Design and Construction of Gravity Dams

Design and construction of the gravity dams mean the construction of the dams with earthen material. For the construction of gravity dams, first, earth material is removed from the river, then water is allowed to move into the trench then the dam is constructed to store the water on the upstream side.

The design and construction of gravity dams should be such that it ensures safety due to overturning and their stability. Designing gravity dams is an important part of the GATE CE exam and should be done according to the standard parameters fixed by the government authorities. And It should be done based on the norms of the IS code 6512.

Classification of Dams

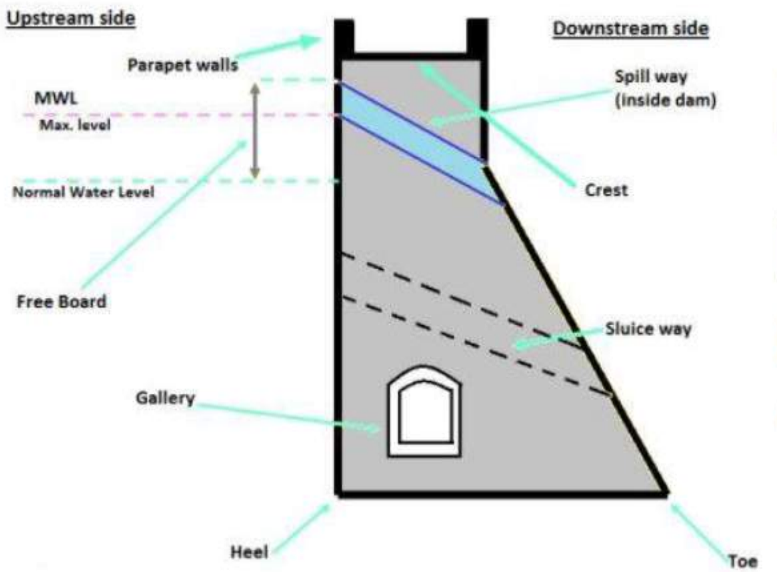
Dams can be classified in several ways. But the most usual ways of classification i.e. types of dams, are mentioned below. Based on the functions of dams, they can be classified as follows:

1. **Storage dams**: They are constructed to store water during the rainy season when there is a large flow in the river. Many small dams impound the spring runoff for later use in dry summers. Storage dams may also provide a water supply or improved habitat for fish and wildlife. They may store water for hydroelectric power generation, irrigation or a flood control project. Storage dams are the most common type of dam; generally, the dam means a storage dam unless qualified otherwise.
2. **Diversion dams**: A diversion dam is constructed for the purpose of diverting water from the river into an off-taking canal (or a conduit). They provide sufficient pressure for pushing water into ditches, canals, or other conveyance systems. Such shorter dams are used for irrigation and for diversion from a stream to a distant storage reservoir. It is usually of low height and has a small storage reservoir on its upstream. The diversion dam is a sort of storage weir which also diverts water and has a small storage. Sometimes, the terms weirs and diversion dams are used synonymously.
3. **Detention dams**: Detention dams are constructed for flood control. A detention dam retards the flow of the river on its downstream during floods by storing some flood water. Thus the effect of sudden floods is reduced to some extent. The water retained in the reservoir is later released gradually at a controlled rate according to the carrying capacity of the channel downstream of the detention dam. Thus the area downstream of the dam is protected against flood.
4. **Debris dams**: A debris dam is constructed to retain debris such as sand, gravel, and driftwood flowing in the river with water. The water, after passing over a debris dam, is relatively clear.
5. **Coffer dams**: An enclosure constructed around the construction site excludes water so that the construction can be done dry. A coffer dam is thus a temporary dam constructed to facilitate construction. These structures are usually

constructed upstream of the main dam to divert water into a diversion tunnel (or channel) during the dam's construction. When the flow in the river during the construction of hydraulic structures is not much, the site is usually enclosed by the coffer dam and pumped dry. Sometimes a coffer dam downstream of the dam is also required.

Structure of a Gravity Dam

The structure of the gravity dam consists of different parts at its downstream and upstream sides. These are explained below in the following diagram.



- **Toe:** Portion of structure in contact with ground or riverbed downstream.
- **Abutment:** Sides of the valley on which the structure of the dam rest.
- **Galleries:** Small rooms like structures left within the dam for checking operations.
- **Spillways**: It is the arrangement near the top to release the excess water of the reservoir to the downstream side.
- **Sluice way**: An opening in the dam near the ground level is used to clear the silt accumulation on the reservoir side.
- **Crest**: The top of the dam structure. These may, in some cases, be used for providing a roadway or walkway over the dam.
- **Parapet walls**: Low Protective walls on either side of the roadway or walkway on the crest.
- **Heel**: Portion of structure in contact with ground or riverbed upstream.
- **Spillway**: It is the arrangement made (kind of passage) near the top of the structure to pass surplus/ excessive water from the reservoir.
- **Abutments**: The valley slopes on either side of the dam wall to which the left & right end of the dam is fixed.

