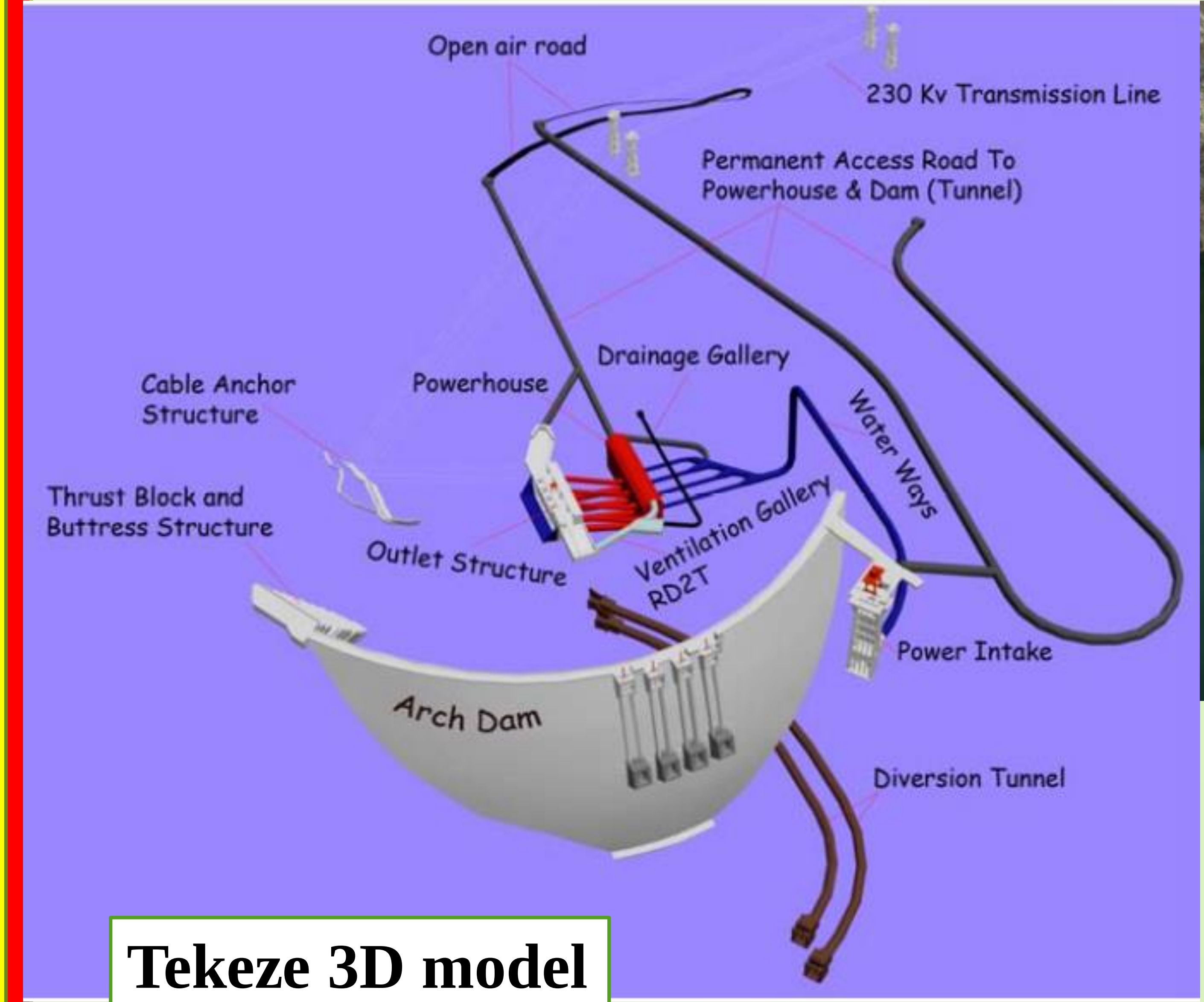
Chapter 4: Design of Hydropower Plants



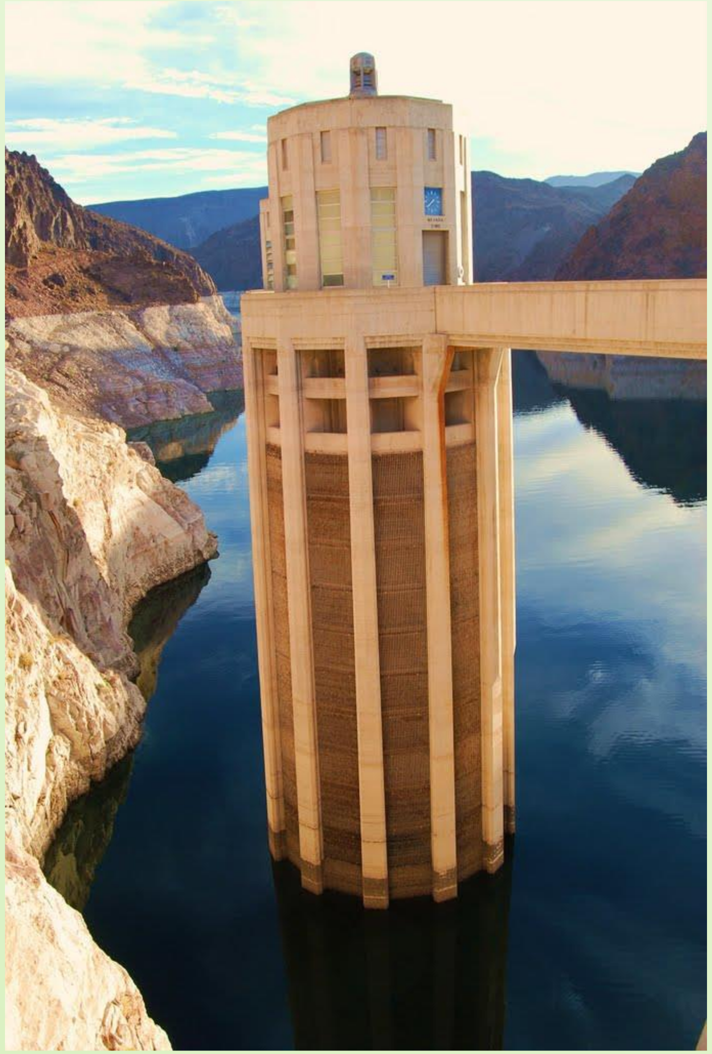
Tekeze 3D model

Arch Dam upstream view

Design of Civil Structures

Intakes

- The intake structure (or head regulator) is a hydraulic device constructed at the head of power canal, or a tunnel conduit through which water is withdrawn from the reservoir.
- In high-head structures the intake can be either an integral part of a dam or separate;
- In the form of a tower with entry ports at various levels which may aid flow regulation when there is a wide range of fluctuations of reservoir water level.



Functions of Intakes

- To control flow of water in to the conveyance system. The control is achieved by a gate or a valve.
- To provide smooth, easy and vortex or turbulence free entry of water in the conveyance system which is to minimize head loss.
- To prevent entry of coarse river born trash matter such as boulders, logs, tree branches etc.
- To exclude heavy sediment load of the river from entering the conveyance system.

Types of Intakes

- Run -of -river intakes
- Dam intakes
- Tower intakes
- Shaft intakes
- Intakes of special type

Run -of -river intakes

These are low head intakes which lead water into the diversion canals.

