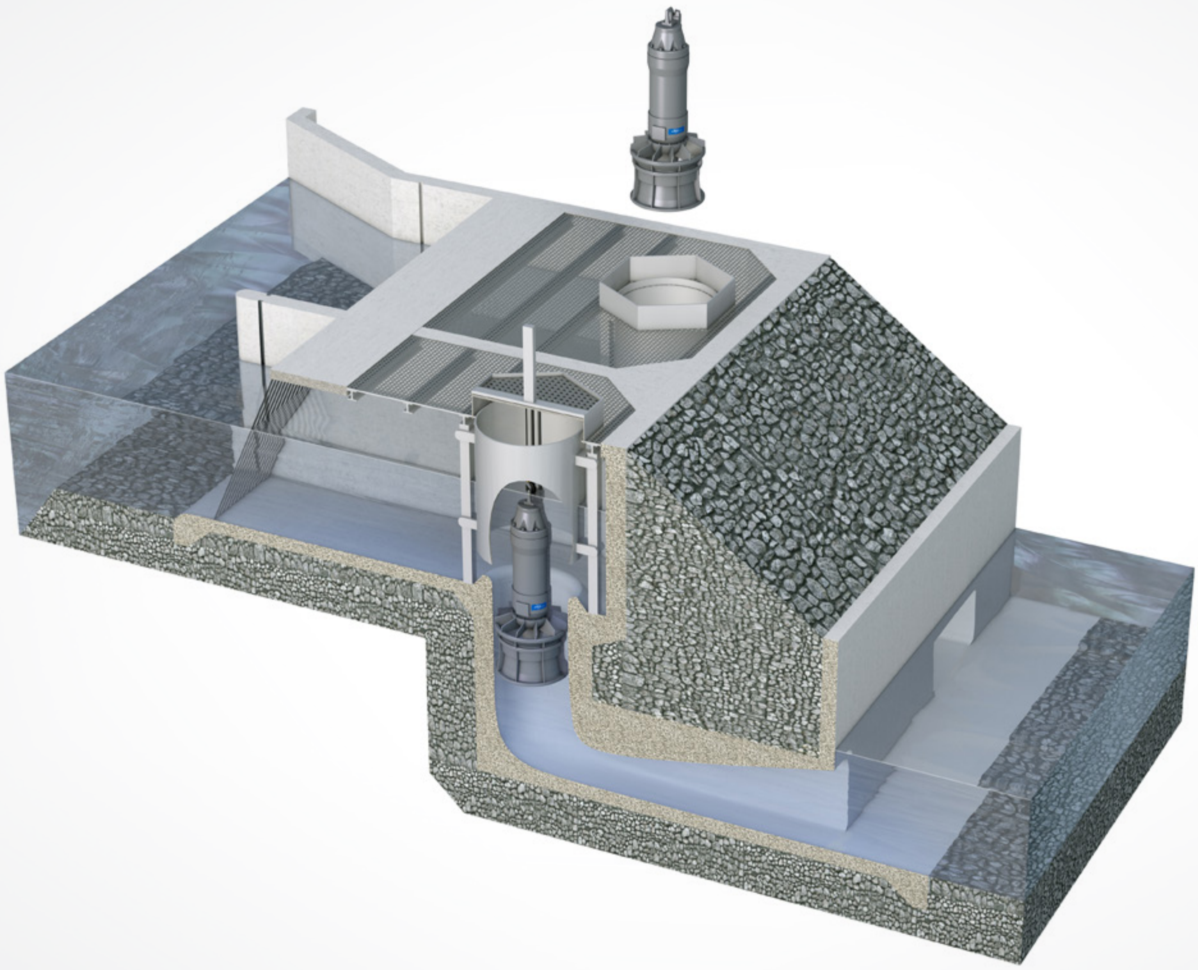


Flygt hydro turbines

SMART AND COMPACT HYDROPOWER – WITH FIGURE PLACEMENT

FLYGT
a xylem brand

Contents

Introduction

This brochure is intended to help application engineers, designers, planners and clients incorporating submersible Flygt hydroturbines. The information given is aimed at providing a broader understanding of the functional requirements of a small hydropower station.

Xylem's knowledge is based on more than three decades of experience about designing hydropower stations. This allows us to produce advanced and detailed solutions best suited for Flygt hydroturbines. The project documentation, in the form of drawings, design and set-up support that we can provide to prospective clients and consultants makes Xylem an attractive partner for developers.

The basic layouts presented here should readily apply to the majority of practical cases and thus significantly simplify design work. They illustrate the principles of the correct set-up of Flygt hydroturbines required to achieve the expected efficiency, power output and longevity.

Many of the auxiliary station elements described in this brochure can be used in combination with alternate layouts to fit the particular requirements of a prospect project. However, the configuration of the water passages nearest to the hydroturbine and their dimensions should comply with the design criteria outlined in this brochure.

Retrofit applications cannot always use these recommended station designs. In these cases, please contact your local Xylem hydroturbine office and they would be glad to assist you with finding a solution that best suits your site.

Three types of hydropower stations are discussed on the basis of different arrangements of water passages upstream of the hydroturbine. These types are:

1. The open flume

2. The penstock

3. The siphon

The open flume

General description
The open flume arrangements are most suitable for the sites with low water head availability. The headrace in a power station of the open flume type is an open channel, thus the water flows with a free surface to the turbine inlet. The location of the power station in a stream or a reservoir should allow undisturbed flow conditions at the flume entrance. Piers and wing walls can be used to guide the flow smoothly towards the entrance. Abrupt changes of the flow direction near the flume entrance, which lead to the separation of the flow from the wall and partial blockage of the entrance, must be avoided.

Seven different layouts for the open flume power stations are presented in the following pages. Their common elements are; the cylinder gate, vertical turbine tube with the bell mouth inlet and the turbine seat at the opposite end. The different layouts are combinations of standard or widened turbine tubes with elbow or straight draft tubes.

Structural design
The concrete cast flumes illustrated in this design brochure serve as guidance only. The structural strength of the construction must be designed individually in each case by a professional engineer.

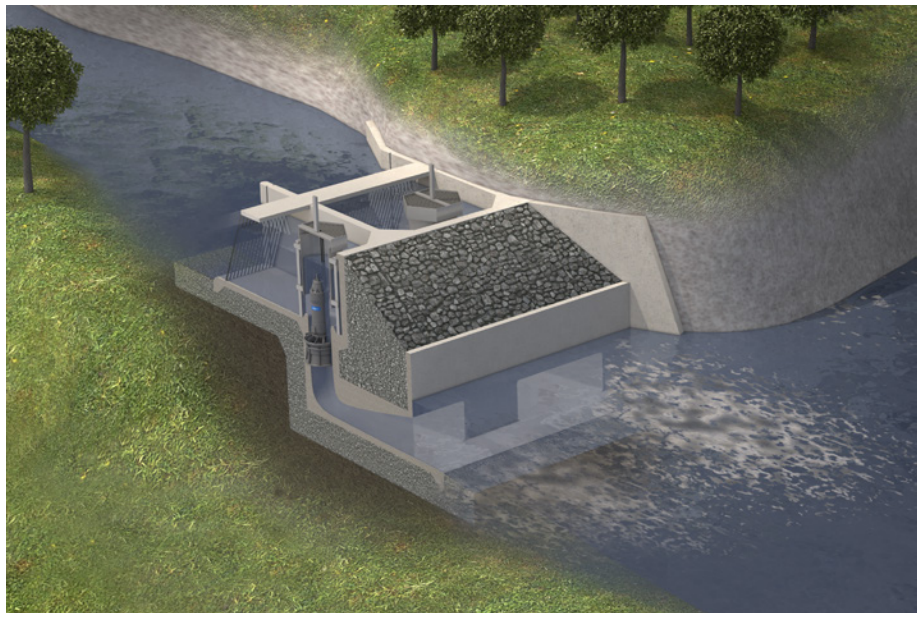
The use of steel turbine tube and draft tube are recommended to form the most crucial water passages with the required dimensional accuracy.

Open flume with straight draft tube.

The cylinder gate is supported on two vertical beams that, in the flume axis, are located in front of and behind the turbine tube. Since the vertical loads are transferred to the beams, this support system is mechanically simple. However, the beams disturb the flow at the turbine tube inlet. To minimize this adverse effect, blunt beams should be avoided. Instead, smooth and slender beams are recommended. The turbine flume usually is covered with a grated-steel deck supported on transverse beams. The trashrack is also supported on a transverse beam.

The control equipment can conveniently be placed in a cabin located beside the flume. If the power station consists of several units, installation of a permanent crane could be beneficial. If the hydroturbines are installed in straight line, one single crane bridge can serve them all.

Inflow control
The cylinder gate is a Flygt innovation for inflow control to the hydroturbine which moves easily through the use of a hydraulic cylinder. It is a very compact gate and provides ease of maintenance as well. Compared to the other measures for inflow control, cylinder gates are very effective for installations with low inlet submergence, also enable closing down the inflow to the turbine in case of a power shot down.



Open flume with elbow draft tube.

Slide gates can also be used for inflow control for Flygt hydroturbines. The set-up for the power station however is not presented in this document. If you are interested in such a set-up, please contact your local Xylem hydroturbine office to find a solution that specifically suits your site.

Overview of the dimensions
The turbine tube diameter, D_T, is used as the characteristic variable for sizing the set-up for the whole Flygt submersible hydroturbine series.

The dimensions of the flume are proportional to the turbine tube diameter as:

- The width is equal to $2D_T$.
- The minimum undisturbed length of the flume upstream of the turbine axis is $4D_T$ and is $6D_T$ if a provision of stoplogs is made.
- The distance from the back wall to the turbine centre is D_T.
- The required depth of the flume, H_F (in meters), depends on three parameters; the design flow rate, Q (m^3/s), the submersible hydroturbine height and finally the inlet submergence requirement for that specific set-up. The maximum value for H_F from the parameters is adopted for the hydropower station.

Flow dependent H_F is determined using equation 1.

$$H_F = Q/(1.2 \times D_T) \quad (1)$$

The water depth must also be sufficient to cover the entire generator in order to ensure its cooling which may supersede the minimum value for H_F calculated in equation 1. However, the submergence of the turbine inlet normally requires even more water depth and thus tends to be the decisive condition for the flume depth. The submergence criteria for different turbine inlets located in a standard flume are presented in a separate section in this design brochure.

In order to prevent formation of vortices at the headrace, behind the hydroturbine, the corners formed by the back wall and the side walls should be eliminated by fillets in all the designs.

If a power station requires two or more hydroturbines, it is recommended to have each unit in a separate flume. If this is not possible, the standard layout for a tandem flume layout given in this brochure can be utilized.