- **Gallery**: Level or gently sloping tunnel-like passage (small room-like space) at transverse or longitudinal within the dam with a drain on the floor for seepage water. These generally provide space for drilling grout holes and drainage holes. These may also accommodate the instrumentation for studying the dam's performance.
- **Freeboard**: The space between the highest level of water in the reservoir and the top of the structure.
- **Dead Storage level**: The permanent storage below which the water will not be withdrawn.
- **Diversion Tunnel**: Tunnel constructed to divert or change the direction of water to bypass the dam construction site. The hydraulic structures are built while the river flows through the diversion tunnel.

Force Acting on a Dam Structure

In designing a dam, the first step is determining various forces acting on the structure and studying their nature. Depending upon the situation, the dam is subjected to the following forces:

1. Water pressure
2. Earthquake forces
3. Silt pressure
4. Wave pressure
5. Ice pressure
6. Self-weight of the dam.

The forces are considered to act per unit length of the dam. For perfect and accurate design, the effect of all the forces should be investigated. Out of these forces, the most common and important forces are water pressure and the self-weight of the dam.

1. Water Pressure

Water pressure may be subdivided into the following two categories:

I) External Water Pressure:

It is the pressure of water on the upstream face of the dam. In this, there are two cases:

(i) Upstream face of the dam is vertical, and there is no water on the dam's downstream side. The total pressure is in the horizontal direction and acts on the upstream face at a height H/3 from the bottom. The pressure diagram is triangular, and the total pressure is given by

$$P_1 = wh^2/2$$

Where w is the specific weight of water. Usually, it is taken as unity.

H is the height up to which water is stored in m.

(ii) Upstream face with batter, and there is no water on the downstream side

Here in addition to the horizontal water pressure $\mathbf{P_1}$ as in the previous case, there is vertical pressure of the water. It is due to the water column resting on the upstream sloping side. The vertical pressure $\mathbf{P_2}$ acts on the base's length portion. This vertical pressure is given by

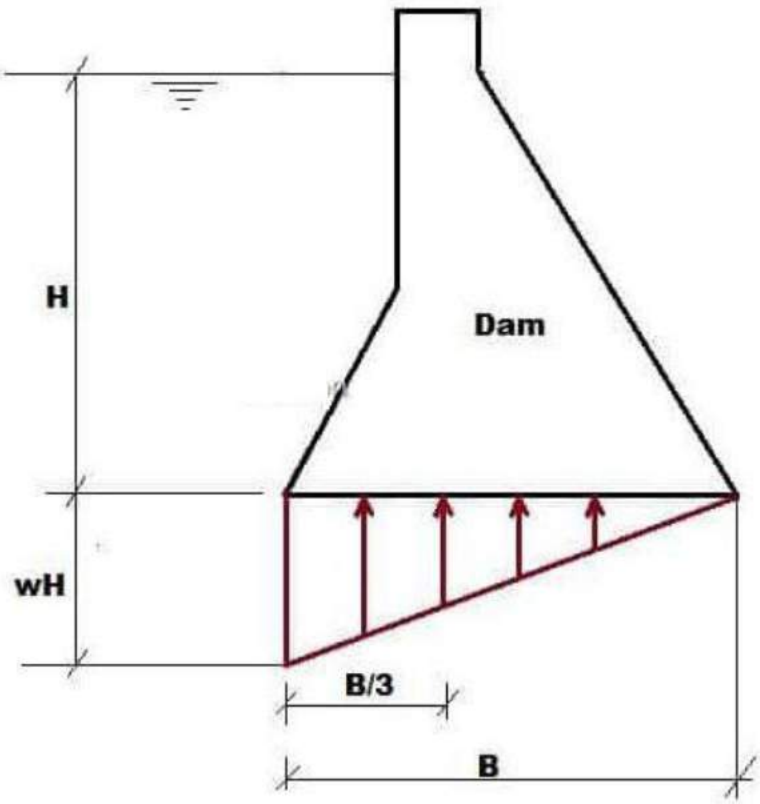
$$P_2 = (b \times h_2 \times w) + (0.5b \times h_1 \times w)$$

Pressure $\mathbf{P_2}$ acts through the center of gravity of the water column resting on the sloping upstream face.

Pressure may be calculated similarly if water is on the dam's downstream side. The water pressure on the downstream face stabilizes the dam. Hence as an additional factor of safety, it may be neglected.