•The inlet invert level of the intake is raised to form a sill so as to prevent entry of rolling bed load into the canal

•A skimmer wall (a diaphragm which extends below the water surface) abstracts the floating material from interring into the canal

•Trash rack is provided at the entrance and may be equipped with either manual or automatic power-driven rack cleaning devices

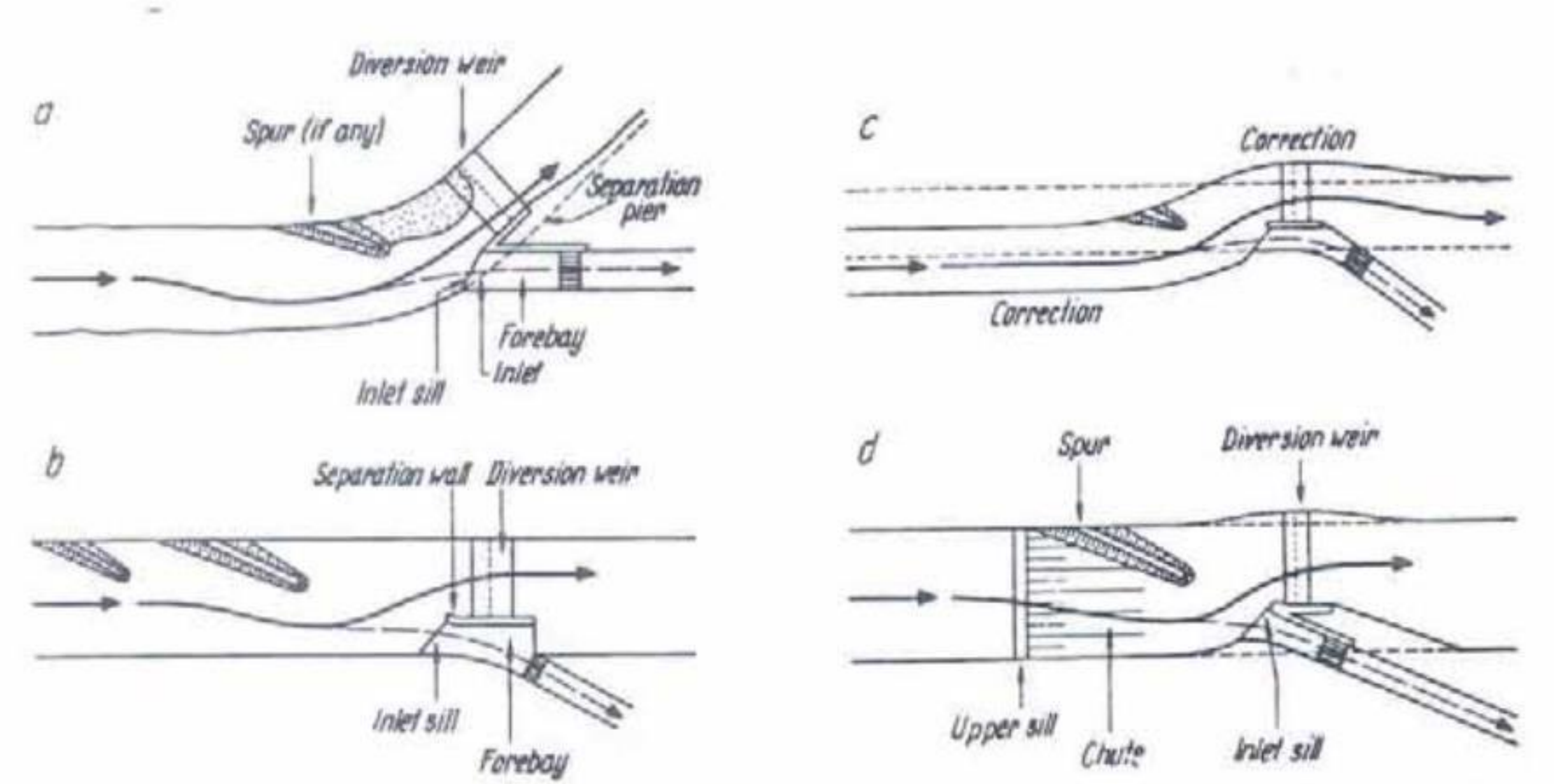


Fig. 2/78. Typical layouts for intake a) in bends, b), c), d) on straight stretches. (After R. Müller)

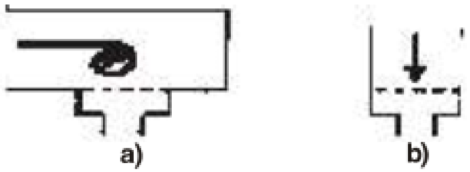
Location and Orientation of Run -of -river intakes

An intake structure leads river water into a waterway, and is designed to meet the following conditions.

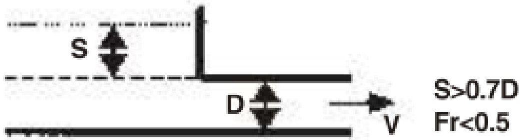
- The maximum plant discharge is taken in constantly and is adjusted as required.
- The head loss is small.
- Inflow is smooth and does not have any air intrusion vortex
- Sediment, driftwood, leaves, etc. do not flow into the intake.
- The intake is not susceptible to damage due to flooding or landslide.
- Maintenance work after completion is easily carried out.

The following criteria should be observed to achieve the above objectives:

1. Intake approach should be symmetrical to avoid vorticity and to minimise entry head loss;



2. Submergence depth should be more than 70 percent of the intake pipe diameter to avoid entry of air pockets and vorticity;

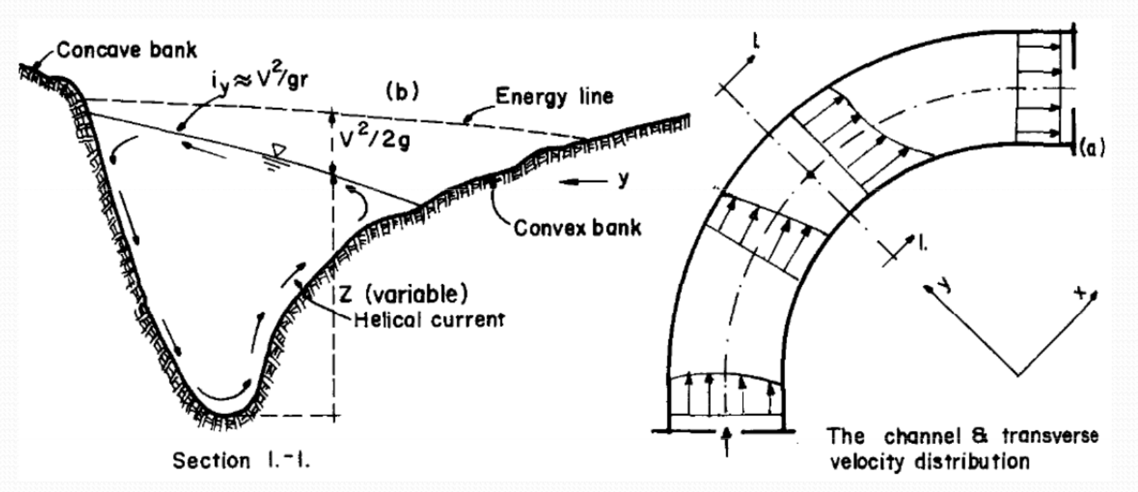


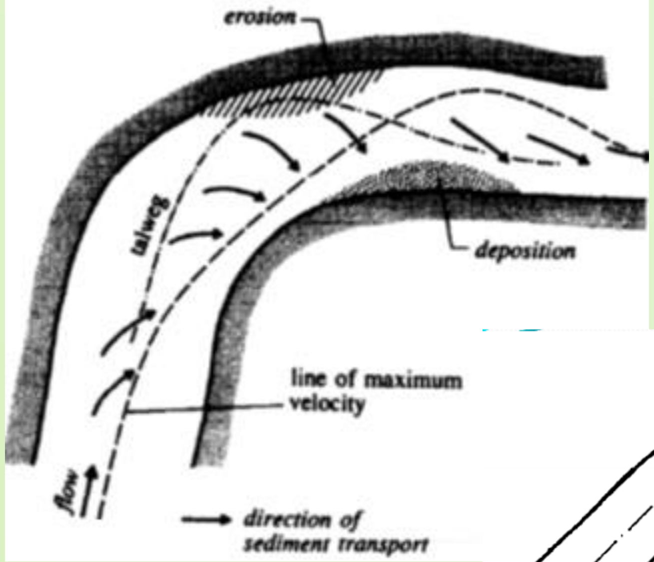
3. Off take from straight reach to be avoided, better coerce water to follow curved path to avoid larger entry of silts;

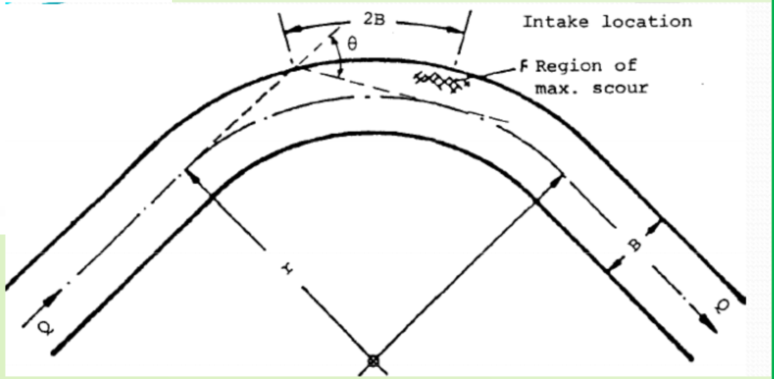
Off take should preferably be located on concave side near the end of the curved stretch to avoid larger entry of silts;