Open flume with elbow draft tube

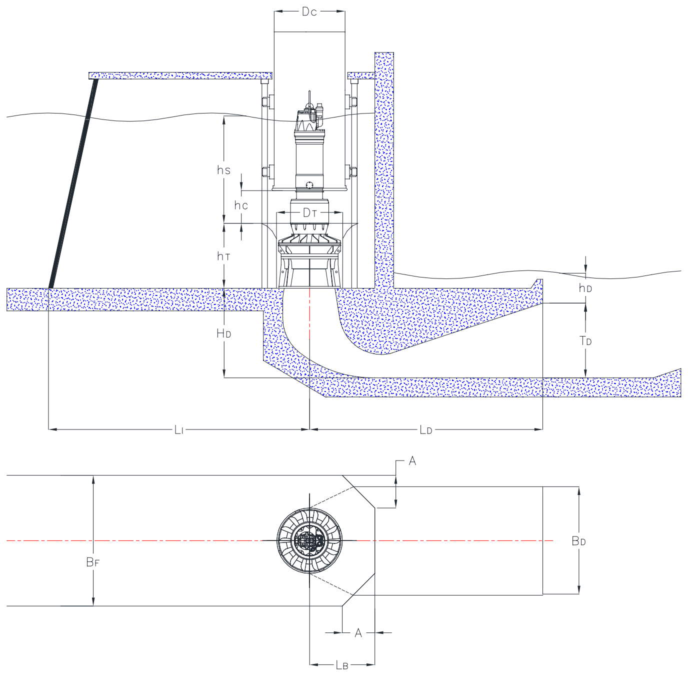
This power station type, as shown in Figurs 1–3, is equipped with both the cylinder gate and the elbow draft tube. This combination is the minimum and the most compact standard construction of the open flume power station of Flygt installations in terms of height and is specifically designed by Xylem to be best suited for the sites with low water head availability. Installing an elbow draft tube allows using a relatively shallow foundation for the entire power station.

Turbines with the inlet elevated above the flume bottom, illustrated in Figure 1, are more suitable for deeper flumes than the ones with the inlet situated at the flume bottom.

Turbines with the inlet situated sunken below the flume bottom, illustrated in Figure 2, is used with the turbines with a gear assembly and the generator partially confined in the turbine tube. The enlarged turbine tube is recommended for the hydroturbines which have a generator that is greater than 0.54 the standard tube diameter as illustrated in Figure 3. Enlarged turbine tubes can also be used for stations with deep tail races to place the turbine much lower than a standard depth while controlling tube losses on the inlet of the turbine.

Figure 1

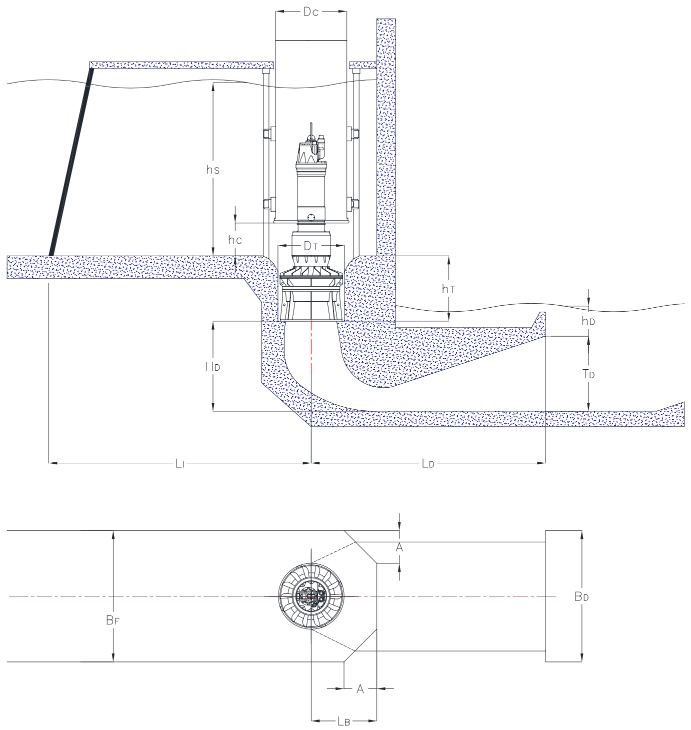
Layout for an open flume power station with an elbow draft tube with the inlet elevated above the flume bottom. All dimensions are given in metres.



Model	D_T	h_T	Min h_S	D_C	Min h_C	H_D	L_D	T_D	Min h_C	B_C	L_I	B_F	A	L_B
EL 7556	0.8	0.8	Calculated by Equations 4-6	0.85	0.3-0.7	1.04	2.75	0.88	0.3	1.10	3.2	1.6	0.4	0.8
EL 7570	1.2	1.2		1.3	0.5-0.9	1.33	3.50	1.12	0.4	1.40	4.8	2.4	0.6	1.2
EL 7585	1.2	1.2		1.3	0.6-1.2	1.63	4.25	1.36	0.4	1.70	4.8	2.4	0.6	1.2
EL 7600	1.4	1.4		1.5	0.7-1.3	1.92	5.0	1.60	0.4	2.0	5.6	2.8	0.7	1.4
EL 7620	1.6	1.6		1.7	1.0-1.6	2.31	6.0	1.92	0.4	2.40	6.4	3.2	0.8	1.6
EL 7650	2.0	2.0		2.15	1.2-1.8	2.90	7.50	2.40	0.5	3.0	8.0	4.0	1.0	2.0

Figure 2

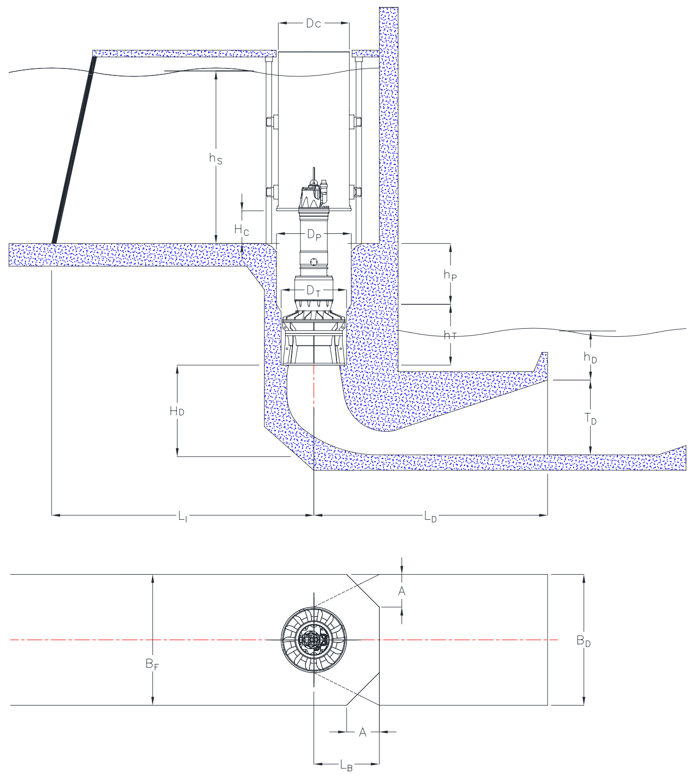
Layout for an open flume power station with an elbow draft tube with the inlet situated at the flume bottom. All dimensions are given in metres.



Model	D_T	h_T	Min h_S	D_C	Min h_C	H_D	L_D	T_D	Min h_C	B_C	L_I	B_F	A	L_B
EL 7556	0.8	0.8	Calculated by Equations 7 and 8	0.85	0.3-0.7	1.04	2.75	0.88	0.3	1.1	3.2	1.6	0.4	0.8
EL 7570	1.2	1.2		1.3	0.5-0.9	1.33	3.50	1.12	0.4	1.4	4.8	2.4	0.6	1.2
EL 7585	1.2	1.2		1.3	0.6-1.2	1.63	4.25	1.36	0.4	1.7	4.8	2.4	0.6	1.2
EL 7600	1.4	1.4		1.5	0.7-1.3	1.92	5.0	1.60	0.4	2.0	5.6	2.8	0.7	1.4
EL 7620	1.6	1.6		1.7	1.0-1.6	2.31	6.0	1.92	0.4	2.4	6.4	3.2	0.8	1.6
EL 7650	2.0	2.0		2.15	1.2-1.8	2.90	7.5	2.4	0.5	3.0	8.0	4.0	1.0	2.0

Figure3

Layout for an open flume power station with an elbow draft tube with the inlet situated sunk below the flume bottom. Dp is applied only for an enlarged turbine tube. All dimensions are given in metres.



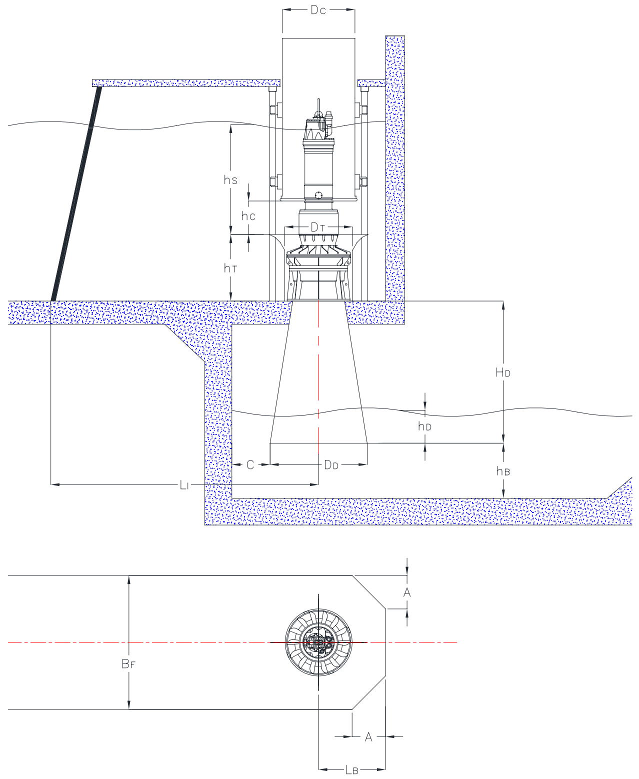
Model	D_T	D_P	h_T	Min h_P	Min h_S	D_C	Min h_C	H_D	L_D	T_D	Min h_D	L_I	B_F	A	L_B	B_D
EL 7556	0.8	1	0.85	0.15	Calculated by Equations 4-6	0.85	0.3-0.5	1.04	2.75	0.88	0.3	3.2	1.6	0.4	0.8	1.1
EL 7570	1.2	1.4	1.10	0.2		1.3	0.4-0.7	1.33	3.50	1.12	0.4	4.8	2.4	0.6	1.2	1.4
EL 7585	1.2	1.4	1.15	0.2		1.3	0.6-1.2	1.63	4.25	1.36	0.4	4.8	2.4	0.6	1.2	1.7
EL 7600	1.4	1.6	1.30	0.25		1.7	0.7-1.3	1.92	5.0	1.60	0.4	5.6	2.8	0.7	1.4	2.0
EL 7620	1.6	1.8	1.55	0.3		2.15	1.0-1.5	2.31	6.0	1.92	0.4	6.4	3.2	0.8	1.6	2.4

Open flume with straight draft tube

If the available height allows for installation of a long straight draft tube without extra excavation, the layout given in Figures 4–6 is advantageous to the open flume set-up with the elbow draft tube. The straight draft tube is a more economical set-up than the elbow type draft tube and the entire constructed structure is more compact compared to the previous installation configurations.

