Water intake structures for hydropower

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Abstract

In the age of industrial development, lakes, rivers and canals have been exploited to an ever increasing extent, and dams and weirs for the diversion of river water have been constructed on flowing waterways for various purposes. Likewise, river intakes have been developed even further for agriculture and the generation of hydroelectric power. Now, when in the industrialized countries, particularly in Europe, this development has practically come to an end. In Albania a very big number of sites for large-scale and small-scale river water intakes are developing in the field of energy production.
The exploitation of rivers and streams requires thorough planning, irrespective of whether large-scale or small-scale projects are concerned. The ecological aspects, the compatibility of a project with the environment and the minimization of subsequent damage caused by any measure taken are important planning criteria. For large-scale and small-scale projects, experienced planning engineers and experts are normally appointed. In addition to the individual types of intake structures, the necessary hydraulic and static calculation methods are given and explained. The prerequisites to be met by the intake structure are different for each river and stream, and therefore only the basics can be described here. The operativeness of an installation depends largely upon the planning and, thus, upon the experience of the planning engineer. In just such a sensitive field as the intervention in a river or stream with a view to tapping water for general purposes, a great number of criteria are to be considered, and it is these which rare given in this planning guide.

Introduction

Which is the most adequate layout plan for an intake structure?
The most adequate layout plan is the one which allows the intake structure to function in the most effective manner while allowing the necessary amount of water at the required elevation. In this section, the design and analysis of the intake structure elements, which influence the effectiveness of conveying water to the turbine, have been treated. The purpose of hydraulic calculation for all the elements of the intake structures with or without pressure is that the designers have the possibility for optimization of the hydraulic scheme of a small hydropower plant, and water to be conveyed to the turbine with lower costs and high efficiency.
Traditionaly, the intake structures for the hydropower plants were the structures conveying water from a system without pressure to one with pressure. In this study the definition of “intake structure” includes not only the traditional ones but the ones which serve to the systems without pressure as well.
Intake structures can be categorized as:

- Intake structures which take water directly from the water flow and pass it to the penstock.

- Intake structures which take the water through an auxiliary structure which diverts the flow
- Intake structures placed on reservoirs

Design criteria
The effectiveness of a hydropower plant is directly dependent on the location, orientation, and the water level at the intake structure. In order to have satisfactory and correct results, the hydraulic structures should be adapted to the site. Factors that are considered include:

Water levels

In most of the cases the intake structures should be designed in order to function for different water levels.
For the intake structures placed on reservoirs, studies should be conducted in order to determine the fluctuations of the water level. The efficiency of the structure should be checked for the normal and extreme levels. It can be accepted that the effectiveness of the structure may be lower in the case of maximal levels if they have short time span.
The intake structures placed in rivers or streams should be determined from the water level of the flow, which is determined by hydraulic studies. The influence of the intake structure or the diversion structure on the water levels in the river or stream, the erosion and deposition, the ice blockage etc., should be evaluated. The narrowing or widening of the river at the intake structure should be evaluated as well.

Placement distance

The distance between the intake structure and the powerhouse influences the hydraulic losses as well as the cost of the conveyance structures. Most of the powerhouses should be constructed near dams or diversion structures in order to profit as much as possible in water head, while the intake structures should be placed on the lowest point of the reservoirs. In the cases when the powerhouse is at a considerable distance from the intake structure: should be done an evaluation of the whole diversion system in order to have as few losses as possible.

Geological composition

Bank stability is important, and the intake should be located in a reach of river where the bank is stable because an unstable bank is likely to adversely affect intake performance. Foundation conditions also may affect design. If possible, the intake should be located at a site possessing favorable foundation conditions because overcoming adverse foundation conditions may require costly treatment.

Diverted flow

While placing the intake structure, the diverted flow should be taken into consideration. Intakes are generally oriented to minimize separation of flow which causes portions of the intake to be ineffective and can result in swirl, eddies, and vorticity which may entrain air. Where the rate of withdrawal is small and the intake relatively deeply submerged, flow separation, vorticity, and air entrainment are less likely to occur. Higher withdrawal rates are more conducive to flow separation than lower rates.

Sediment

The intake structures should be placed in such a way to minimize the accumulation of fine materials. The intake structures in reservoirs are placed over the calculated alluvial accumulation level for the lifetime of the structure. Sediment accumulation in the intake approach, result in higher approach velocities, increased head losses, and potentially flow separation. Where the accumulation is severe, removal may be required at periodic intervals. The passage of sediment through the unit may result in undesirable wear of the turbine runner and this should be minimized.

