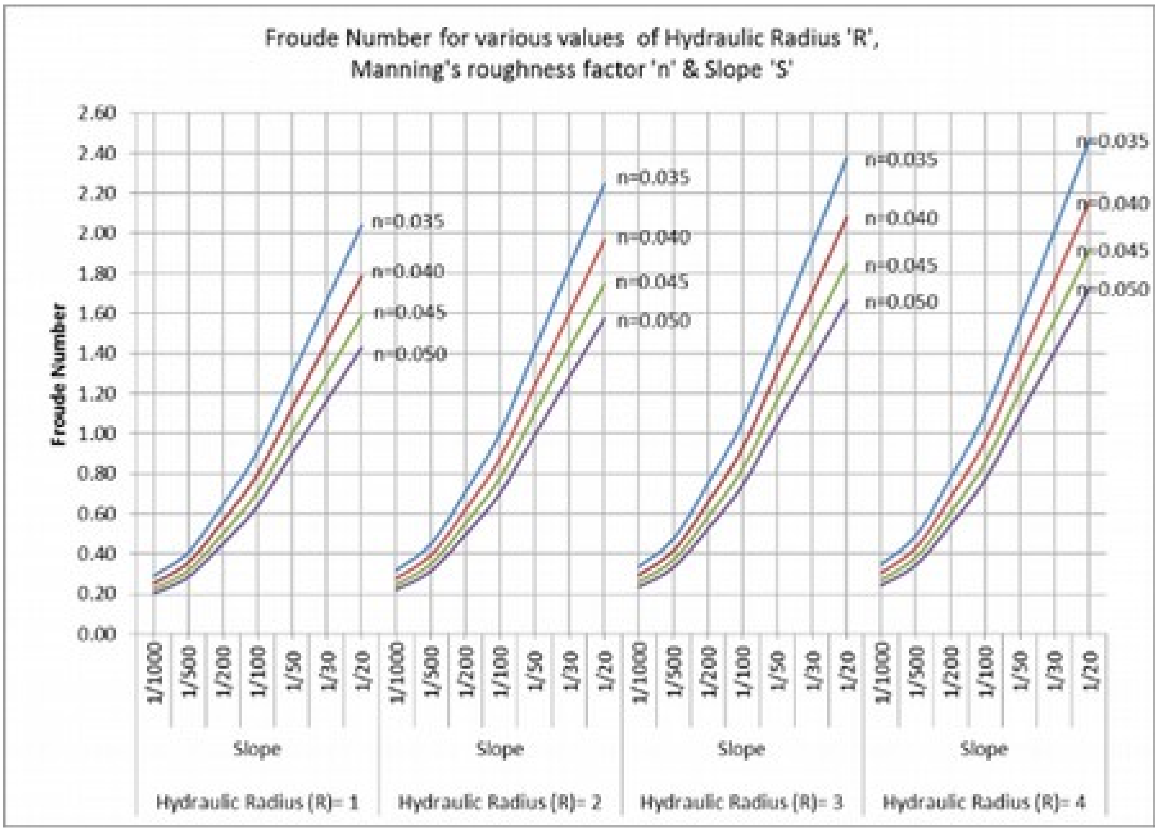

Figure 3. Froude Number for various values of Hydraulic Radius 'R', Manning's roughness factor 'n' & Slope 'S'

Let us consider an average length of the tunnel across a medium dam, say about 800 m, then the fall from intake to outfall structure are worked out and given in the Table 1. The Table 1 indicates, additional fall from upstream intake to downstream portal. In order to avoid, this further increase in velocities, it is suggested that, layout of diversion tunnel be little steeper than the requirement of just maintaining normal depth of flow. This will necessitate additional fall of water from exit portal to the river, where necessary arrangements for energy dissipation can be provided. These conditions are depicted in following Figure 4.

Table 1. Total fall required from intake to outfall structure for various slopes and corresponding velocities for Head between upstream and downstream of tunnel portals for length of 800 m.

Slope	Fall (m)	Velocity (m/s)
1/1000	0.80	3.96
1/500	1.60	5.60
1/200	4.00	8.86
1/100	8.00	12.53
1/50	16.00	17.72
1/30	26.67	22.87
1/20	40.00	28.01