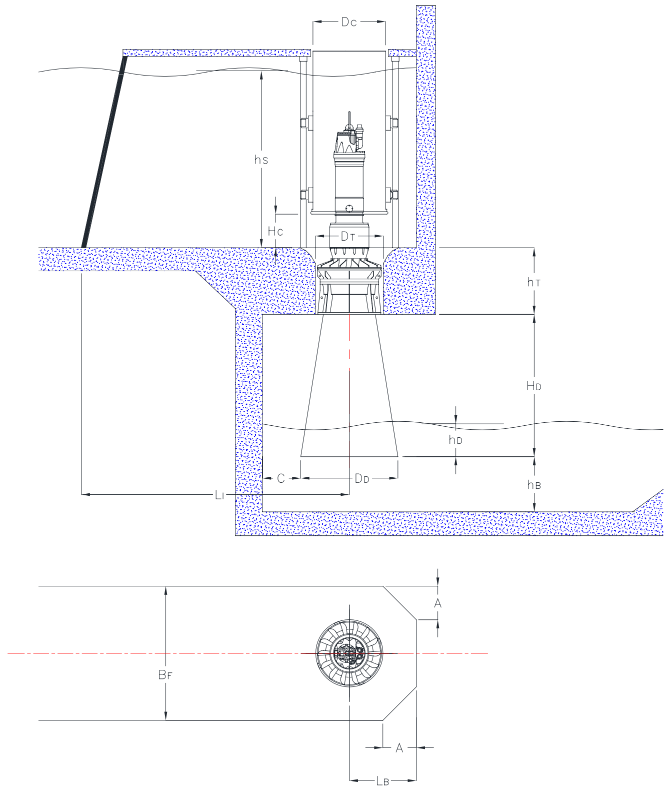
The minimum bottom and side clearances for the outlet of the draft tube must be observed to ensure its proper function. The submergence requirement for the turbine inlet tube is the same as for the open flume set-up with elbow draft tube. Water level at the tailrace for this installation can affect the performance of the turbine and therefore need to closely follow the recommended values for the net positive suction head required for this method of installation. The concept of net positive suction head is presented at a separate section in this brochure.

Figure 4
Layout for an open flume power station with a straight draft tube with the inlet elevated above the flume bottom. All dimensions are given in metres.



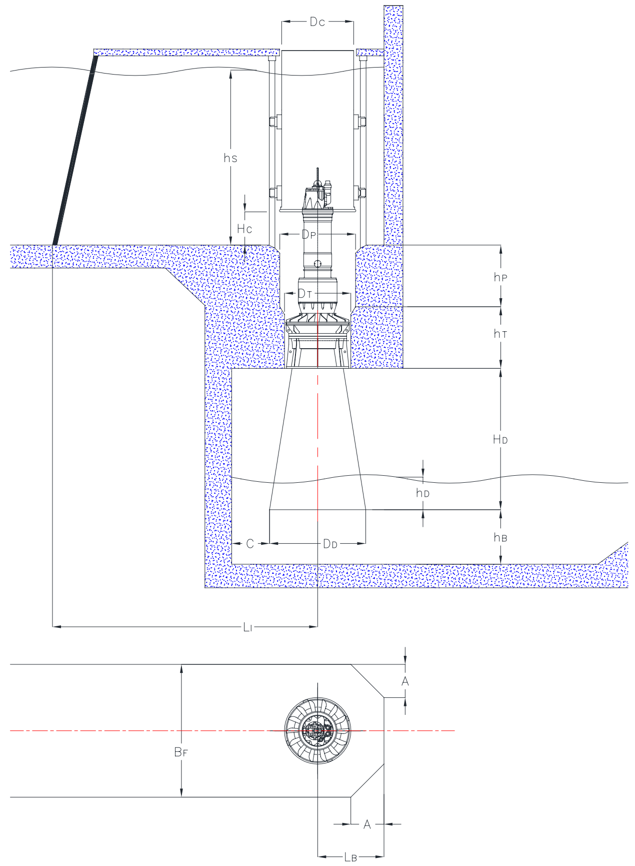
Model	D_T	h_T	Min h_S	D_C	Min h_C	H_D	L_D	T_D	Min h_C	B_C	L_I	B_F	A	L_B
EL 7556	0.8	0.8	Calculated by Equations 4-6	0.85	0.3-0.7	1.63	1.12	0.45	0.3	0.6	3.2	0.8	1.6	0.4
EL 7570	1.2	1.2		1.3	0.5-0.9	2.08	1.42	0.6	0.4	0.65	4.8	1.2	2.4	0.6
EL 7585	1.2	1.2		1.3	0.6-1.2	2.52	1.72	0.7	0.4	1.0	4.8	1.2	2.4	0.6
EL 7600	1.4	1.4		1.5	0.7-1.3	2.97	2.03	0.8	0.4	1.15	5.6	1.4	2.8	0.7
EL 7620	1.6	1.6		1.7	1.0-1.6	3.56	2.43	1.0	0.4	1.45	6.4	1.6	3.2	0.8
EL 7650	2.0	2.0		2.15	1.2-1.8	4.45	3.03	1.2	0.5	1.8	8.0	2.0	4.0	1.0

Figure 5
Layout for an open flume power station with a straight draft tube with the inlet situated at the flume bottom. All dimensions are given in metres.



Model	D_T	h_T	Min h_S	D_C	Min h_C	H_D	L_D	T_D	Min h_C	B_C	L_I	B_F	A	L_B
EL 7556	0.8	0.8	Calculated by Equations 7 and 8	0.85	0.3-0.7	1.63	1.12	0.45	0.3	0.6	3.2	0.8	1.6	0.4
EL 7570	1.2	1.2		1.3	0.5-0.9	2.08	1.42	0.6	0.4	0.65	4.8	1.2	2.4	0.6
EL 7585	1.2	1.2		1.3	0.6-1.2	2.52	1.72	0.7	0.4	1.0	4.8	1.2	2.4	0.6
EL 7600	1.4	1.4		1.5	0.7-1.3	2.97	2.03	0.8	0.4	1.15	5.6	1.4	2.8	0.7
EL 7620	1.6	1.6		1.7	1.0-1.6	3.56	2.43	1.0	0.4	1.45	6.4	1.6	3.2	0.8
EL 7650	2.0	2.0		2.15	1.2-1.8	4.45	3.03	1 .2	0.5	1.8	8.0	2.0	4.0	1.0

Figure 6
Layout for an open flume power station with an straight draft tube with the inlet situated sunk below the flume bottom. Dp is applied only for an enlarged turbine tube. All dimensions are given in metres.

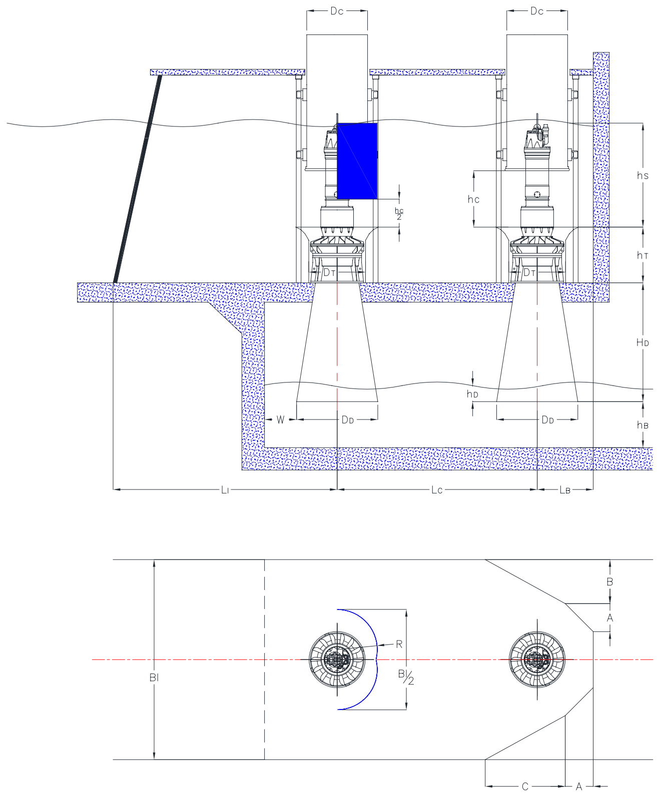


Model	D_T	D_P	h_T	Min h_P	Min h_S	D_C	Min h_C	H_D	L_D	T_D	Min h_D	L_I	B_F	A	L_B	B_D
EL 7556	0.8	1	0.85	0.15	Calculated by Equations 4-6	1.1	0.3-0.5	1.63	1.12	0.45	0.3	0.6	3.2	0.8	1.6	0.4
EL 7570	1.2	1.4	1.10	0.2		1.5	0.4-0.7	2.08	1.42	0.6	0.4	0.65	4.8	1.2	2.4	0.6
EL 7585	1.2	1.4	1.15	0.2		1.5	0.6-1.2	2.52	1.72	0.7	0.4	1.0	4.8	1.2	2.4	0.6
EL 7600	1.4	1.6	1.30	0.25		1.7	0.7-1.3	2.97	2.03	0.8	0.4	1.15	5.6	1.4	2.8	0.7
EL 7620	1.6	1.8	1.55	0.3		1.9	1.0-1.5	3.56	2.43	1.0	0.4	1.45	6.4	1.6	3.2	0.8

Open flume with tandem turbines

If a power station requires two or more hydroturbines, it is recommended to have each unit in a separate flume. If this set-up is not possible, the standard layout for a tandem flume set-up which is presented in Figure 7 below can be adopted. In this set-up the turbines are separated by baffle walls. The submergence criteria for each turbine should be considered independently and the highest value should be considered. If the power station consists of several units, a permanent crane is useful.

Figure 7
Layout for an open flume power station with tandem turbines and a straight draft tube. All dimensions are given in metres.