Angle of diversion should be 20° to 30° , if discharge ratio =0.2 to 0.3 & 45° to 60° & if discharge ratio = 1.0 larger entry of silt to be avoided. :

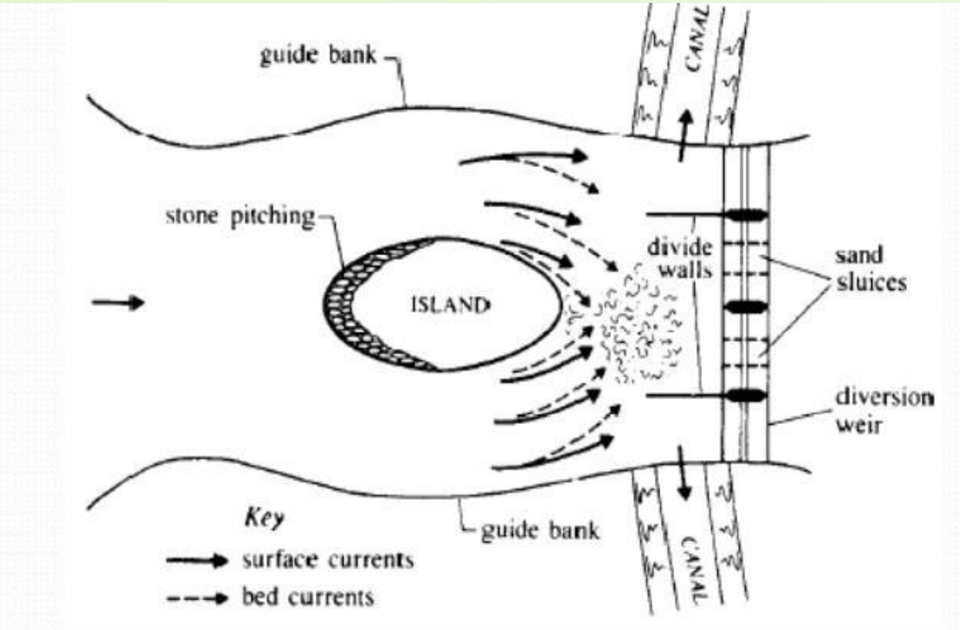
Smooth flow transition should be ensured to minimise entry head loss. A sudden acceleration or deceleration of the flow generates additional turbulence with flow separation and increases the head losses.



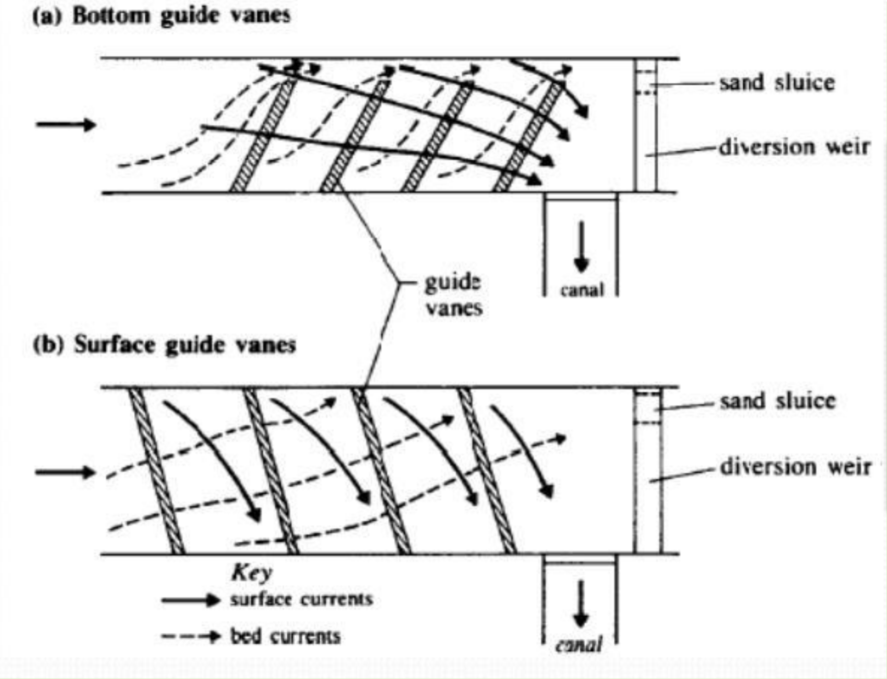




- The secondary current near the bed, transports sediment away from the region and draws in water from the top layers where the sediment concentration is relatively low.
- Since the sediment concentration is highest at the bed the water diversion structure should be located where the flow near the bed is away from the intake.
- Such conditions occur at river bends where the spiral (helicoidal) current carries sediment towards the inner bank away from the outer bank.
- In straight channel reaches an artificial bend, a groyne island or guide vanes may be designed to cause the required curvature of flow



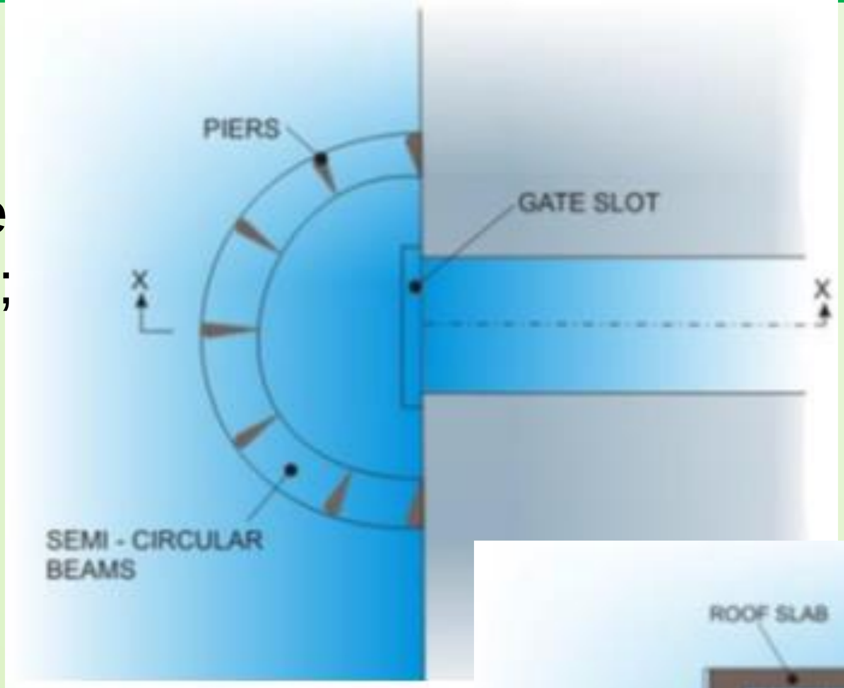
Use of artificial groyne (e.g. island) to induce desired curvature to flow at intakes



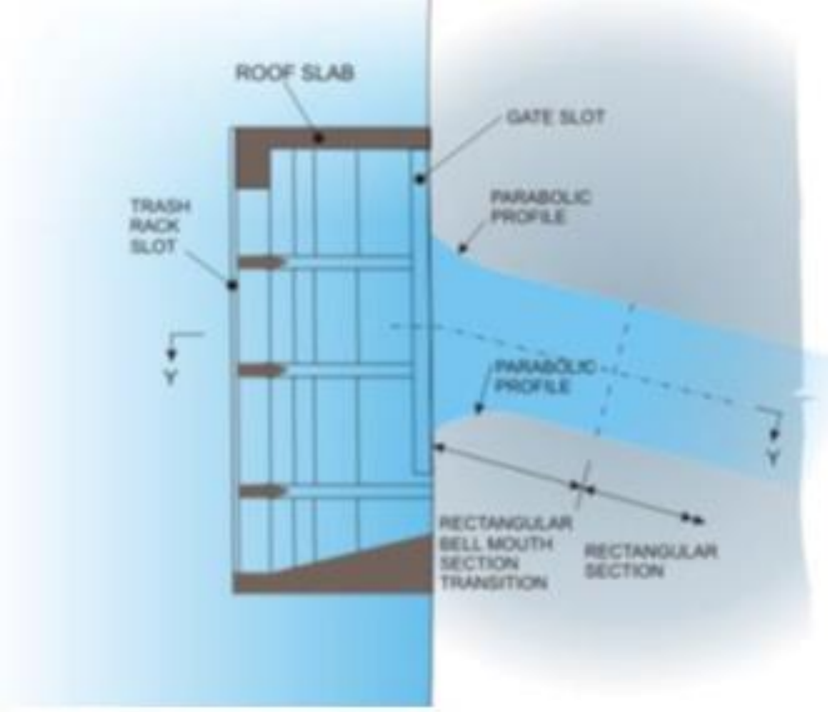
Guide vanes layouts upstream of intake for sediment exclusion