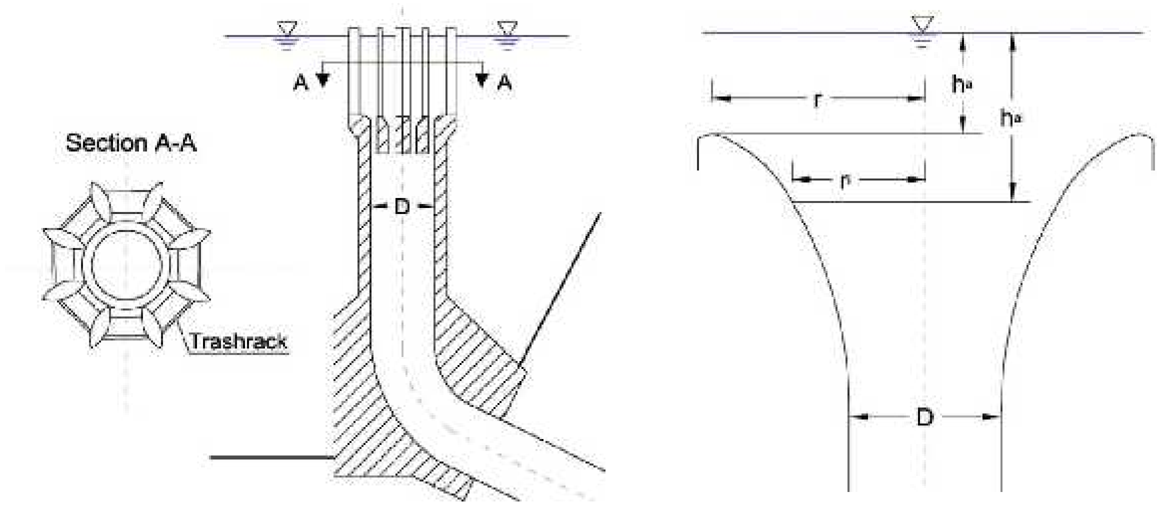
Ice

Ice is a major hazard for intake structures as in cases of: trash rack blockage, increase in hydraulic losses, reduction of the diverted flow, and additional measures for its cleanup. The placement of the intake structures in order to minimize the problem of ice requires a detailed study of the annual ice regime. The general principles are to locate the intake where ice flows are minimal and to provide facilities for passing ice through the project such as ice sluices and overflow sections or gates.

Power intake

Vertical intake

Vertical intakes are commonly used where there is a great difference in elevation between the reservoir bottom at the intake and the turbine, and where the penstock or power tunnel is vertical for some distance to the level of the powerhouse.
The dimensions of the vertical intake are conditioned from the penstock diameter or the power tunnel diameter. This diameter is determined from the comparison of the energy proficiency to the construction cost. The main criteria for the structural dimensioning should be the minimization of the hydraulic losses and the avoidance of eddies.



a) b)

Figure 1 Vertical intake [Ref. 3]

Hydraulic losses caused by the vertical intakes:

$$H_L = K\frac{V^2}{2g} \quad (1)$$

$H_L -$ hydraulic losses from the water surface level to the diametric constant of the intake (m), $V -$ velocity in the penstock (m/s), $K -$ the loss coefficient which varies from 0.1 up to 0.3

The adequate shape of the vertical intake is as shown in the figure 1. b):
The equation for the entrance shape which is derived from laboratory tests is:

$$R = 0.204\frac{Q^{\frac{1}{2}}}{H_a^{\frac{1}{4}}} \quad \text{[Ref. 3]} \quad (2)$$

$Q -$ discharge (m³/s), $H_a -$ distance between the water surface and the plan where we want to determine the radius (m)

A special care should be provided in determining if trash racks will be used or not. The racks are usually placed on the outter perimeter of the structure where the flow velocity is low. The cleanup of the trash racks is very difficult when the water depth is very high. But in these cases, problems with their blockage are not expected to occur.
The hydraulic losses from the trash racks depend on the thickness of the rods, the depth and the distance between them.