Model	D_T	h_T	Min h_S	D_C	h_C	H_D	D_D	h_B	hD	W	L_I	L_C	L_B	BI	R	A	B	C
EL 7556	0.8	0.8	1.7	0.85	0.8	1.63	1.12	0.6	0.3	0.5	3.2	2.8	0.8	2.8	0.6	0.4	0.6	1.0
EL 7570	1.2	1.2	1.8	1.3	1.0	2.08	1.42	0.7	0.4	0.6	4.8	4.2	1.2	4.2	0.8	0.6	0.9	1.6
EL 7585	1.2	1.2	2.5	1.3	1.2	2.52	1.72	1.0	0.4	0.7	4.8	4.6	1.2	4.6	0.9	0.6	1.1	1.9
EL 7600	1.4	1.4	2.6	1.5	1.4	2.97	2.03	1.2	0.4	0.8	5.6	5.0	1.4	5.0	1.0	0.7	1.1	2.0
EL 7620	1.6	1.6	2.7	1.7	1.6	3.56	2.43	1.5	0.4	1.0	6.4	5.6	1.6	5.6	1.2	0.8	1.2	2.1
EL 7650	2.0	2.0	2.8	2.15	1.8	4.45	3.03	1.8	0.5	1.2	8.0	7.0	2.0	7.0	1.5	1.0	1.5	2.6

Required inlet submergence

In order to prevent formation of vortices at the turbine inlet, a certain water depth above the inlet, referred to as the inlet submergence, is required.

For a particular geometry of the inlet, the required submergence depth depends on the diameter of the inlet and on the water velocity at the inlet.

The guidelines presented in this brochure are based on model studies conducted on the open flume of a standard design. The minimum submergence depth from these studies for our hydroturbines set-ups are:

hsI: An inlet mounted at the bottom of the channel (Figures 2, 3, 5 and 6)
hsII: Inlet elevated $1.2D_T$ above the flume bottom (Figures 1 and 4)

The water velocity at the inlet, V, is calculated by dividing the flow rate, Q, by the cross-sectional area of the turbine tube, A. No reduction of the inlet area by the generator is considered.

$$V = \frac{Q}{A} = \frac{\pi Q D_T^2}{4} \quad (2)$$

The results are expressed as the required submergence depth, hs, as a function of the water velocity at the inlet, V, and the inlet diameter, D_T in the Equations below. For hsI, three equations are given (Equations 4-6). Equation 3 is for calculating the optimal gate clearance (h_{opt}). Equations 4 and 5 are for the cases with a gate clearance equal to h_{opt} and Equation 6 is for the cases with the gate clearance of 1.5 times h_{opt}.

$$h_{opt} = 0.21\,VD_T + 0.09D_T \quad (3)$$

$$hs_I = 0.35\,VD_T + 0.64D_T \quad V \leq 3m/s \quad (4)$$

$$hs_I = 2.26\,VD_T - 5.31D_T \quad V > 3m/s \quad (5)$$

$$hs_I = 0.48VD_T + 1.31D_T \quad (6)$$

In the case of the inlet mounted at the bottom, the cylinder gate, if lowered below the water surface, tends to reduce the required submergence which is reflected in equations 4-6. The optimum gate clearance, h_{opt}, for which this favorable effect is maximized, also depends on the flow velocity (Eq. 3). If the gate clearance is increased by 50 % from the optimum value, the cylinder gate no longer has any effect on the required submergence.

In the case of the inlet placed $1.2D_T$ above the bottom, two equations are given (equations 7 and 8) for calculating the minimum required submergence depth. Equation 7 is valid for cases with all gate clearances with V ≤ 3.3m/s and Equation 8 is for the cases with V > 3.3m/s.

$$hs_{II} = 0.45\,VD_T + 0.50D_T \quad V \leq 3.3\ m/s \quad (7)$$

$$hs_{II} = 1.15\,VD_T - 1.75D_T \quad V > 3.3\ m/s \quad (8)$$

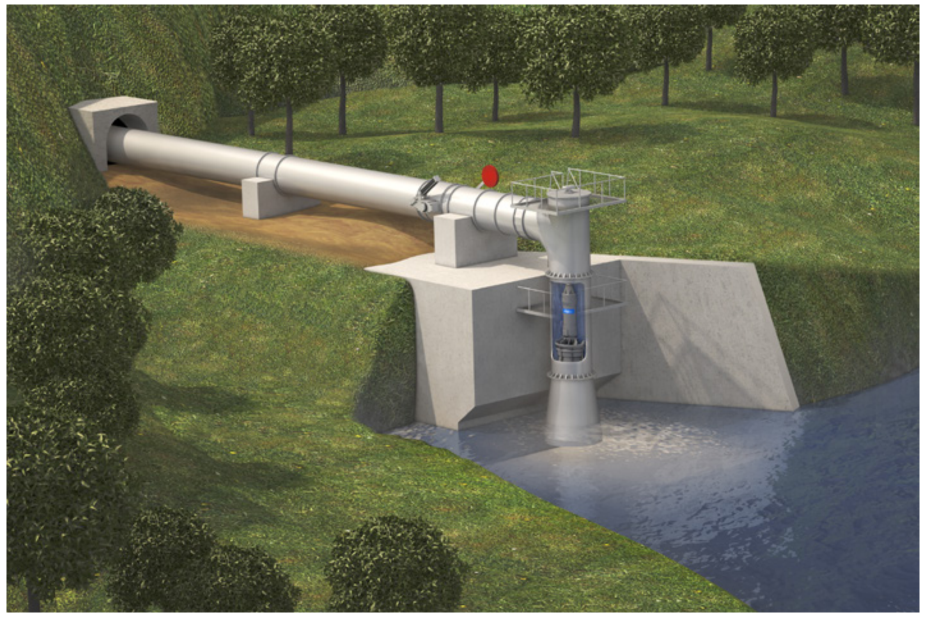
For high velocities, the cylinder gate enhances vortex formation and thus should be opened by at least 1.5 h_{opt} to eliminate this adverse effect, which increases the submergence requirement even more. This is reflected in equation 8. For higher velocities, the cylinder gate enhances vortex formation and thus should be opened by at least 1.5 h_{opt} to eliminate this adverse effect, which increases the submergence requirement even more.

The penstock

General description
The penstock-type power stations are advantageous for relatively high water head availability. A typical arrangement is illustrated in Figure 8. It consists of an intake, a penstock (the pressure conduit conveying water to the turbine column), a turbine with a draft tube, and a tailrace.

Four recommended layouts of the penstock-type power stations are included in this design guide. The hydroturbine is installed in a vertical tube of matching diameter, D_T, as specified below. The lower end of the tube is furnished with a turbine seat. If the diameter of the generator is greater than $0.54D_T$, a greater tube diameter is required for the upper part of the tube.

Structural design and Overview of the dimensions
The water intake to the penstock and the penstock system are vital components of the system and require careful designing. A well designed intake should uniformly accelerate the flow from a canal or a reservoir into the penstock with a minimum head loss. Vortex formation at the inlet, which can lead to air entrainment into the penstock, must be prevented by streamlining the inlet and providing a sufficient submergence. Moreover, an intake must be furnished with a trashrack and a gate. An air inlet behind the gate is always required. A flow regulating valve can be installed at the end of the penstock prior to the turbine entrance. The main concern in designing a penstock is minimizing its length, diameter and wall thickness for a selected construction material. Ideally, a penstock will follow a straight line between the intake and the power station. To facilitate its construction, the penstock route shouldbe altered to fit the terrain. For very long penstocks, the optimization procedure is used to select the diameter. The optimum diameter is determined when the sum of the construction cost and the capitalized cost of energy loss due to friction is minimum. For more details on the design of the water intake of the penstock, please contact Xylem for assistance. Xylem can provide you with typical design recommendations as well as site and case specific solutions.



The penstock
The penstock power station with straight draft tube

A penstock supplying a single hydrogenerator should have a diameter at least equal to the diameter of the turbine tube, D_T. The minimum wall thickness should be selected so as to provide a sufficient strength in relation to the critical internal pressure and to ensure a sufficient stiffness of the structure. Often, analysis of the water-hammer phenomenon is required in order to determine the critical pressures.

If the distance between an intake and a power station is long and the hydropower potential requires several hydrogenerators, two alternatives can to be considered with multiple penstocks or with one penstock with a manifold branching into individual turbine columns. For details on installation of multiple hydrogenerators please contact us for case specific support.

The minimum length of the turbine tube is equal to the total height of the hydroturbine.

The junction of the penstock and the turbine column is a crucial part of the system as it has two functions:

- To provide access to the hydroturbine
- To turn the flow without excessive head loss

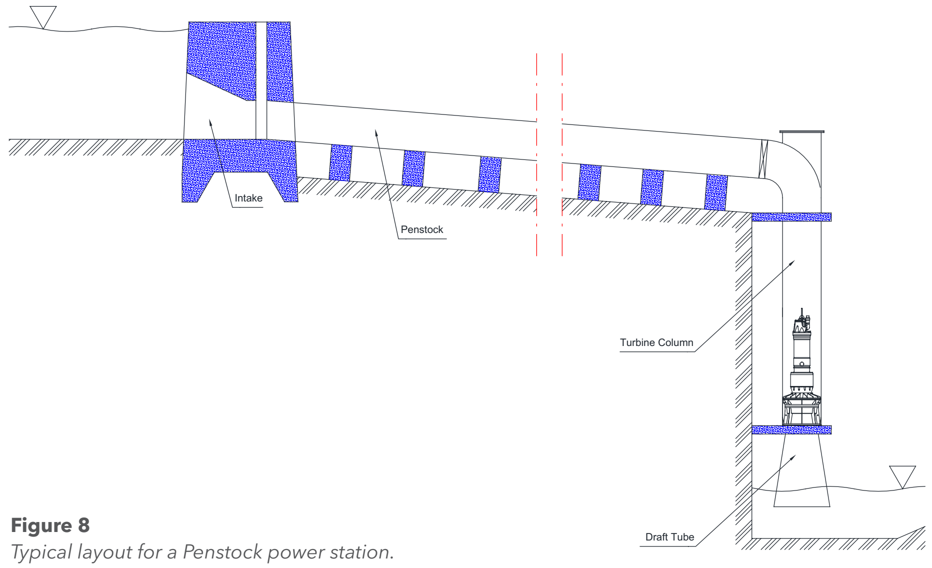


Figure 8
Typical layout for a Penstock power station.

A Y-junction with one leg aligned with the penstock and two legs aligned with the turbine tube is the best solution. The junction and the turbine tube thus form a vertical column which is most convenient for the installation of a hydroturbine. The access to the machine is provided through the top cover of the column.

In order to enable smooth turning of the flow, the nearly right angle connection should be formed as a mitered bend with a radius of curvature equal to the penstock diameter. A guide vane shaped as the outer wall of the bend should be installed inside the column. Two major constructions alternative of turbine columns are discussed in this section. Both designs use the basic layouts, yet they show the application of different construction techniques.

Penstock power station with elbow draft tube

The combination of the turbine column and the elbow draft tube gives the minimum amount of excavation power station of the penstock type as illustrated in Figures 9 and 10. Also, the turbine placement is the lowest that can be achieved if high Net Positive Suction Head required is a concern. The minimum head suitable for this type of power station ranges from about 5 m for EL 7565 through 7 m for EL 7620.