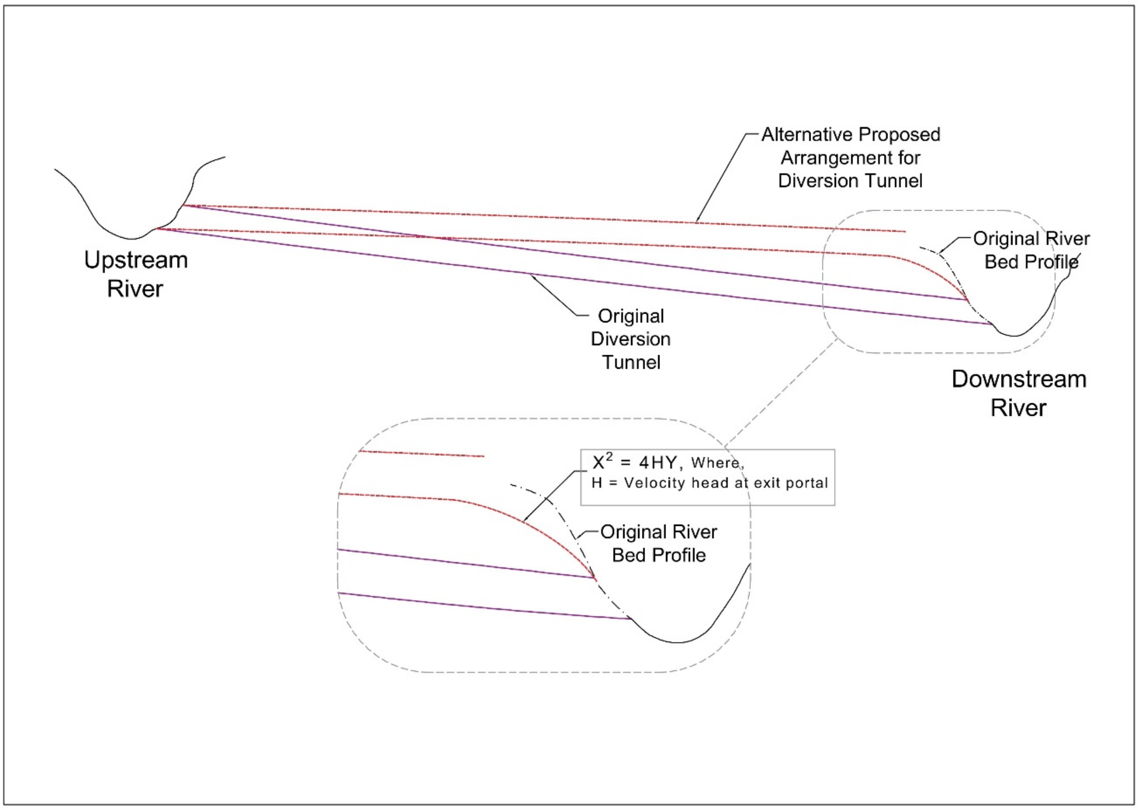

Figure 4. Section through the diversion tunnel, along with exit portal energy dissipator

Such a design consideration will reduce the possibility of cavitation damage throughout the length of tunnel as velocities would be considerably lower. The cavitation index can be worked out by the following formula.

$$\sigma = \frac{\left(P_0 - P_v\right)}{\left(\frac{\rho . v^2}{2 . g}\right)} \qquad (1)$$

It could be seen from the above Table 1, that due to fall, the velocities along the tunnel can be generated much in excess of 15 m/s, and there is a possibility that the flow cavitation number σ cr would be lower than the critical cavitation number of σ cr = 0.2, then there would be possibility of cavitation occurring throughout the length of the tunnel. Moreover, as classified by the United States Bureau of Reclamation (USBR), there would be numerous offsets into the flow and offsets away from the flow, which would further reduce the local pressure and thereby more susceptible for cavitation damage.

In view of this, it is recommended that the tunnel slopes may be little steeper than the requirement of the normal flow so as to take into consideration any change in the frictional characteristics as well as flow conditions due to curvature in the alignment. This will ensure that, there will not be any formation of intermittent hydraulic jump in the tunnel. The above discussions present the overall design philosophy for diverting the flow from open channel flow of the river to diversion tunnel.

3. SEDIMENTATION

In the Himalayan region during the floods, the sediment concentration becomes very high and sometimes reach up to 3000 ppm to 5000 ppm. In extreme cases, some of the projects have been designed for sediment load as high as 5000 ppm. It will be seen that, during normal and low flows, sediments and small boulders would be deposited upstream of intake. However, during yearly high floods, the velocities would be very high, as shown in Figure 2. For such velocities, even medium sized boulders will wash away through the intake structure and downstream into the tunnel. As the tunnel intake is along the bank, there will be circulatory currents even after possible care in the alignment. During the passage of the boulders, the concrete near the sill beam and downstream gets eroded, due to impact of boulders and continuous friction of sediments.

Once the scour takes place at the intake, it would have cascading effect and the tunnel invert may get eroded throughout, because of high velocities and passing of boulders. In order to protect the intake and tunnel from undermining, up to the 50% depth of the tunnel may be constructed by using high performance concrete.

4. DISCUSSIONS AND CONCLUSIONS

1. The diversion of the steeply flowing rivers into the diversion tunnel, pose many hydraulic situations. The diversion of supercritical flow having high velocities, when diverted through the tunnel, accompanies return flows which need to be taken care of.
2. In order to reduce the impact of return flows on the toe of the coffer dam, it is recommended that, the coffer dam be at least 30 m to 50 m upstream of centre line of intake structure. This will also facilitate proper flow conditions in the vicinity of intake structure.
3. Large bell mouth needs to be provided on both sides of the diversion tunnel, so as to reduce swirling flows at the intake. The fall across the diversion tunnel may be in order of 20 m to 30 m for steeply flowing rivers. Such a fall would create higher velocities in the range 20 m/s or so at the outlet of diversion tunnel. It would be very difficult and uneconomical to provide energy dissipater for such higher velocities in the narrow portion of the river.
4. In order to reduce the flow velocity through diversion tunnel, it is suggested that the tunnel slope should be such that, flow through the tunnel is near about normal flow. A little additional fall may be provided along the tunnel so as to account for frictional and alignment losses.
5. At the outlet portal, for the design of tunnel with normal slope, we have to negotiate a fall of 15 m to 20 m, by providing a chute type structure extending right into the river. Such an arrangement will facilitate diverting of flow towards the river.
6. The outlet structure should be provided with keys wherever necessary, so as to protect against the unexpected scour in the river portion.
7. In order to avoid scour and damage due to passing of boulders with high velocity of flows, the intake may be constructed in high performance concrete, so also the 50% height of the tunnel from the bottom.
8. This paper highlights the various scenarios based on prototype experiences of the performance of tunnels over the last decade. A case study by the project Engineers would be very interesting and the project people are encouraged to publish the prototype experiences.

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