$h_L -$ trashrack head loss (m)

$$h_L = K_t\frac{v_n^2}{2g} \quad (3)$$

$v_n -$ velocity through the net trashrack area (m/s), $K_t -$ trashrack loss coefficient

$$K_t = 1.45 - 0.45\frac{a_n}{a_g} - \left(\frac{a_n}{a_g}\right)^2 \quad (4)$$

$a_n -$ net area through rack bars (m²), $a_g -$ gross area of the racks and supports (m²)

An important criteria in the functionality of vertical intakes is the submerged depth which usually is grater compared to horizontal intakes. To avoid the formation of eddies, at the entrance of the intake structure are placed some piles which reduce the velocity and disperse the eddies.

Horizontal intake
The great majority of hydroelectric project intakes are horizontal. Even in cases where a large elevation difference exists between the intake and the powerhouse, the intake is normally horizontal, followed by a curve to an inclined or vertical power tunnel or penstock.
The advantage of horizontal intakes consists in the possibility to easily place gates, trash racks and stoplogs. Horizontal intakes are categorized in two groups:

- High head intakes H>15m.

These structures are usually placed in reservoirs or in the body of arch, gravity, earth dams. In this case the intake structure is placed directly in the resirvoir, and water is conveyed through diversion systems to the forebay from where it passes through the intake to the penstock or pressure tunnel.
In high head intakes, the hydraulic losses are relatively small compared to the head and the costs for increasing the dimensions of the intake to decrease the velocity are not neccesary.

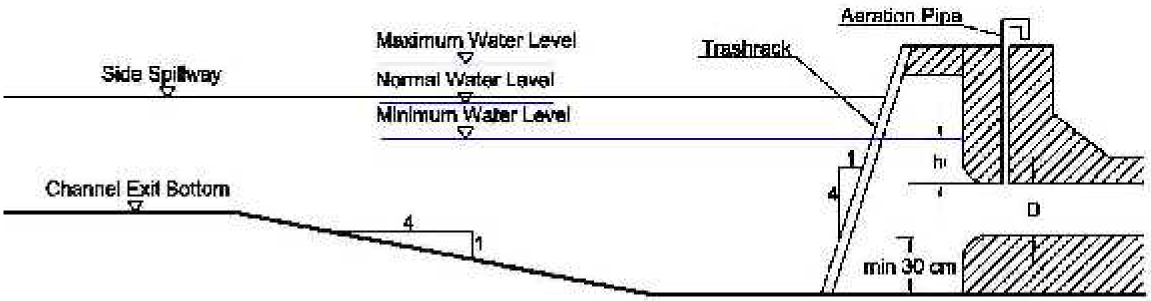


Figure 2 Horizontal intakes [Ref. ICE designe]

- Low head intakes H<15m.

These structures are usually placed in rivers, where the intake is integrated in the body of the dam together with the turbines.

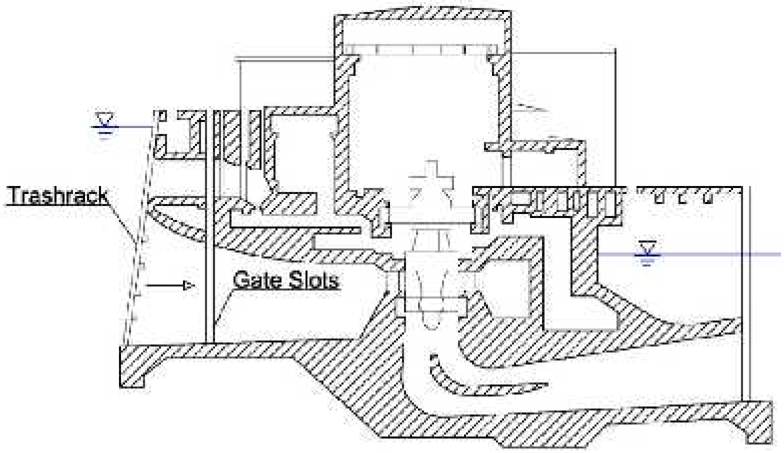


Figure 3 Low head horizontal intake [Ref. 1]

In low head intakes, the hydraulic losses have a great impact on energy production. In these structures, an increase in dimensions in order to decrease the velocity is required.

Components of horizontal intakes

Trashrack location and design
Depending on the working process of the trashrack they will have an automatic cleanup device or will be cleaned manually. The cleanup method depends on the amount of waste expected to accumulate. For an easy cleanup the trashracks are placed with an inclination 1H:4V. In high head intakes the trashracks are installed just before the entrance. It is recommended that the flow

velocity of the water passing through the trashracks should not exceed the velocity 0.8-1.2 m/s. In case of presence of ice, it is recommended that the trashracks are placed under the normal water level at 0.5-1m depth and have a protecting wall at this height. From the construction practice it has been observed that the head losses have not been calculated accurately, because the depth of the alluvial deposits and suspended waste has not been considered.