Dam intakes

- For valley dam plants, the intake structure is provided usually in the body of the dam;
- The penstocks are embodied in the dam
- The main features of such an intake are:
  - ➢a trash rack structure in front of the dam,
  - ➢a bell mouth inlet horizontal or inclined alignment,
  - ➢control gate installed either at or after the bell mouth,
  - ➢Cage-shaped intakes resting against the face of the dam and supported on slab cantilevered from the dam provide larger area of entry than the penstock intake area thus reducing entrance losses



Intake from a reservoir upstream of
(b) Sectional plan Y - Y.



Intake from a reservoir upstream of a storage dam
(a) Sectional elevation X - X.

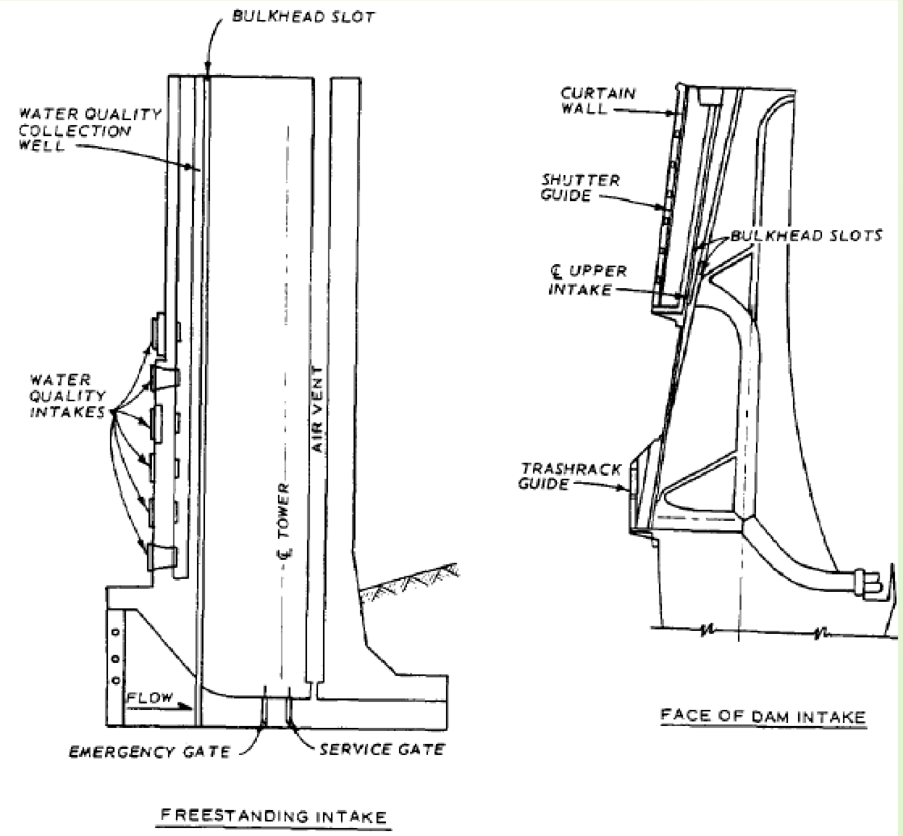
Tekeze Dam intake structure

Free-standing/ Tower intake structure

- The most common type of intake structure is the vertical structure, generally referred to as a free-standing intake tower.
- It allows increased flexibility when locating the outlet works at the site.
- The vertical tower is usually more economical and easier to layout than the inclined intake structure.
- Conduits and openings, operating equipment, and access features lend themselves more readily to arrangement in the vertical structure.
- A service bridge provides access to the top of the structure.

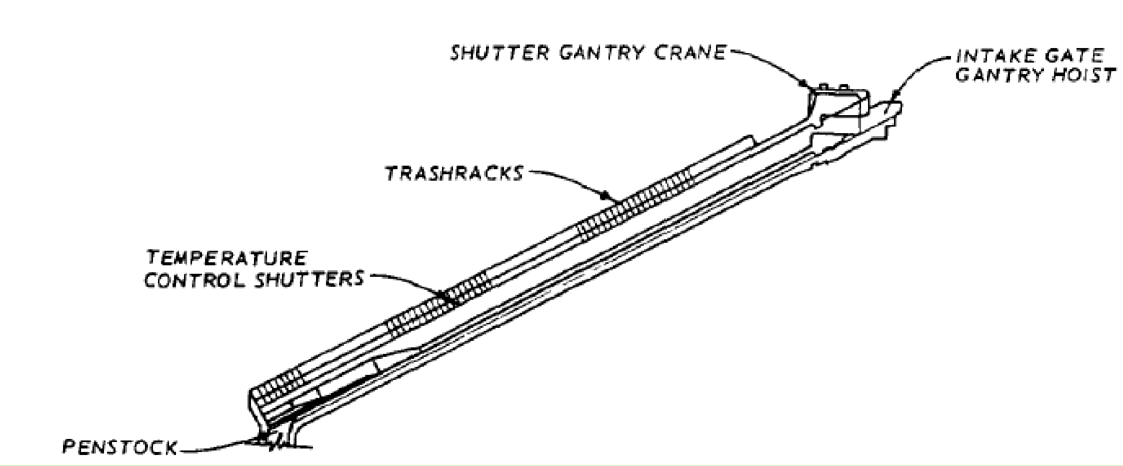
Intake structures fall into three general types

(a) inclined intake on a sloping embankment; (b) freestanding intake tower, usually incorporated into the flood control outlet facilities of embankment dams; and (c) face-of-dam intake, constructed as an integral part of the vertical upstream face of a concrete dam



Inclined intake structure

- For higher embankment dams in high seismic risk areas where a vertical structure may not be feasible, an inclined intake structure supported against the abutment is an alternative for consideration.
- An inclined structure has the advantage of increased stability over a vertical structure.
- In high seismic locations and on steep abutment slopes, anchoring of the structure to the abutment to maintain stability and prevent liftoff should be investigated.



Design of intakes

- There are no standard designs for intake structures.
- Each design is unique and may take on many forms and variations.
- Design depends on a number of considerations including site conditions, economics, and effectiveness in meeting project requirements.
- Project requirements can include reservoir operating range, drawdown frequency, discharge range, trash conditions and required frequency of intake cleaning, water quality, and environmental requirements such as fish passage.
- It is designed such that the following points are complied, as far as possible:
  - There should be minimum head loss as water enters from the reservoir behind a dam or the pool behind a barrage into the water conducting system.
  - There should not be any formation of vortices that could draw air into the water conducting system.
  - There should be minimum entry of sediment into the water conducting system.
  - Floating material should not enter the water conducting system.

Design considerations and criteria

The intake structure size and configuration are based on:

- wells size,
- control gate passages,
- inlet hydraulic configuration,
- exit passages, and
- clearance requirements for the mechanical and electrical equipment.

Design criteria

Water levels

- The intake structures should be designed in order to function for different water levels.
- The efficiency of the structure should be checked for the normal and extreme levels.

Placement distance

- The distance between the intake structure and the powerhouse increases the hydraulic losses and increases the cost of the conveyance structures.
- Thus , most of the powerhouses should be constructed near the dam or the diversion structure in order save water head, while the intake structures is placed on the lowest point of the reservoirs.

Geology

- The intake should be located in a reach of river where the bank is stable
- If possible, the intake should be located at a site possessing
- favorable foundation conditions to minimize costly treatment.

Diverted flow orientation

- Intakes are generally oriented to minimize separation of flow and formation of swirl, eddies, and vorticity which may entrain air.
- Where the rate of withdrawal is small and the intake mouth is relatively deeply submerged, flow separation, vorticity, and air entrainment are less likely to occur.