Figure 9
Layout for a penstock power station with an elbow draft tube and a normal size turbine tube. All dimensions are given in metres.

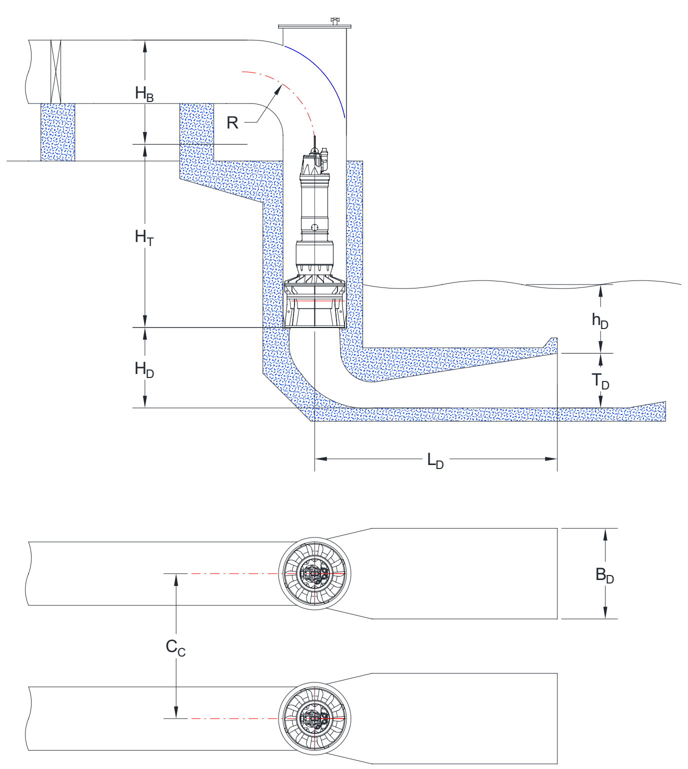
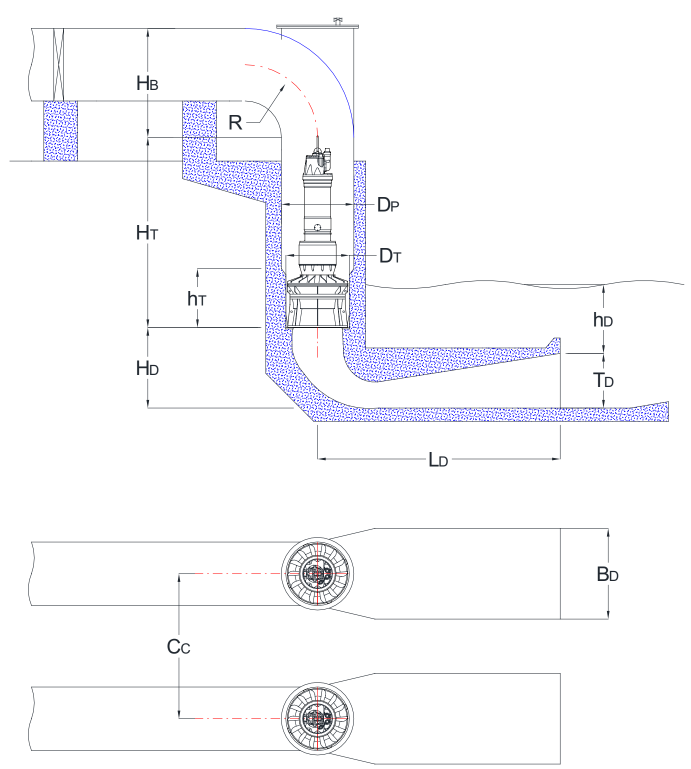


Figure 10
Layout for a penstock power station with an elbow draft tube and an enlarged turbine tube. All dimensions are given in metres.



Model	D_T	Min H_T	R	H_B	H_D	L_D	T_D	Min h_D	B_D	C_C
EL 7556	0.8	1.0	0.85	2.4	1.0	1.5	1.04	2.75	0.88	0.3
EL 7570	1.2	1.4	1.10	2.4-3.0	1.4	2.1	1.33	3.50	1.12	0.4
EL 7585	1.2	1.4	1.15	3.0-4.0	1.4	2.1	1.63	4.25	1.36	0.4
EL 7600	1.4	1.6	1.30	3.6-4.2	1.6	2.4	1.92	5.00	1.60	0.4
EL 7620	1.6	1.8	1.55	3.7-4.3	1.8	2.7	2.31	6.00	1.92	0.4
EL 7650	2.0	2.0	2.8	2.15	1.8	4.45	3.03	1.8	0.5	1.2

Model	D_T	D_P	h_T	Min H_T	R	H_B	H_D	L_D	T_D	Min h_D	B_D	C_C
EL 7556	0.8	1.0	0.85	2.4	1.0	1.5	1.04	2.75	0.88	0.3	1.1	1.6
EL 7570	1.2	1.4	1.10	2.4-3.0	1.4	2.1	1.33	3.50	1.12	0.4	1.4	2.4
EL 7585	1.2	1.4	1.15	3.0-4.0	1.4	2.1	1.63	4.25	1.36	0.4	1.7	2.4
EL 7600	1.4	1.6	1.30	3.6-4.2	1.6	2.4	1.92	5.00	1.60	0.4	2.0	2.8
EL 7620	1.6	1.8	1.55	3.7-4.3	1.8	2.7	2.31	6.00	1.92	0.4	2.4	3.2

Penstock with straight draft tube

As an alternative to Penstock power station with elbow draft tube, a turbine tube can be combined with a straight draft tube as illustrated in Figures 11 and 12. The straight draft tube is more cost effective than the elbow and the entire turbine column can be mounted in the open. Thus the volume of concrete required for the power station is reduced and therefore the entire construction is cost effective.

The straight draft tube, on the other hand, is longer than the elbow draft tube and its exit must be mounted at a certain distance above the bottom. The combined penstock column and straight draft tube is thus significantly higher than the former combination. The difference ranges from 1.2 meters for the EL 7556 to 1.9 meters for the EL 7650.

The practical minimum heads for a penstock power station with straight draft tube are:

- 6.5 meters for EL 7555
- 8 meters for EL 7570
- 9 meters for EL 7585
- 10.5 meters for EL 7600
- 11.5 meters for EL 7620

If the water depth at the tailrace is not greater than the length of the straight draft tube, the turbine will be situated above the tail water. The cavitation criteria for the runner setting can then be a limitation for the use of straight draft tubes.

The maximum distance between the draft tube exit and the bottom (min h_B) is valid for tailrace channels of a limited width equal to the width of the headrace flume. This situation applies primarily to stations with multiple turbines where the spacing among the units is determined by the flume width. For tailrace channels which are significantly larger than the standard configurations specified in this design brochure, the bottom clearance can be reduced to $0.4D_D$, as shown on the dimensional drawings for the draft tubes.

If the combination of the required runner setting and insufficient water depth require deepening of the tailrace channel, a straight draft tube of a reduced length could be considered as an alternative. The choice of the draft tube can be made by comparing the compounded value of the reduced energy production due to the reduced draft tube efficiency with the extra cost for excavation.

The alternative draft tubes are not shown in this design brochure. However, the basic layouts for the long, straight draft tube can be readily used with the correction of the draft tube length, H_D, and diameter, D_D.

Figure 11
Layout for a penstock power station with a straight draft tube and a normal size turbine tube. All dimensions are given in metres.

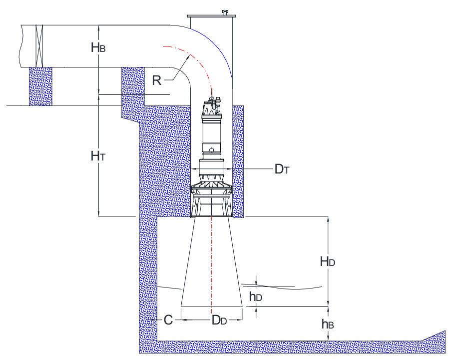


Figure 12
Layout for a penstock power station with a straight draft tube and an enlarged turbine tube. All dimensions are given in metres.

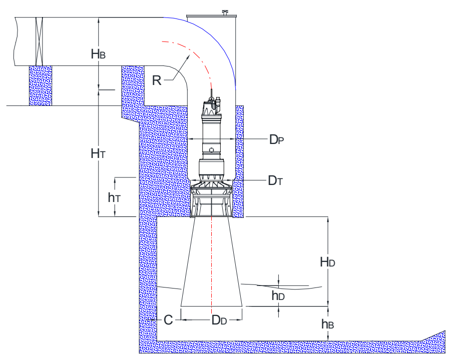


Table for figure 11

Model	D_T	Min H_T	R	H_B	H_D	D_D	Min C	Min h_D	Min h_B	B_D	C_C
EL 7556	0.8	2.4	0.8	1.2	1.63	1.12	0.45	0.3	0.6	1.6	1.6
EL 7570	1.2	2.4-3.0	1.2	1.8	2.08	1.42	.60	0.4	0.65	2.4	2.4
EL 7585	1.2	3.0-4.0	1.2	1.8	2.52	1.72	0.70	0.4	1.00	2.4	2.4
EL 7600	1.4	3.6-4.2	1.4	2.1	2.97	2.03	0.80	0.4	1.15	2.8	2.8
EL 7620	1.6	3.7-4.3	1.6	2.4	3.56	2.43	1.00	0.4	1.45	3.2	3.2
EL 7650	2.0	3.8-4.4	2.0	3.0	4.45	3.03	1.20	0.5	1.80	4.0	4.0

Table for figure 12

Model	D_T	D_P	h_T	Min H_T	R	H_B	H_D	D_D	C	Min h_D	h_B	B_D	C_C
EL 7556	0.8	1.0	0.85	2.4	1.0	1.5	1.63	1.12	0.45	0.3	0.60	1.6	1.6
EL 7570	1.2	1.4	1.10	2.4-3.0	1.4	2.1	2.08	1.42	0.60	0.4	0.65	2.4	2.4
EL 7585	1.2	1.4	1.15	3.0-4.0	1.4	2.1	2.52	1.72	0.70	0.4	1.00	2.4	2.4
EL 7600	1.4	1.6	1.30	3.6-4.2	1.6	2.4	2.97	2.03	0.80	0.4	1.15	2.8	2.8
EL 7620	1.6	1.8	1.55	3.7-4.3	1.8	2.7	3.56	2.43	1.00	0.4	1.45	3.2	3.2

The siphon

General description
The two siphon-type power stations, shown in Figures 13 and 14, have different layouts and applicability and their only common feature is the use of a siphon intake. As priming of a siphon usually takes several minutes (i.e. up to 15 minutes), these power stations are unsuitable for on-off operation with short cycles.