Entrance shape

Usually it resembles to the trajectory of contracted flow. Generally it has bellmouth shape. But it can be rectangular as well, which then narrows until the dimensions reach those of the penstock. In the case of low head intakes, when the turbine is integrated in the dam body to avoid cavitation, the geometry of the intake structure is determined from the turbine supplier.

Transition zone

The length of this zone is based on the requirement of conservation of the constant acceleration of the flow. In case of presence of openings divided from piles, may be necessary a longer and wider transition zone.

Bulkheads or stoplogs

They are usually placed between the trashracks and the service gates in case of their damage. Their placement is done by slots created on the walls of the structure which are placed at the beginning or the end of the curvatures. The hydraulic losses caused from the stoplogs depend on the slot dimensions.

Service gates

Can be placed on the curved part or in its end. The placement of the gates is done through slots created at the walls of the structure. The gates can be mechanical or automatic. The gates are used in case of different problems which can occur at the structure or at the turbines. The gate dimensions are determined from the space they have to cover. Greater gate dimensions influence in hydraulic losses, so that an economic evaluation needs to be done between the hydraulic losses and the gained energy.

Air vent

Air vents are typically included in forebay or intake designs that incorporate power conduit and some type gate valve. The function of an air vent on a guard gate is to provide air into the downstream power conduit so that the conduit does not experience unacceptable vacuum pressures when the gate is closed during standard flow conditions.

Hydraulic calculations of the horizontal intake

Trashrack

A trash rack is required at the entrance of penstock to avoid the entrance of floating debris. The flow water through the rack also gives rise to a head loss. Though usually small, it can be calculated by a formula developed by Krischmer:

$$h = K_t\left(\frac{t}{b}\right)^{\frac{4}{3}}\left(\frac{V_0^2}{2g}\right)\sin ¤ \qquad \text{[Ref. 1]} \qquad (5)$$

h – head loss (m), t – bar thickness (mm), b – width between bars (mm), V_0 – approach velocity (m/s), ¨ – angle of inclination from horizontal (°)

Where the parameters are identified in figure 4.

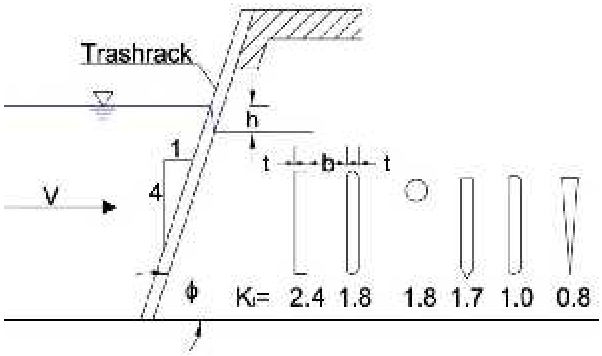


Figure 4 Adequate shapes for the trashracks [Ref. 5]

This formula is valid if the length L of the bars is smaller than 5 times their diameter. If the grill is not perpendicular but makes an angle with water flow. The result of equation 5 should multiplied by correction factor k provided in table 1.

Table 1 Correction factor k [Ref. 1]

t/b	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
0º	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10º	1.06	1.07	1.08	1.09	1.10	1.11	1.12	1.14	1.50
20º	1.14	1.16	1.18	1.21	1.24	1.26	1.31	1.43	2.25
30º	1.25	1.28	1.31	1.35	1.44	1.50	1.64	1.90	3.60
40º	1.43	1.48	1.55	1.64	1.75	1.88	2.10	2.56	5.70
50º	1.75	1.85	1.96	2.10	2.30	2.60	3.00	3.80	-------
60º	2.25	2.41	2.62	2.90	3.26	3.74	4.40	6.05	--------