Sediment

- Intakes in reservoirs should be placed above the computed sediment deposit of the design period of the structure.
- Sediment accumulation in the intake approach causes higher approach velocities, increased head losses, and flow separation.
- The passage of sediment through the unit may result in wear of the turbine runner

Siting

Selection of the location for an intake structure depends on:

- foundation conditions,
- alignment of conduit, and
- tunnel access.
- For an embankment dam, the structure is often located adjacent to a hillside into which the outlet works pass.
- A cut-and-cover-conduit, the structure is generally located at the upstream toe of the embankment dam.

Locations of control gates

- The control gates are usually located in the intake structure, in a shaft or gate chamber.
- Under special conditions, the control gates may be located at the downstream end of a pressure tunnel.

Control gates at upstream end

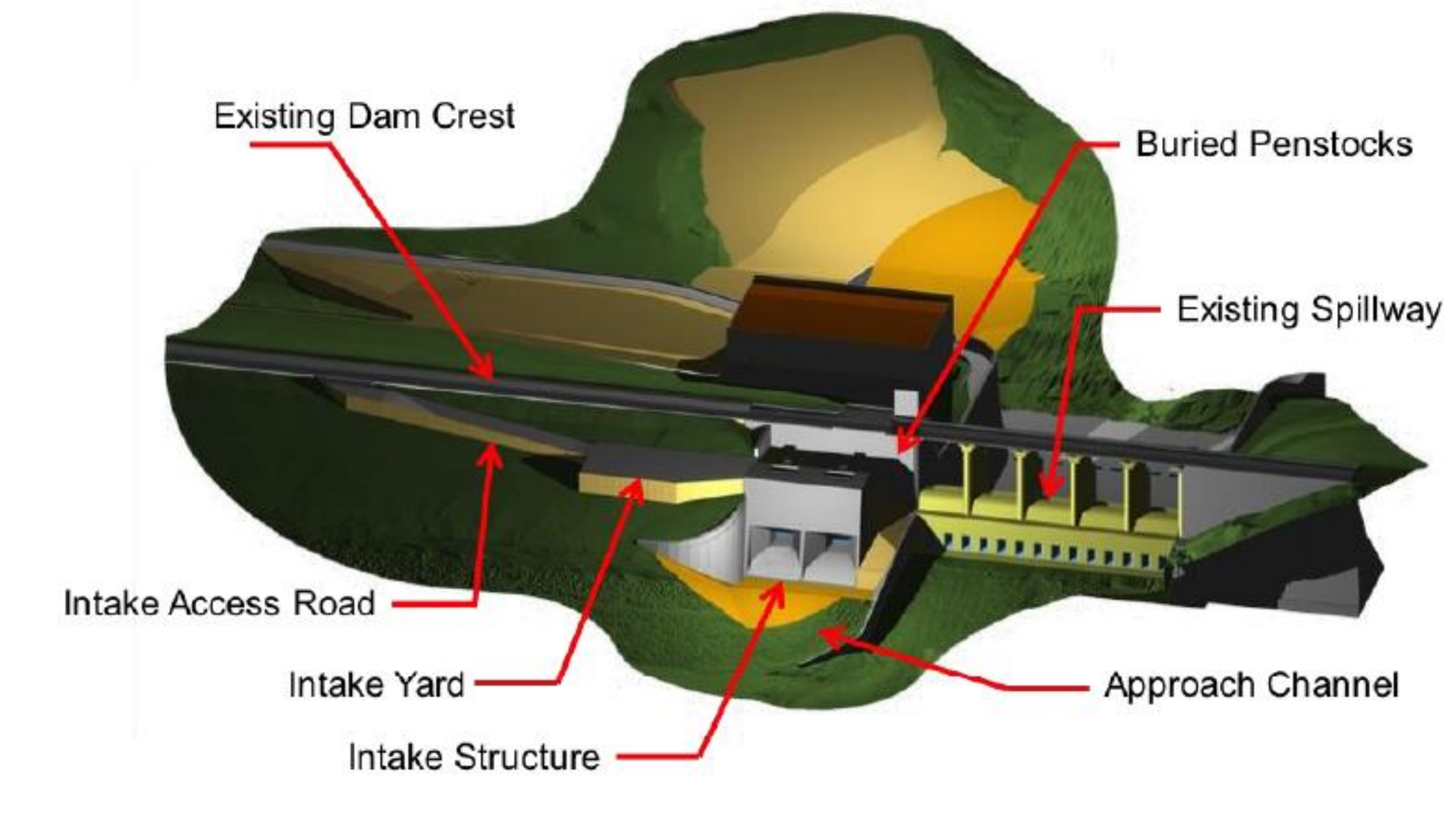
- When the gates are placed at the upstream end of the outlet works, the emergency gates, bulkheads, service gates, and trash rack are all combined into a single structure.
- Closing of the gates allows for inspection and repair of the entire tunnel and to readily removing accumulated trash, sediment, or other deposits.
- A disadvantage with upstream control gates is the cost of extending the structure above the pool and requiring an access bridge.

Intake structure shape

Rectangular

- Are more functional for low-head reservoirs that are designed for large discharges.
- Provide for more efficient layout of entrances and openings, gates and operating equipment, and other features.
- Rectangular intake structures are usually more easily constructed and site-adaptable.

Intake structure shape



Circular

- Circular intake structures are structurally more efficient, providing economic savings, particularly in high-head projects.
- The lower section of the structure may be rectangular to provide arrangement of the water intakes, trash racks, and bulkheads.

Octagonal

- The tower cross-section can also be of an octagonal shape.

Irregular

- An irregular design may result in the development of very complex and unusual shapes.

Intake towers

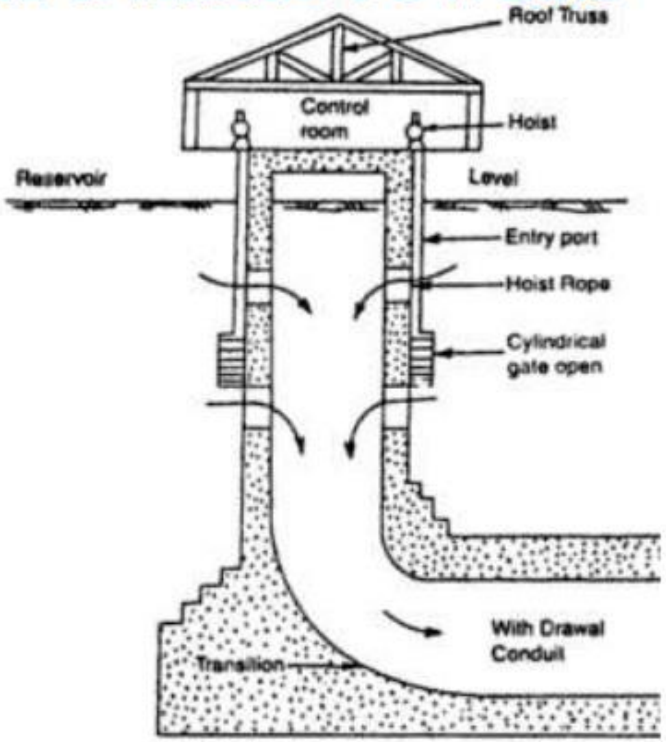
Wet intake tower

- A Wet intake is a type of intake tower in which water level in the tower is the same as the reservoir water level and has a vertical inside shaft connected to the withdrawal conduit
- Opening s are made into the outer concrete shell as well as into the inside shaft