Air-tightness of the fittings and concrete are vital to the operation of the siphon set-up. If the amount of air entering the system is greater than the capacity of the flowing water to transport air, the siphon action will eventually break and disrupt the operation of the hydroturbine.

Priming of the siphon requires usage of a vacuum pump. The vacuum line should be connected in the highest part of the system.

In order to stop the hydroturbine, the siphon must be deprimed by admitting air through a siphon-breaker valve. The valve must be sized appropriately to the discharge and be located in the upper part of the bend.

Siphon power station with siphon intake type I.

Siphon intake type I

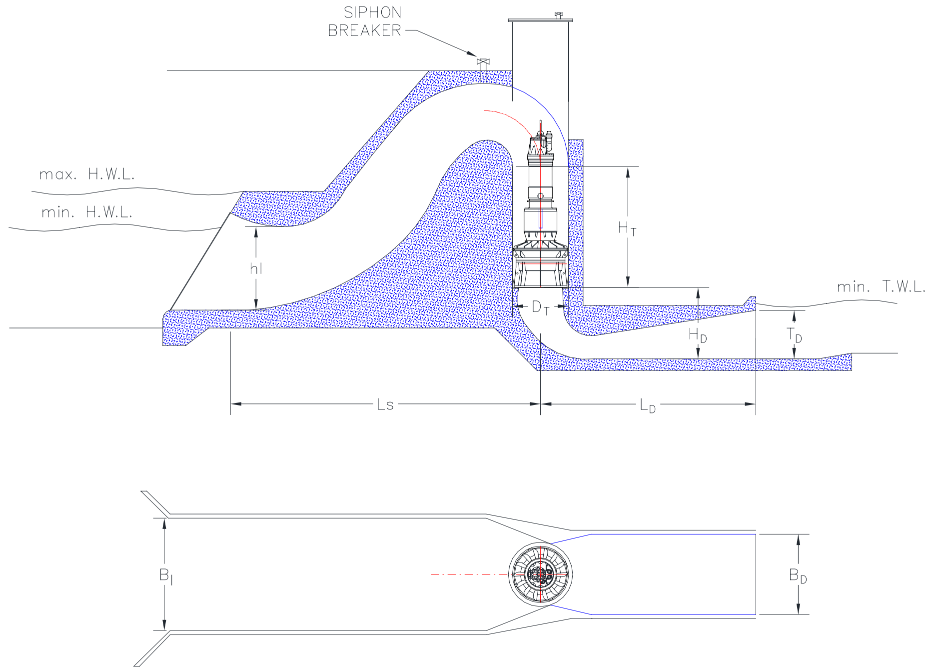
Siphon intake type I is designed for our large EL 7620 and 7650 models. It can be applied in the head range between 3 and 5 meters as an alternative to the open flume power station with an elbow draft tube. The siphon intake enables the hydroturbine to be set higher and a shallower excavation for the draft tube is possible compared to the open flume configurations.

The power station is designed as a concrete block incorporating the intake, the turbine tube, and the draft tube. Such a power station is constructed in a river bed inline with a dam and/or a weir.

The intake is designed so as to prevent vortex formation since air entrainment is unacceptable in siphon operations. The 90° bend between the uppermost cross-section and the turbine tube also serves as a transition from a rectangular to a circular cross-section. An appropriate opening in the upper wall of the bend must be provided to enable installation of the hydroturbine.

The bend with the lid covering the access hole should be fabricated of steel. Similarly, the turbine tube and the draft tubes should also be made of steel and used as forms in the concrete structure.

Figure 13
Siphon power station with siphon intake type I. All dimensions are given in metres.



Model	D_T	H_T	R	h_I	d_D	T_D	h_D	Ls	L_D	B_I	B_D
EL 7620	1.6	3.0	1.6	2.8	1.30	1.92	0.4	7.7	6.0	3.2	2.4
EL 7650	2.0	3.0	2.0	3.5	1.62	2.40	0.5	8.5	7.5	4.0	3.0

Siphon intake type II

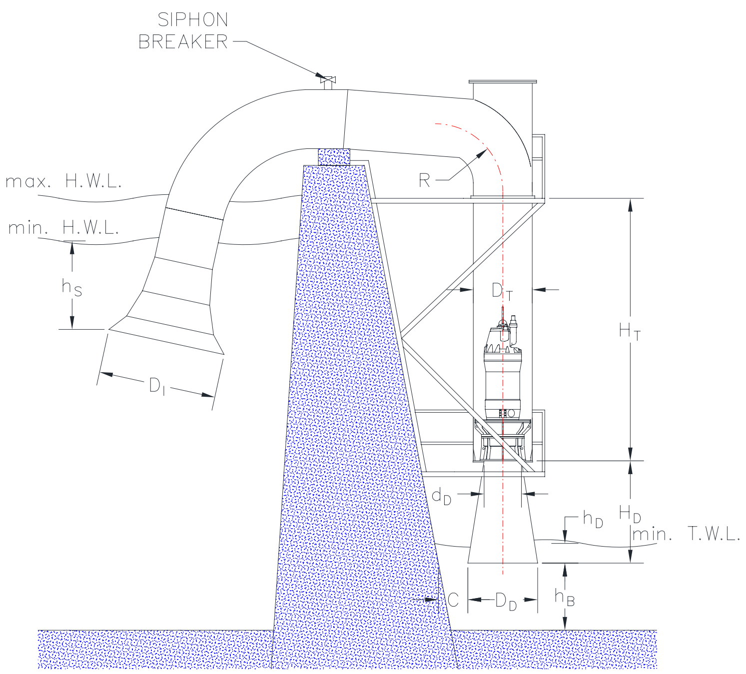
The design of siphon intake type II, as demonstrated in Figure 14, combines an intake in form of a penstock siphon with a turbine column. The penstock has a bellmouth inlet and is supported on the crest of a dam. As this solution is used only with existing dams, the shape of the penstock can vary with the form of the dam. The size and weight of the installation are limited by the strength of the dam which must withstand the additional load. For practical reasons, this type of installation is best suited for our smaller hydroturbine models which included Models EL 7556, EL 7570 and EL7585.

The turbine column is designed in accordance with the same criteria as the penstock power station with a straight draft tube. However, if it is found more convenient, the elbow draft tube can be used instead of a straight one. Shap e and submergence of the inlet requires special considerations. The recommended diameter of the bellmouth inlet is $D_{Inlet} = 2 \times D_T$ and the minimum required submergence $hs = l.5 \times D_T$.

The vacuum line required for priming the siphon should be connected to the top cover of the turbine column in this set-up. The siphon-breaker valve is preferably fitted at the highest point of the penstock rather than in the top cover as the air flow can be obstructed by the guide vane in the Y-junction.

A conventional trashrack recommended for our other set-up, cannot be used for this set-up. However, for this system, the submerged inlet is less exposed to floating debris than the surface intakes. A grid installed in the inlet or a trashrack forming a cage around the inlet can be used if deemed necessary.

Figure 14
Siphon power station with siphon intake type II. All dimensions are given in metres.



Model	D_T	Min h_T	R	D_I	Min h_S	d_D	D_D	H_D	C	h_B	h_D
EL 7556	0.8	2.4	0.8	1.6	1.2	0.61	1.12	1.63	0.45	0.45	0.3
EL 7570	1.2	2.4-3.0	1.2	2.4	1.8	0.76	1.42	2.08	0.6	0.6	0.4
EL 7585	1.2	2.9-4.1	1.2	2.4	1.8	0.92	1.72	2.52	0.7	1.0	0.4

Auxiliary considerations for the hydroturbine station design

Net Positive Suction Head (NPSHR)
When selecting a hydroturbine , it is of crucial importance to make sure not to overlook the net positive suction head requirements of the selected hydroturbine when focusing on the highest efficiency at the rated condition (i.e. available head and flow). Where the rated condition falls close to the best efficiency point.

A hydroturbine may provide acceptable performance despite lower efficiencies, while a hydroturbine that demands more net positive suction head than the system makes available will never operate as designed. As a result, internal damage can be expected with relatively lower operational hours.

Ensuring the net positive suction head required for the hydroturbine is compatible with the net positive suction head made available by the system is a critical step in the hydroturbine selection process.

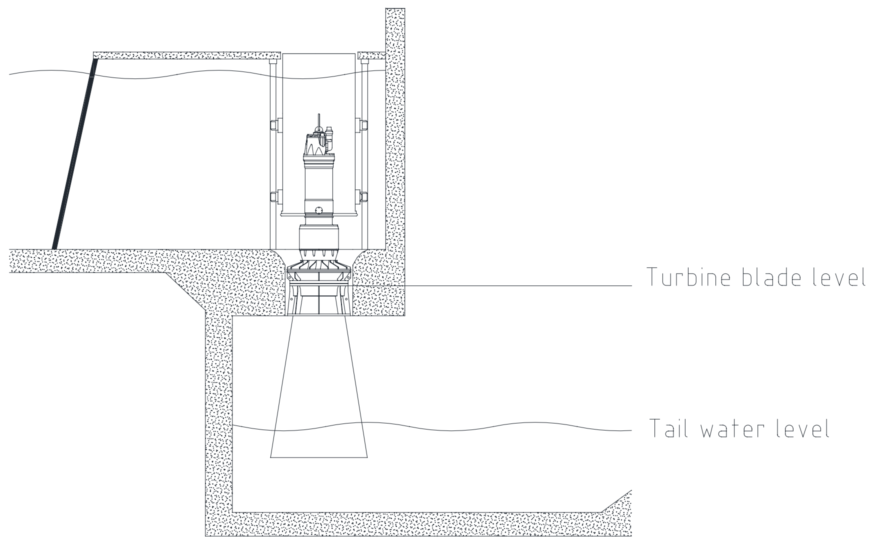
When talking about net positive suction head, there are three terms that need to be considered; Cavitation phenomenon, Net Positive Suction Head Required (NPSHR) and Net Positive Suction Head Available (NPSHA).

Cavitation is the formation of small vapor bubbles in a liquid which then collapse almost as quickly as they form. In a hydroturbine, cavitation occurs at the point of the lowest pressure which is at the outlet to the runner. When the vapor bubbles produced by cavitation collapse they generate a tremendous amount of pressure applied on a very small point. As a result, cavitation will cause significant internal damage to the hydroturbine.

NPSHA is the absolute pressure that must be present to avoid cavitation while running the hydroturbine as illustrated in Figure 15 the NPSHA is equal to the 10.132 meters minus the height difference between the tailwater level and turbine blade level. Note that NPSHA must be reduced by almost 1m per 1000m above sea level and for water temperatures above 40° C.

NPSHR varies from one turbine and blade number to the next and it also depends on the rated condition. NPSHR for each turbine is provided in its Turbine-Generator Performance Curveas. When selecting a hydroturbine the NPSHA in the hydroturbine system must be higher than the NPSHR of the turbine at all times.