Submergence depth

Minimum submergence depth at penstock inlet is required. There are different formulas for minimum depth at the inlet to avoid vortices and air entrainment:

$$h_t \geq D \cdot (1 + 2.3 \cdot \frac{V}{\sqrt{g \cdot D}}) \quad \text{(Knauss)} \quad \text{[Ref. 6]} \quad (6)$$

$$h_t \geq 1.474 \cdot V^{0.48} \cdot D^{0.76} \quad \text{(Rohan)} \quad \text{[Ref. 6]} \quad (7)$$

$$h_t \geq c \cdot V \cdot \sqrt{D} \quad \text{(Gordon)} \quad \text{[Ref. 6]} \quad (8)$$

c = 0.74245 and 0.5434 for non-symmetric and symmetric approach

D – penstock diameter (m), h_t – submergence depth (m), V – flow velocity in penstock (m/s)

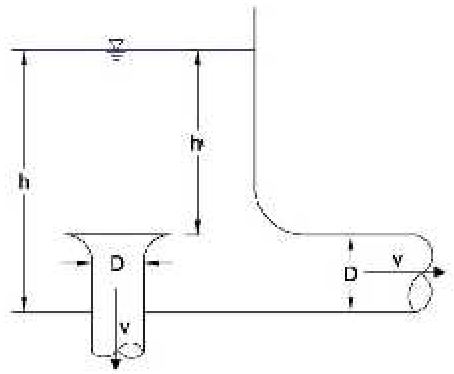


Figure 5 Submergence depths [Ref. 3]

Entrance shape
Based on studies and laboratory tests it has been concluded that the bellmouth shape satisfies the above conditions.

$$\frac{x^2}{(3K_xD)^2}+\frac{y^2}{(K_yD)^2}=1 \qquad \text{[Ref. 3]} \qquad (9)$$

For a circular entrance $K_x = 0.167, K_y = 0.15$

For rectangular or square entrance $K_x = K_y = 0.33$

Suppressed bottom and side contractions $K_x = K_y = 0.5$

Suppressed one side only, for unsuppressed side $K_x = 0.33, K_y = 0.67$

Where: X and y are the coordinate axes. The axis x-x is displaced parallel to the pipe axis with the value 0.65D and y-y is perpendicular with the pipe axis is displaced 0.5D from the entrance.

Head losses for intake entrance
Head losses for intake are represented by equation:

$h_l -$ entrance head loss (m)

$$h_l = \left(\frac{1}{C^2}-1\right)\frac{V^2}{2g} \qquad \text{[Ref. 3]} \qquad (10)$$

Table 2 Coefficient for different forms of entrance [Ref. 3]

Intake Condition	**1/(C²-1)**
Well-designed bell mouth	0.04-0.05
Well rounded	0.1
Slightly rounded	0.25
Square edged	0.47-0.56
Projecting	0.62-1.0

Head loss due to slots
Based on hydraulic consideration E. Mosonyi suggests the following approximating formula for the calculation of the head loss at the slots:

$\Delta h_s -$ head loss due to slots (m)

$$\Delta h_s = 1.2 \frac{v^2}{2g} \left[\left(1 - \quad \right)^2 + \left(\frac{1 - \sim}{\sim} \right)^2 \right]$$ [Ref. 1] (11)

$-$ cross-section coefficient

$$= \frac{Bh}{Bh + 2y^* h + yB}$$ (12)

$\sim -$ Weisbach coefficient

$$\sim \; = 0.63 + 0.37 \quad ^3$$ (13)

$v -$ velocity in the entrance flume, just before the slots (m/s), $B -$ width of entrance flume (m), $h -$ depth of entrance flume (m), $e -$ width of slot (m), $d -$ depth of slot (m), If $d > 0.2e$ then $y^* = 0.2e$, If $d \leq 0.2e$ then $y^* = d$

The disturbing effect of the opening necessary for the hoisting of the gate is accounted for by dimension

$$y = 0.2e$$ (14)

Representing the widening yB of the cross-section.

Air vent

The air vent can be dimensioned in different methods: A rule of thumb used for sizing air vent piping is to provide from one half to one percent of the area of the power conduit as an air vent. Using the following formula.

Area of air vent is :

$$F = \left[\frac{Q\sqrt{s}}{2460000 \cdot c} \cdot \left(\frac{d}{t} \right)^{\frac{3}{2}} \right] \cdot k$$ [Ref. 3] (15)

$Q -$ flow of air through inlet (usually set equal to conduit flow) (m^3/s), $c -$ coefficient of discharge through air inlet, values of c range from 0.5 for ordinary air-inlet valves to 0.7 for short air-inlet valves, $F -$ area of air inlet (m^2), $t -$ thickness of power conduit (mm), $d -$ diameter of power conduit (mm), $s -$ safety factor for collapse of power conduit, use s=5 for buried conduit and s=10 for exposed conduit on saddles, $k -$ conversion coefficient from US unit to SI (0.305)

Conveyance intake

Lateral intake with damming up of the river
These structures are widely used in exploitation schemes of rivers and streams with bed slope 0.001%-10%.
The purpose of constructing these structures is:

- To avoid, or to reduce the deposits of fine materials in the conveyance channel.