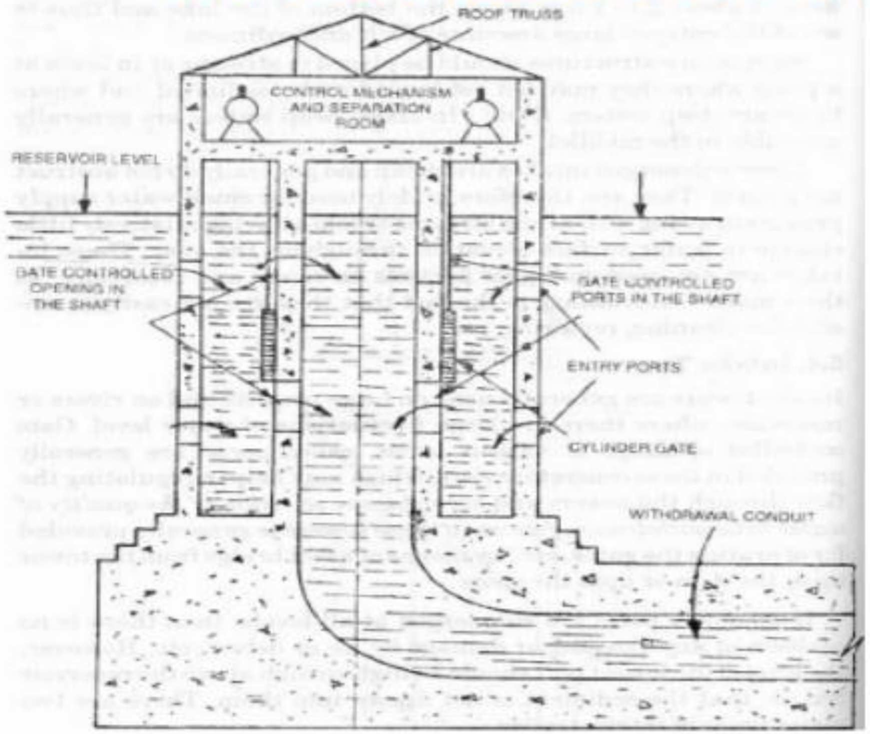
Dry intake tower

- Water enters through entry port directly into the conveyance
- When the entry ports are closed, a dry intake tower will be subjected to additional buoyant forces
- Hence it must be of heavier construction than wet intake tower
- Costlier than wet intake since it is heavy to balance buoyant force acting on it.
- Its main advantage that water can be withdrawn from any selected level.

DRY INTAKE TOWERS

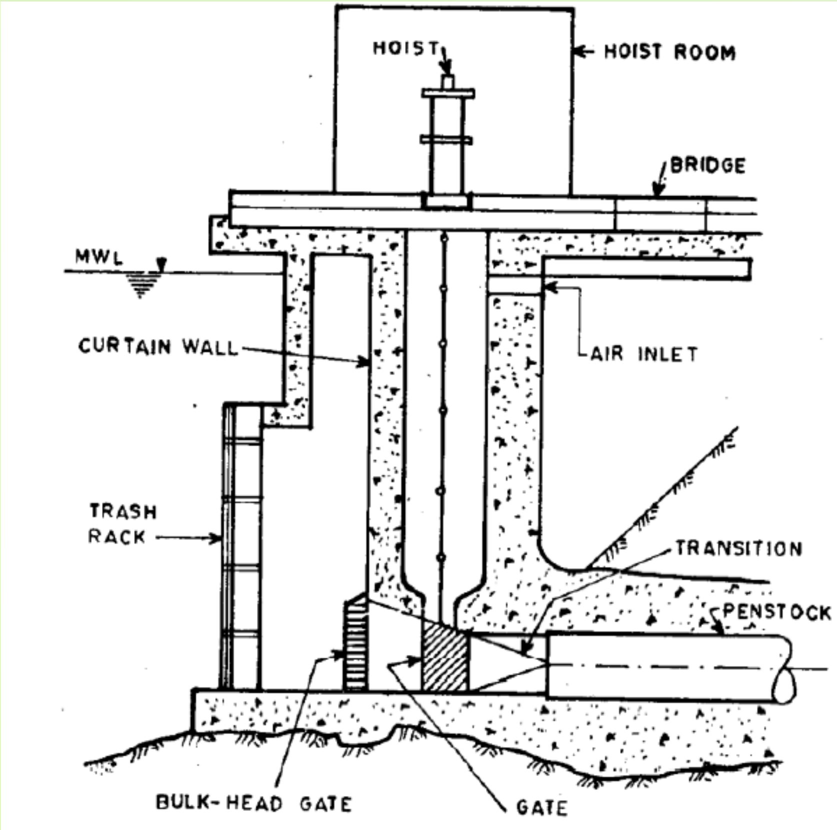


WET INTAKE TOWERS

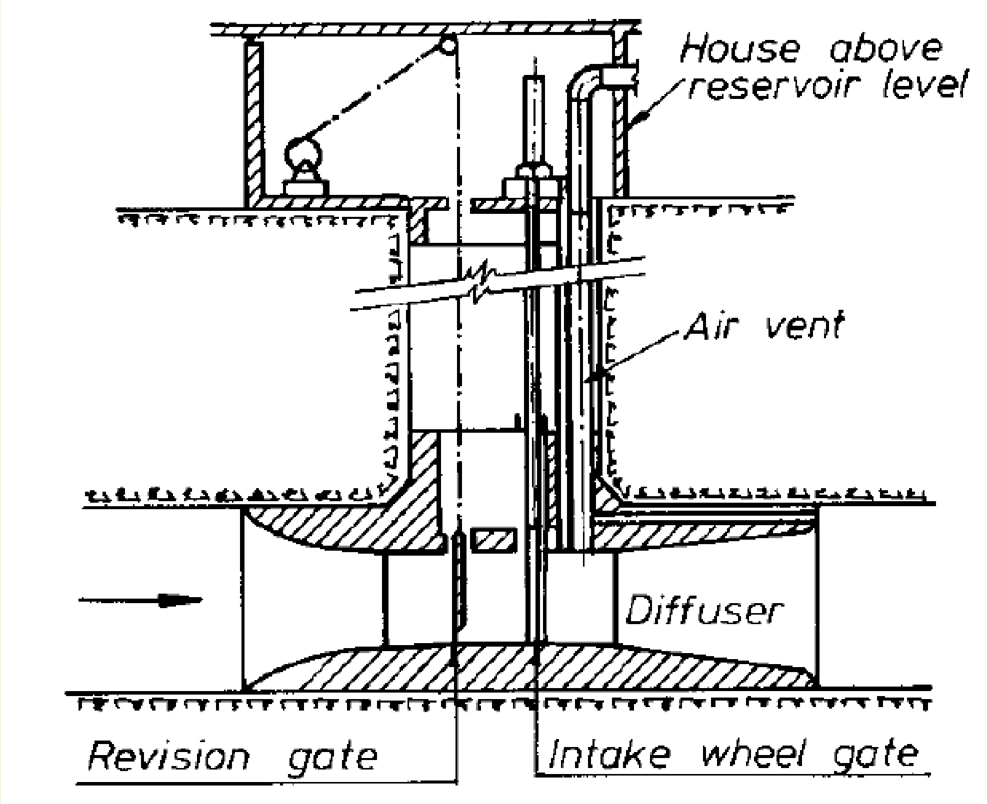


Intake Tower Design Considerations

- After all the purposes of the project are established and the functions and criteria for the outlet works have been clearly defined, the geometry and layout of the intake tower can proceed.
- Multiple alternatives should be developed and evaluated to determine the optimum plan.



Tower Intakes



Shaft Intake

Setup

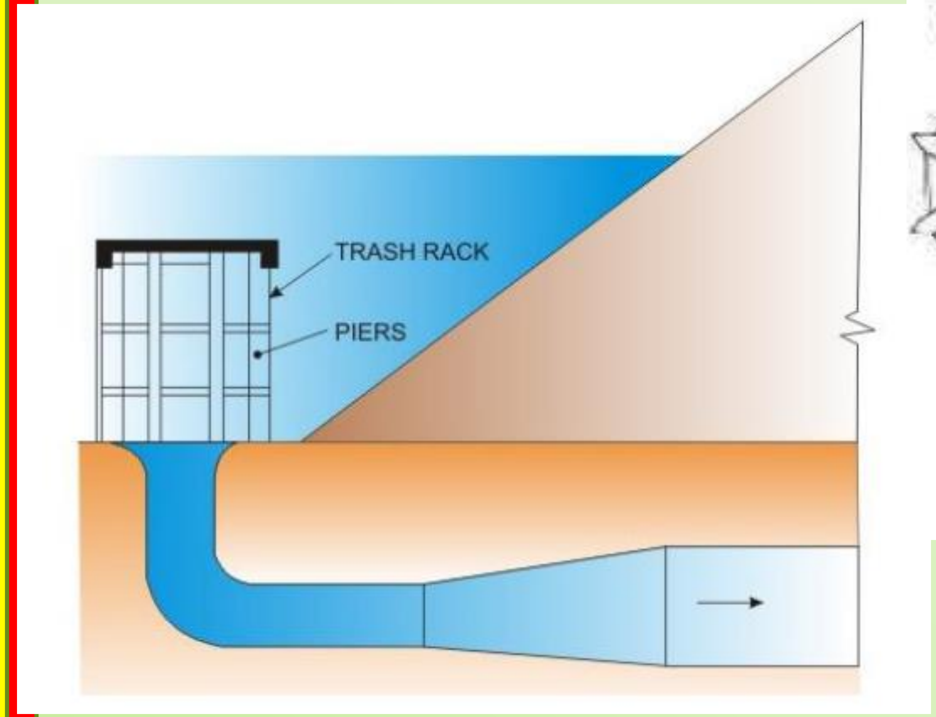
- The entrance floor will hold all the gate lifts including electrical motors, the instrumentation terminals, cranes, working space, storing space, etc.
- The water supply from the intake tower will be started only after the water level is well be above the lower 3 gates, which will be then opened and the tower allowed to fill with water to ensure that the water impact is minimum on the floor and walls of the tower.