Figure 15
The Net Positive Suction Head Available (NPSHA) for hydroturbine selection.



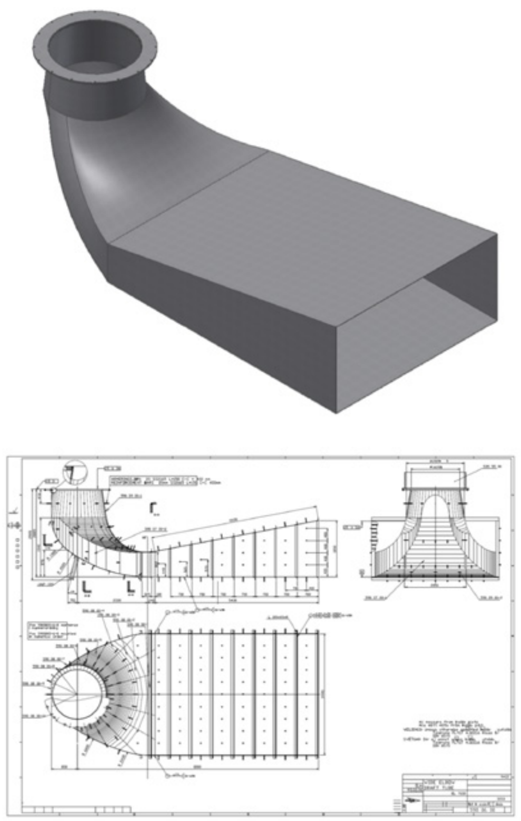
Draft tube

The draft tube is a flow diffuser used in hydroturbines that has a gradual increase in cross sectional area from its inlet to outlet. It is one of the important components of reaction turbines and connects the runner exit to tail race. The main functions of a draft tube is to convert major part of kinetic energy coming out of the runner into pressure energy. This makes it possible to install the turbine above the tail race level without loss of head The kinetic energy leaving the runner may be up to 50% of total available energy therefore the recovery of this kinetic energy in form of pressure is of vital importance. This recovery is achieved by systematically increasing the cross-sectional area of the draft tube in the flow direction.

Generally, draft tubes are designed case specifically for each power station. The most common types of draft tubes used are straight draft tubes and elbow type draft tubes. A straight draft tube consists of a conical diffuser with a half angle generally less than or equal to 10° to prevent flow separation. The elbow type draft tubes consist of an extended elbow type tube which is generally used when turbine has to be placed close to the tail race to help to cut down on the cost of excavation.

A poorly constructed functioning draft tube can lead to lower output power and thereby missing power guarantees. Xylem has designed standard draft tubes in both elbow and conical style draft tubes that suit the Flygt hydroturbines. Due to the crucial effect that draft tubes have on the hydroturbines performance, Flygt hydroturbines power production guarantee is given just when Flygt standard draft tubes are adopted for the station.

Figure 16
Illustration of a standard Flygt elbow draft tube in 3D and the manufacturing drawings.



Head losses

Water flow, as every kind of motion, requires energy. The energy is lost in overcoming the resistance to flow caused by friction at the walls of the conduit it flows within and by disturbances in the flow induced by such elements as valves, gates, bends, diffusers, etc. The loss of energy is conveniently expressed as the loss of head which is equivalent to the loss of energy per unit rate of mass flow.

The power potential of a hydroelectric power station is proportional to the flow rate and to the available head. The gross head, which is a difference in headrace and tailrace water levels, cannot be utilized in full. A part of the gross head is lost in overcoming the flow resistance. The remaining part, the gross head minus the head loss, is the useful head, or the net head.

The head loss in a complex hydraulic system, such as a power station, is computed as a sum of component losses. Each single loss is, in turn, determined as a product of a characteristic loss coefficient and the velocity head. The losses are conveniently categorized as:

1) the conduit losses
2) the local losses

The conduit losses, which apply to pipes, culverts, tunnels, and open channels, depend on the friction characteristics of the conduit and on its relative length, and is expressed as:

$$h_f = f \times \frac{L}{D} \times \frac{V^2}{2g} \quad (9)$$

in which,
f = friction coefficient for conduit
L = length of conduit
D = pipe diameter or hydraulic diameter for non-circular conduits
V = flow velocity
g = acceleration of gravity.

For the flow velocities encountered in practical applications, the friction coefficient is a function of relative roughness of a conduit only and can be calculated using Prandtl's formula:

$$\frac{1}{\sqrt{f}} = 2 \log \frac{3.71D}{k} \quad (10)$$

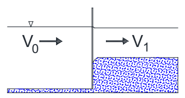
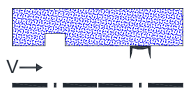
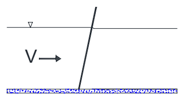
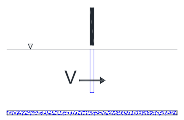
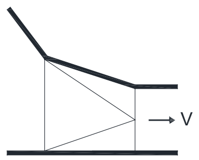
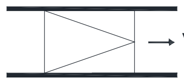
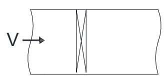
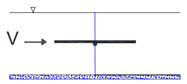
in which k is the absolute roughness (known also as equivalent sand roughness) for a particular surface finish and material of which the conduit is made. The local head loss due to such a system component as a valve or a bend depends on the geometry of the component and is expressed as:

$$h_K = K \times \frac{V^2}{2g} \quad (11)$$

in which K is the characteristic loss coefficient. The usefulness of this method stems from the universal K-coefficient, which makes it independent of the system of units. Thus, for instance, two valves of different sizes can have equal loss coefficients.

Values of loss coefficients K for a wide range of components, and k for a variety of constructional materials, are available in handbooks for hydraulic engineering. In this design brochure the loss coefficient for some of the typical structural elements used in our hydropower station set-ups are given to be used for estimating the head losses prior to the installed hydroturbine.

Table 1.
Penstock type power station

#	Component		k	h
1	Entrance		0.2-0.3	$K\frac{v_1^2 - v_0^2}{2g}$
2	Stoplog grooves		0.1-0.2	$K\frac{v^2}{2g}$
3	Trashrack (seperate chart)		0.5-0.8	$K\frac{v^2}{2g}$
4	Slide gate (open)		0.1-0.2	$K\frac{v^2}{2g}$
5	Transition-Type 1 squre to circular		0.2	$K\frac{v^2}{2g}$
6	Transition-Type 2 squre to circular		0.15	$K\frac{v^2}{2g}$
7	Penstock (seperate chart)		$f\frac{L}{D}$	$f\frac{L}{D}\times\frac{v^2}{2g}$
8	Butterfly valve (open)		0.2-0.5	$K\frac{v^2}{2g}$

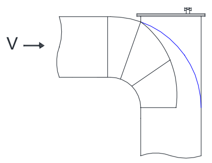
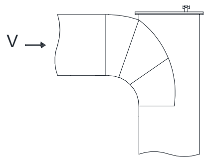
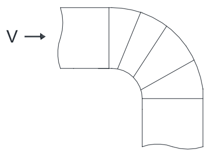
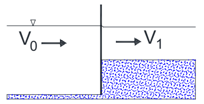
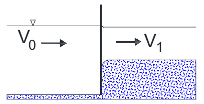
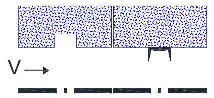
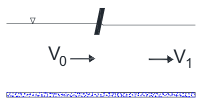
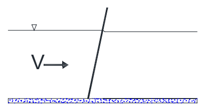
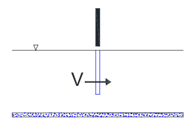
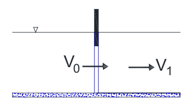
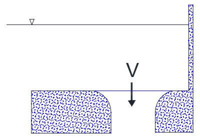
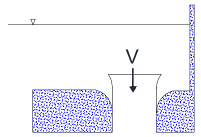
#	Component		k	h
9	Y-Junction with vane		0.7-1.0	$K\frac{v^2}{2g}$
10	Y-Junction without vane		1.0-1.5	$K\frac{v^2}{2g}$
11	Mitre bend		0.4	$K\frac{v^2}{2g}$

Table 2.
Open flume power station

#	Component		k	h
1	Entrance sharp		0.5-0.6	$K\frac{v_1^2 - v_0^2}{2g}$
2	Entrance sharp		0.2-0.3	$K\frac{v_1^2 - v_0^2}{2g}$
3	Stoplog grooves		0.1-0.2	$K\frac{v^2}{2g}$
4	Curtain wall		1.0-1.1	$K\frac{v_1^2 - v_0^2}{2g}$
5	Trashrack (seperate chart)		0.5-0.8	$K\frac{v^2}{2g}$
6	Slide gate (open)		0.1-0.2	$K\frac{v^2}{2g}$
7	Slide gate (partly closed)		1.0-1.15	$K\frac{v_1^2 - v_0^2}{2g}$

#	Component		k	h
8	Turbine tube inlet Type1		0.1-0.15	$K\frac{v^2}{2g}$
9	Turbine tube inlet Type2		0.3	$K\frac{v^2}{2g}$

Penstock:

A head loss in a close conduit entirely filled with water is expressed with equation 9.

The friction coefficient, f, as expressed earlier, depends on the relative roughness of the conduit walls, k/D given in equation 10.

For non-circular conduits, the hydraulic diameter, D, is calculated by:

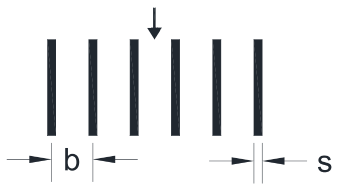
$$D = \frac{4A}{P} \quad (11)$$

Typical values of the absolute roughness, k, in millimeter for the most common materials are given below:

Table 3
Values of k for various pipe materials

Material	k (mm)
Concrete pipes:	
- new, smooth concrete and joints, steel forms	0.10
- precast pipes, good surface finish average joints	0.25
- rough concrete, average workmanship, wooden forms	1.50
Steel pipes:	
- new smooth pipes	0.05
- light rust	0.25
- heavily rusted	0.50-3.00

Figure 17
Illustration of a trashrack with approaching velocity of V, spacing of b and structural framing of s.



Recommended clearance between bars for a trashrack is b = 25 mm. Head loss due to trashrack can be calculated using the formula:

$$\Delta H = K\frac{V^2}{2g} \quad (12)$$

in which V is the mean velocity immediately upstream of the trashrack.