It is advisable to place the intake on the outter curve of the river, because in this part the flow has greater velocity and the material deposits are very small.
A shallow channel should be build in front of the intake in order to avoid the entrance of deposits. It should be constructed with a slope of 2%-5%, a change in elevation from the riverbed of 1-1.5m and is accompanied with a gate which opens when these deposits need to be cleaned.

- To take the required amount of water while having minimal hydraulic losses.

The dimensioning of the intake entrance should be such that velocities greater than 0.8-1.2 m/s are avoided. The hydraulic losses should be taken into consideration giving an adequate shape. An important factor is also the direction of the intake in relation to the river axis. To guide the water entering the intake and to close it in case of defects are placed gates and stoplogs.

- To prevent the entrance of ice and solid materials in the conveyance channel.

To prevent the entrance of solid materials into the intake, some trashracks with inclination 1H:4V are installed, which can be cleaned manually and automatically.
The intake structure is placed in the inside part of the curve to protect the structure from ice. In the upper part of the intake entrance are placed some vertical or inclined walls submerged at a depth of 0.5-1m to the water surface.

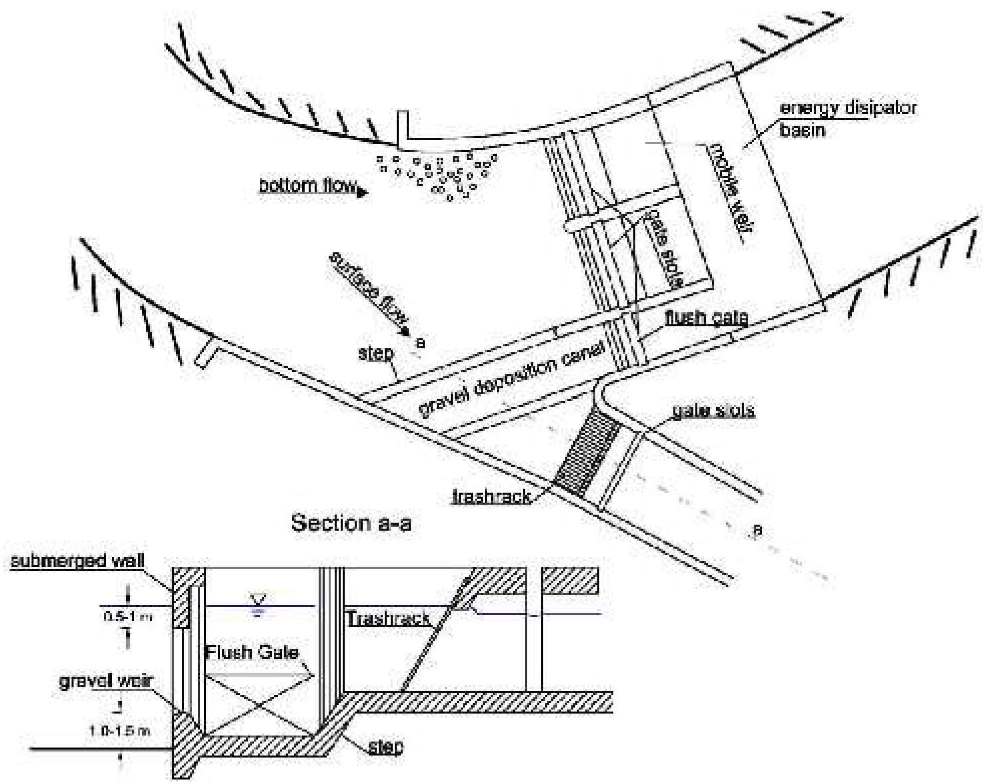


Figure 6 Optimal layout of a lateral intake [Ref. 5]

Hydraulic calculation of lateral intakes.