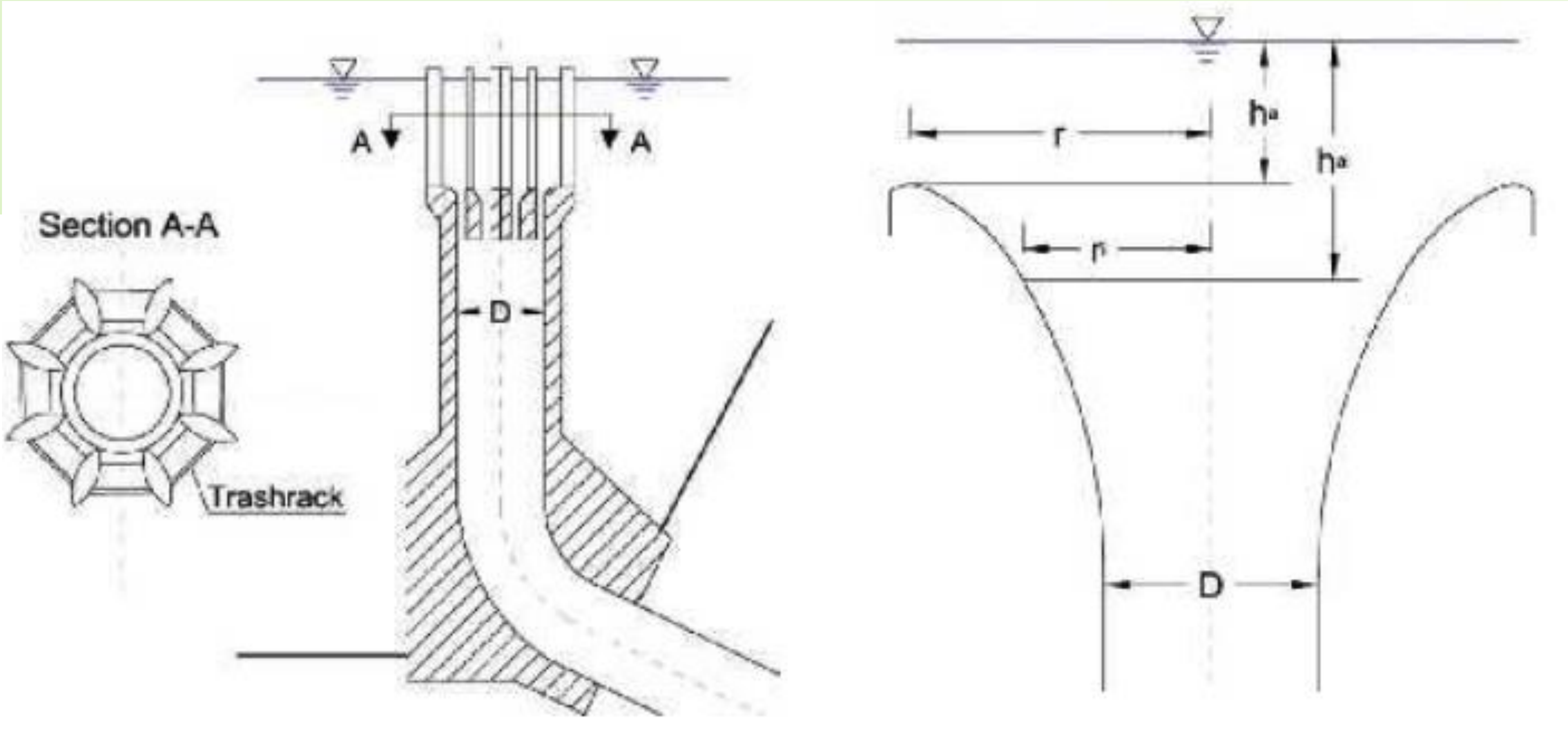
Shaft/ Glory Hole intake

- This is a vertical or a near-vertical shaft, driven at the reservoir site that carries water to the penstock tunnel reservoir site that carries water to the penstock tunnel feeding the power house.
- 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.

Shaft/ Glory Hole intake

- The main criteria for the structural dimensioning is the minimization of the hydraulic losses and the avoidance of eddies.





- Hydraulic losses caused by the vertical intakes:

$$h_L = K\frac{V^2}{2g}$$

- Where h_L is hydraulic losses of the entrance section and
  V is velocity flow in the penstock
  K the loss coefficient which varies from 0.1 up to 0.3

The equation for the entrance shape which is derived from laboratory tests is (ASCE, 1995): $R_L = 0.204\frac{Q^{0.5}}{h_a^{0.25}}$

- Where Q is discharge (m^3/s) and h_a is distance between the water surface and the point where we want to determine the radius (m).

- The hydraulic losses from the trash racks depend on the thickness of the rods and the distance between them.

$$h_{lt} = K_t\frac{v_n^2}{2g}$$

- Where h_{lt} is trash rack loss
  v_n velocity through the net trashrack area (m/s)
  K_t trash rack loss coefficient

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

- Where a_n is net area through rack bars (m^2) and a_g is gross area of the racks and supports (m^2)

Conduit entrance

- In most cases conduit entrance should be rounded or bell mouthed to reduce hydraulic entrance losses.
- If square-edged entrance is provided separation of flow is more likely to take place and the consequent danger of cavitation.

The shape of the bell mouth is generally elliptical, and is given by:

- For circular conduits

$$4x^2 + 44.4y^2 = d^2$$

- For rectangular conduits or tunnels

$$x^2 + 10.4y^2 = d^2$$

Where x, y = coordinates of any point on the curve

d = diameter of circular conduit (for circular)

or

d = width or high of conduit, depending on whether the sides or top & bottom curve is being designed.

Control gates

- The control gates located in each gated passage to the outlet tunnel or conduit generally consist of an emergency gate followed by a service gate.

Service gates

- Service gates are used for flow regulation, and one gate is required for each water passage.
- For low-and medium-head conditions, the type of gate may be a tractor (mechanically or hydraulically operated), hydraulically operated slide gate, or hydraulically operated tainter gate.
- For high-head conditions, hydraulically operated slide gates are generally preferred for long periods of operation at partial gate openings.

Emergency gates

- Emergency gates should be located within the intake structure immediately upstream of the service gates.
- Emergency gates are required in reservoirs having water conservation, power, or a similar type pool to prevent loss of stored water if a service gate is inoperable.
- Emergency gates must be designed to withstand the maximum reservoir head.

Trash Racks

- A trash rack intercepts the entire flow and removes any large debris, whether it is floating, suspended, or swept along the bottom.
- Frequently, it is located in the intake structure to prevent debris from entering the water conveyance system.
- A design approach velocity of 0.5 m/s is usually used.
- If a trash rack is located immediately in front of the inlet to a penstock and the penstock velocities are significantly higher than 0.5 m/s, the trash rack can be built in a circular area to increase the area of the trash rack and correspondingly decreases velocity through it.
- The trash rack is usually placed vertical or near vertical (< 25° from the vertical).
- The trash rack loss may be taken as 0.03, 0.09, and 0.15m for the velocities of 0.3, 0.45, and 0.6m/s respectively.