Values of the K coefficient for b = 25 mm with three different thicknesses and various shapes of bars are given below. If other size of bars or clearance is used, K can be calculated as:

$$K = \beta \times \left(\frac{s}{b}\right)^{4/3} \quad (13)$$

Table 4
Values of K coefficient for various trashrack configurations

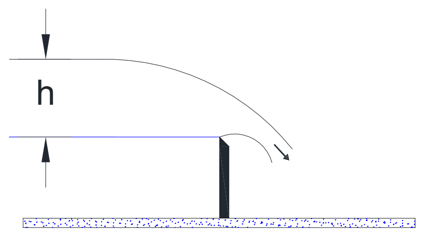
	K for b=25 mm						
S=6 mm	0.36	0.27	0.25	0.15	0.14	0.11	0.27
S=8 mm	0.53	0.40	0.37	0.23	0.20	0.17	0.39
S=10 mm	0.71	0.54	0.49	0.30	0.27	0.22	0.53
β	2.42	1.82	1.67	1.03	0.92	0.7	1.7

Approximating discharge capacities

Weirs, sluice gates and bottom outlets are the most common structures installed across open flumes in order to control the flow and widely used in designing the power stations. They are used to control water levels and prevent backward water flow for efficient water intake and waterway use and also control the outflow from the flume. In this section some simplified equations are given in order to approximate their discharge capacities and estimate their performance.

Figure 18a
Discharge over a sharp-crested weir.

Sharp-crested weir

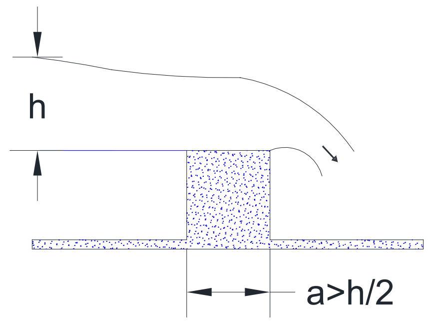


$$Q = mb\sqrt{2g}h^{3/2}$$

$$m = 0.4 - 0.5$$

Figure 18b
Discharge over a broad-crested weir.

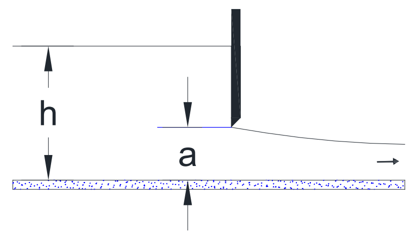
Broad-crested weir



$$Q_{max} = 0.38b\sqrt{2g}h^{3/2}$$

Figure 18c
Discharge through a sluice gate.

Sluice gate



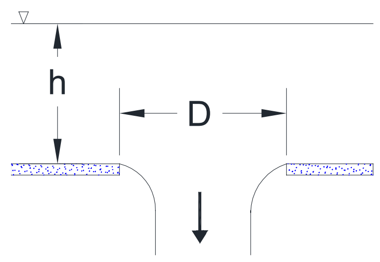
$$Q = mab\sqrt{2gh}$$

$$m = 0.6 \; if \;\; a/h < 0.1$$

$$m = 0.5 \; if \;\; a/h > 0.5$$

Figure 18d
Discharge through a bottom outlet.

Bottom outlet



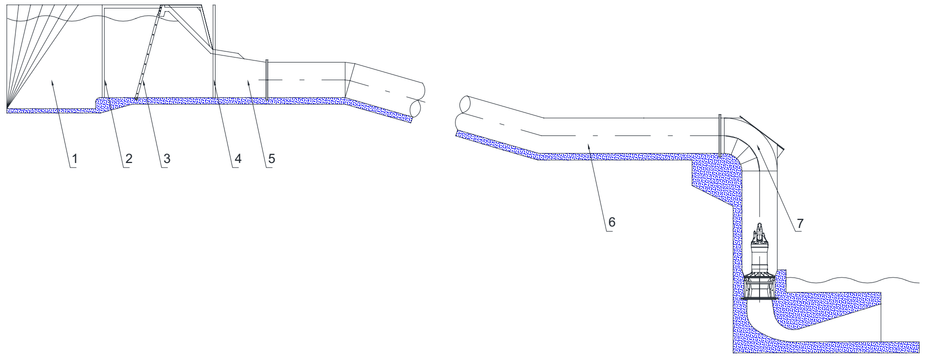
$$Q = 0.6A\sqrt{2g(h + D/2)}$$

$$A = \pi D^2/4$$

Examples

Example 1
– Penstock-type power station
The power station consists of an intake designed as the Intake 1, a 100 meter long concrete penstock, and a penstock-column 1. The station has a hydroturbine EL 7585/51-56-8, one of which has adjustable blades. As the maximum flow is the same for both turbines, only one calculation of the losses is necessary. The maximum flow for each turbine/combined , check is Q = 4 m3/s. The head losses are computed in the flow direction beginning with the entrance. (All data in SI units).

Figure 19
Penstock-type power station losses prior to the turbine



1. Entrance

$$A_0 = 2.8\times2.4 = 6.72\ (m^2)\ V_0 = {}^{Q}/_{A_0} = 0.6\ (ms^{-1})$$

$$A_I = 2.5\times2.0 = 5.0\ (m^2)\ V_I = 0.8\ (ms^{-1})$$

$$h_I = K\times\frac{V_I^2 - V_0^2}{2g} = 0.2\times\frac{0.8^2 - 0.6^2}{2g} = 0.003(m)$$

2. Stoplog grooves

$$A = 2.5\times2.0 = 5.0\ (m^2)\ V = 0.8\ (ms^{-1})$$

$$h_2 = K\times\frac{V^2}{2g} = 0.1\times\frac{0.8^2}{19.6} = 0.003(m)$$

3. Trasbrack

$$A = 5.0\ (m^2)\ V = 0.8\ (ms^{-1})$$

$$h_3 = K\times\frac{V^2}{2g} = 0.7\times\frac{0.8^2}{19.6} = 0.023(m)$$

4. Slide gate

$$A = 1.8\times2.0 = 3.6\ (m^2)\ V = 1.11\ (ms^{-1})$$

$$h_4 = 0.1\times\frac{1.11^2}{19.6} = 0.006(m)$$

5. Transision

$$A = \frac{3.14\times1.4^2}{4} = 1.54\ (m^2)\ V = 2.6\ (ms^{-1})$$

$$h_5 = 0.2\times\frac{2.6^2}{19.6} = 0.069(m)$$

6. Penstock (D=1.4 m)
Precast pipes, average joints k=0.25 mm

$$\frac{D}{k} = \frac{1400}{0.25} = 5600 \rightarrow f = 0.0134$$

$$A = 1.54(m^2)\ V = 2.6\ (ms^{-1})$$

$$h_6 = f\times\frac{L}{D}\times\frac{V^2}{2g} = 0.0134\times\frac{100}{1.4}\times\frac{2.6^2}{19.6} = 0.330(m)$$

7. Y-junction with vane

$$A = 1.54(m^2)\ V = 2.6\ (ms^{-1})$$

$$h_7 = 0.7\times\frac{2.6^2}{19.6} = 0.241(m)$$

The total head loss:

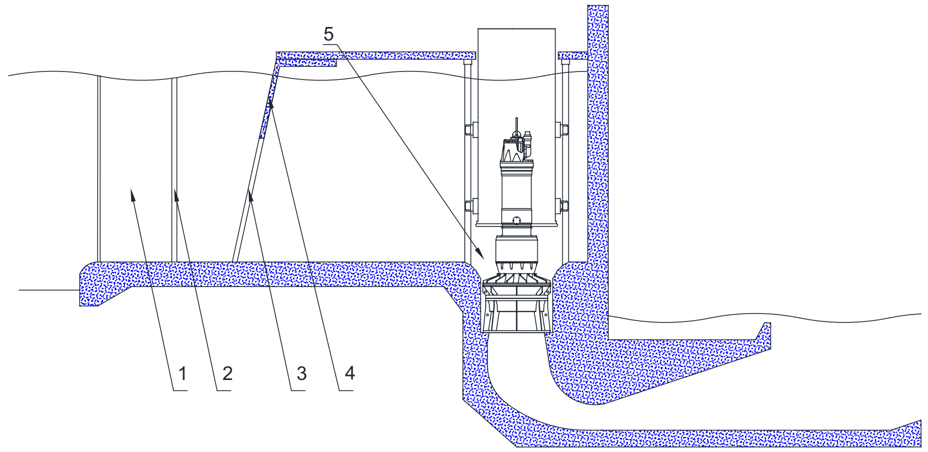
$$h = \sum_{i=1}^{7} h_i = 0.003 + 0.003 + 0.023 + 0.006 + 0.069 + 0.330 + 0.241 = 0.675\ (m)$$

The total head loss is 0.675 m and is dominated by the loss in the penstock and the Y-Junction.
Note: The head loss in the draft tube is accounted for in the Hydroturbine Performance Curve.

Examples

Example 2
– Open flume power station
The power station is designed as the open flume I and is furnished with EL 7585/51-56-8. The maximum flow is Q = 4 m_3/s. (All data in SI units)

Figure 20
Penstock-type power station losses prior to the turbine



1. Entrance

$$A_0 = 4.5\times3.0 = 13.5\ (m^2)\ V_0 = {}^{Q}/_{A_0} = 0.3\ (ms^{-1})$$

$$A_I = 4.0\times2.4 = 9.6\ (m^2)\ V_I = 0.42\ (ms^{-1})$$

$$h_I = K\times\frac{V_I^2 - V_0^2}{2g} = 0.2\times\frac{0.42^2 - 0.3^2}{19.6} = 0.0009(m)$$

2. Stoplog grooves

$$A = 9.6\ (m^2)\ V = 0.42\ (ms^{-1})$$

$$h_2 = K\times\frac{V^2}{2g} = 0.1\times\frac{0.42^2}{19.6} = 0.0009(m)$$

3. Trasbrack

$$A = 3.7\times2.4 = 8.9\ (m^2)\ V = 0.45\ (ms^{-1})$$

$$h_3 = K\times\frac{V^2}{2g} = 0.7\times\frac{0.45^2}{19.6} = 0.007(m)$$

4. Curtain wall

$$V_1 = \frac{Q}{bh_1} = \frac{4.0}{2.4\times3.7} = 0.45(ms^{-1})$$

$$V_2 = \frac{Q}{bh_2} = \frac{4.0}{2.4\times4.0} = 0.417(ms^{-1})$$

$$h_4 = \frac{V_I^2 - V_0^2}{2g} = \frac{0.45^2 - 0.417^2}{19.6} = 0.002(m)$$

5. Turbine tube inlet

$$A = \frac{\pi}{4}(D_T^2 - D_G^2) = \frac{3.14}{4}\times(1.2^2 - 0.64^2) = 0.81\ (m^2)\ V = 4.94\ (ms^{-1})$$

$$h_5 = 0.1\times\frac{4.94^2}{19.6} = 0.135(m)$$

The total head loss:

$$h = \sum_{i=1}^{5} h_i = 0.0009 + 0.0009 + 0.007 + 0.002 + 0.135 = 0.149\ (m)$$

The head loss is about 0.15 m and is dominated by the loss at the turbine inlet.
Note: The head loss in the draft tube is accounted for in the Hydroturbine Performance Curve.

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