Direction of the intake

Based on different studies conducted from D.Y.Sokolov, the angle of the intake direction is determined from the formula:

$$\cos \cdot \; = \pounds \left(1 - \frac{h_f - h_c}{h_f}\right)\frac{q_f}{q_c} \qquad \text{[Ref. 1]} \qquad (16)$$

$\pounds -$ the coefficient of contraction at the intake structure (m³/s)

$$\pounds = \frac{b_c}{b} \qquad (17)$$

$b_c -$ contracted width of flow (m), $b-$ width of the conveyance channel (m), $q_f -$ river discharge (m³/s), $q_c -$ discharge entering the intake (m³/s), $h_f -$ depth of water in the river or stream (m), $h_c -$ depth of water in the intake (m)

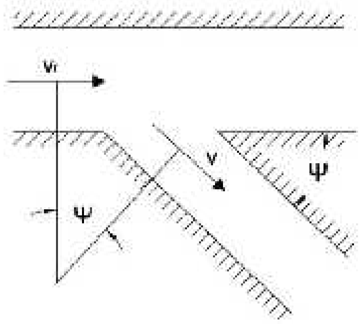


Figure 7 Teorical water movement scheme [Ref. 1]

Entrance dimensioning

The surface required at the entrance of the intake is calculated with the formula:

$$F = \frac{q_c}{v} \qquad \text{[Ref. 1]} \qquad (18)$$

$v-$ prefered 0.8-1.2 m/s

Entrance head losses

Losses at the entrance are calculated with the formula:

$$\Delta h_e = \frac{v^2}{2g} - \pounds \frac{v_f^2}{2g} \qquad \text{[Ref. 1]} \qquad (19)$$

$\pounds -$ varies 0.8-0.4 depending on the angle of the intake direction where the highest values can be considered for the narrow angles, v_f – flow velocity in the river, v – flow velocity in the intake

In case of a step at the entrance and the lateral walls or rounded piles, the maximal loss at the entrance is calculated as:

$$\Delta h_e = 1.3\frac{v^2}{2g} - £\frac{v_f^2}{2g} \qquad \text{[Ref. 1]} \qquad (20)$$

Hydraulic losses as a result of trashracks, gate slots are treated at the pressure intakes.

Drop intake

Drop intake or Tyrolean intakes are commonly used for small and steeply sloped motains rivers with reliable rock foundation. This type of intake consists essentially of a channel built in the river bed, stretching across it and protected by a trash rack with a sloping face oriented in the direction of the river flow.

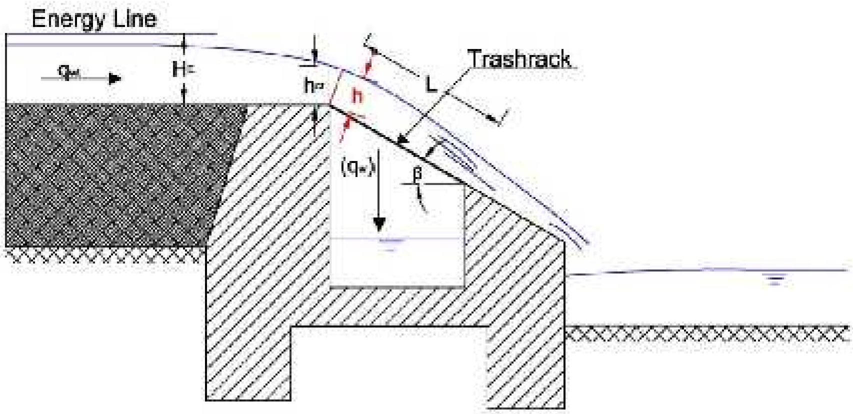


Figure 8 Drop intakes [Ref. 6]

Trashrack

Trash rack function essentially as filters to remove material and stones, floating on or just below the water surface from enter into the intake. In design of the trash rack type and dimensions precautions should be taken to prevent clogging of the racks. The basic design variables of the trash rack are the opening between adjacent bars ‘a’ and the center spacing ‘b’. These values for SHP depend on the size of material allowed to pass through the intake. Fig. 9 shows some types of rack bars with different profiles.