Velocity Through Trash Racks

Velocity should be sufficiently low to avoid high head loss and should be sufficiently high to avoid large intake and trash rack cross section. The following are suggested limiting entrance velocities:

i) Justin and Creager formula:

$$V \leq 0.12\sqrt{2gh}$$

h = head from center line of gate to normal water surface

ii) Mosonyi's formula to eliminate eddies and vortices:

$$V \leq 0.075\sqrt{2gh}$$

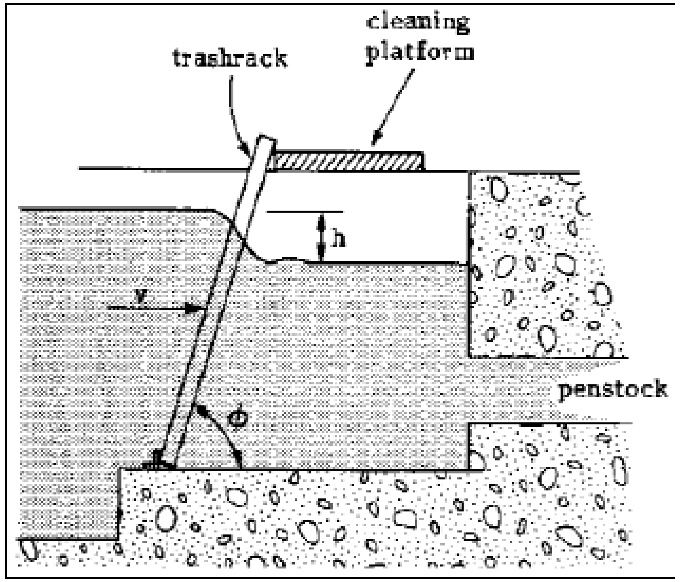
iii) U.S.B.R's criterion: permissible velocity in the range of 0.6 to 1.5 m^3/s

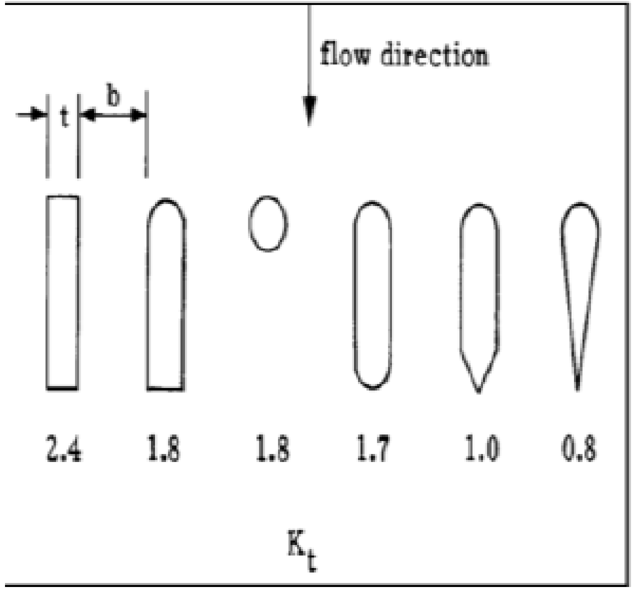
Rack Losses

- There are numerous expressions available for predicting head loss across trash racks. One such expression (*after Kirschmer's*) is:

$$\Delta h_r = K_t \left(\frac{t}{b}\right)^{4/3} \frac{V_a^{\ 2}}{2g} \sin\phi$$

Where, K_t is trash rack loss coefficient (a function of bar shape), t is bar thickness, b is spacing between bars, V_a is approach velocity, and ϕ is angle of inclination of bars with the horizontal

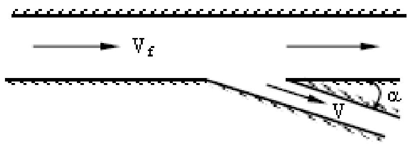




Entrance Losses

- Loss due to change in direction is given by:

$$\Delta h_e = \frac{V^2}{2g} - C\frac{V_f^2}{2g}$$



Where:

V is velocity in the diversion canal

V_f is velocity of flow in the main river

C is a constant which depends on the off-take angle of the diversion canal.

According to Mossonyi, C is equal to 0.8 for 30^0 off-take angle and 0.4 for 90^0 off-take angle.

- The losses due to sudden contraction of the area at the inlet section is given by:

$$\Delta h_e = K\frac{V^2}{2g}$$

Where K is a constant, which depends on the shape of the entry.

K=0.03 for bell-mouthed entry

K=1.3 for sharp cornered entry.

V = the velocity in the conduit just d/s of the entrance.

Gate Losses

$$\Delta h_g = \frac{1}{2g}\left(\frac{Q}{C_d A}\right)^2$$

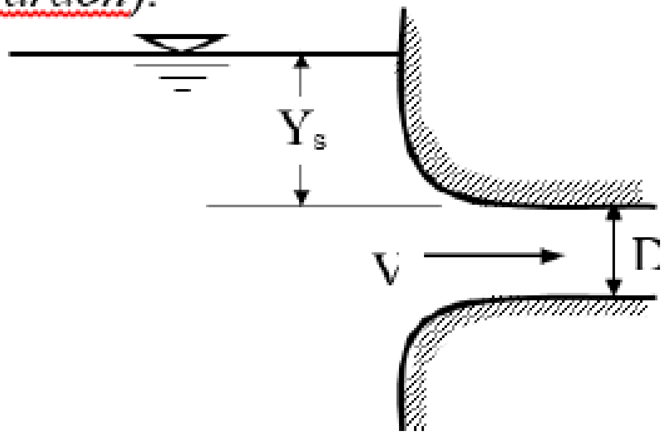
Where, Q is flow in the canal or conduit, A is area of gate opening, and C_d is discharge coefficient which varies between 0.62 and 0.83.

Vortex Formation at Intakes

For the condition of no vortices at intakes (*after J. B. Gardon*):

$Y_s > 0.545V\sqrt{D}$ *for symmetrical approach*

$Y_s > 0.725V\sqrt{D}$ *for asymmetrical approach*



Where, Y_s is necessary submergence depth, V is velocity at inlet to the canal, and D is diameter of the conduit.

Air Vent

- Intakes normally have a bulk head gate at the front and a control gate inside on the downstream side. An air vent is always provided just downstream of a control gate.
- The functions are:
  - To avoid vacuum effect, which could be created when the penstock is drained after control gate closure.
  - Intake gates operate under conditions of balanced pressure on both sides of the gate.
  - Thus the conduit is required to be filled with water through a by-pass pipe. The entrapped air is therefore driven out through the air vent.

Size of the air vent: There are several recommendations

1. $Q_a = 400Ca(p)^{1/2}$

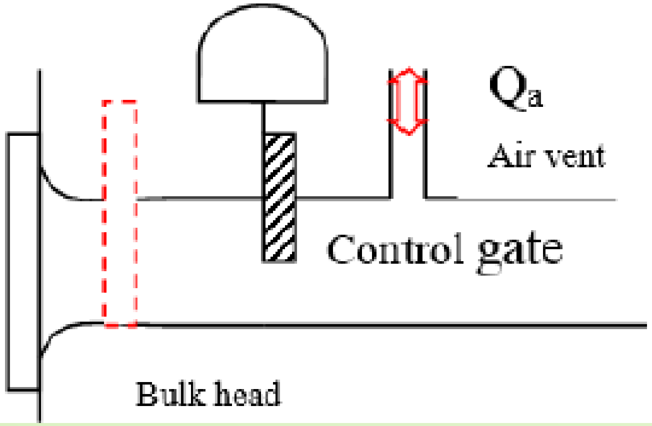
Where Q_a = Discharge of air in cumecs a= Area of vent pipe in m^2 C=Constant ~7

p =Pressure difference between the atmosphere and pressure in the penstock in kg/cm^2

2. 4th Congress on Large Dams (ICOLD)

   Area of air vent =10% of control gate area

3. USBR design guide: Capacity of air vent = 25% of conduit discharge



Skimmer wall

- A skimmer wall is an obstruction placed at the water surface, usually at an angle to the stream flow which skims floating debris from the passing water.
- If the water level changes markedly as, for example, at the intake of stream, the skimmer can be a floating piece of timber secured at both ends.
- If changes in water level are small, a fixed skimmer can be used.
- Because some debris usually passes under the skimmer, a trash rack is still necessary.
- Skimmer walls are made, for the most part, of reinforced concrete with a service bridge on top.
- They are designed usually for a horizontal pressure of 1000 kg/m2 acting on the submerged surface.

Skimmer wall