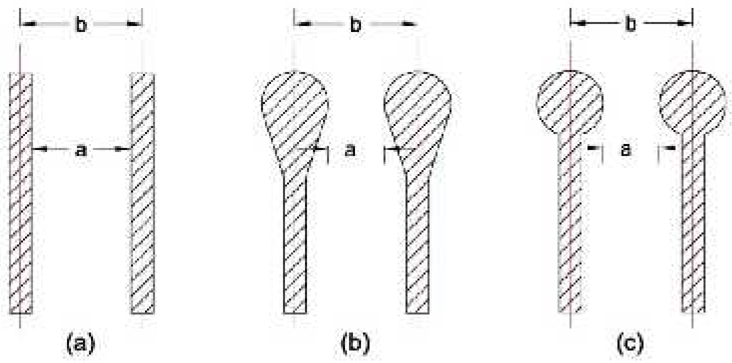


Figure 9 Typical profiles of racks for Drop intake (Tyrolean intake) [Ref. 6]

The rectangular racks are not recommended to be used for intake as they are easily and rapidly clogged by stones. Fig. 9a. The bulb-ended bars have better performance and are more rigid if required Fig. 9b. The best shape is round-head bars that prevent sediments from jamming and have better resistance against impact of stones because of higher moment of inertia Fig. 9c. So,

this last type of bars should be used systematically for Tyrolean intake. The recommended opening rack bars for this type is 20 to 40 mm.
The racks have to be inspected and cleaned at regular time intervals to prevent potential obstruction by debris.

Design criteria
The dimensions of the Tyrolean intake must be sufficient to capture all the water for the design discharge. According to the shape of the trash rack, head losses, approach flow regime and design discharge, the dimensions of a Tyrolean intake are based on following formula:

$$Q = \frac{2}{3} \cdot c \cdot « \cdot B \cdot L \cdot \sqrt{2gh} \qquad \text{[Ref. 6]} \qquad (21)$$

$L_{calculated}$ – intake length over the trash rack (m), B – trash rack width (m), Q – design flow (m³/s), h – water depth at upstream end of the trash rack (m)

$$h = k_c \cdot h_{cr} \qquad (22)$$

h_{cr} – critical height (m)

$$h_{cr} = \frac{2}{3} h_e \qquad (23)$$

h_e – initial water height (m), k_c – correction factor

$$k_c = 0.88 \cdot (\cos \quad) \text{ for } \quad > 30^o \qquad (24)$$

« – discharge coefficient for trash rack

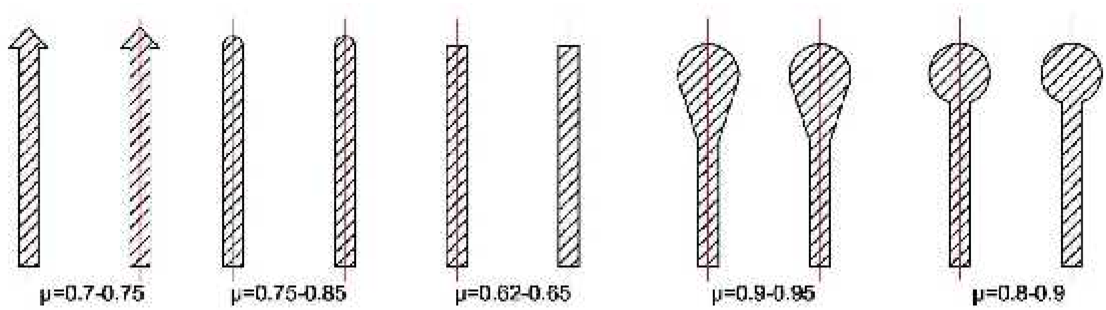


Figure 10 Discharge coefficients for different types of trash racks, [Ref. 7]

$$c = 0.6 \cdot (\frac{a}{b}) \cdot (\cos \quad)^{\frac{3}{2}} \qquad (25)$$

c – trash rack coefficient, – slope angle of the trash rack (º), $30^o < \quad < 45^o$, a – opening between the bars (mm), b – center spacing of bars (mm)

In order to guarantee the diversion of the minimum amount of water when stones become wedged in the trash rack, or branches and leaves remain on the trash rack at low water levels, the trash rack should be selected:

$$L = 1.2 \cdot L_{calculated} \tag{26}$$

Conclusion

The most important factors that should be evaluated for the choice of an intake structure are the climatic, geological, topographic and flow conditions. For the determination of the final design of a hydropower plant, it is very important that all the possible intake structures are analysed and the most optimal structure is chosen.

From the construction practice of intake structures in Albania, it must be emphasized that a certain reserve should be taken into consideration while dimensioning the intake structure. This reserve accounts for the depth of the alluvial deposits accumulated at the bottom of the trashrack and the suspended waste on the water surface during the operational phase of the structure.

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