II) Water pressure below the base of the dam or Uplift pressure

When the water is stored on the upstream side of a dam, there exists a head of water equal to the height upto which the water is stored. This water enters the pores and fissures of the foundation material under pressure. It also enters the joint between the dam and the foundation at the base and the pores of the dam itself. This water then seeps through and tries to emerge out on the downstream end. The seeping water creates the hydraulic gradient between the upstream and downstream sides of the dam. This hydraulic gradient causes vertical upward pressure. The upward pressure is known as uplift. Uplift reduces the effective weight of the structure and consequently reduces the restoring force. It is essential to study the nature of uplift, and also, some methods will have to be devised to reduce the uplift pressure value.



With reference to the figure, uplift pressure is given by

$$P_u = (wH \times B)/2$$

Where P_u is the uplift pressure, B is the base width of the dam, and H is the height upto which water is stored.

This total uplift acts at **B/3** from the heel or upstream end of the dam. Uplift is generally reduced by providing drainage pipes or holes in the dam section. Self-weight of the dam is the only largest force that stabilizes the structure. The total weight of the dam is supposed to act through the center of gravity of the dam section in a vertically downward direction. Naturally, when the specific weight of the construction material is high, restoring force will be more. Construction material is so chosen that the density of the material is about 2.045 grams per cubic meter.

2. Earthquake Forces

The effect of an earthquake is equivalent to an acceleration of the dam's foundation in the direction in which the wave is traveling. Earthquake waves may move in any direction and are resolved in vertical and horizontal directions for design purposes. On average, a value of 0.1 to 0.15g (where g = acceleration due to gravity) is generally sufficient for high dams in seismic zones. Even a value of 0.3g may be adopted in extremely seismic regions and conservative designs.

Vertical acceleration reduces the unit weight of the dam material, and that of water is to **(1- k_v)** times the original unit weight, where **k_v** is the value of g accounted against earthquake forces, i.e. 0.1 when 0.1g is accounted for earthquake forces. The horizontal acceleration acting towards the reservoir causes a momentary increase in water pressure, and the foundation and dam accelerate towards the reservoir, and the water resists the movement owing to its inertia. The extra pressure exerted by this process is known as hydrodynamic pressure.

3. Silt Pressure

If h is the height of silt deposited, then the forces exerted by this silt and the external water pressure can be represented by the Rankine formula.

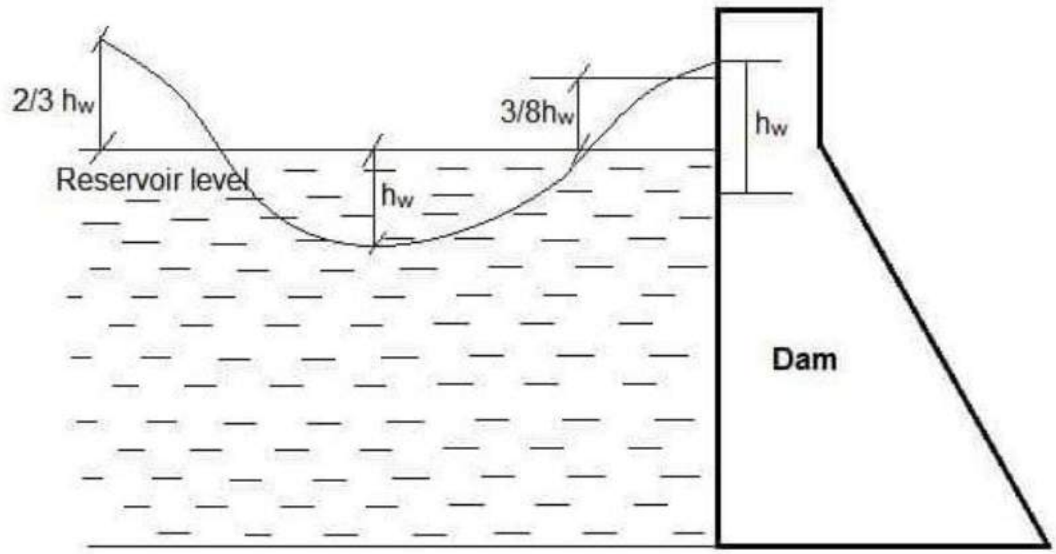
$P_{silt} = 0.5\gamma_s h^2 k_a$; acting at **h/3** from the base.

Where,

- k_a = Coefficient of active earth pressure of silt =[1 - sinΦ]/[1 + sinΦ]
- Φ= angle of internal friction of soil, cohesion neglected.
- γ_s= submerged unit weight of silt material.
- h = height of silt deposited.

4. Wave Pressure

Waves are generated on the surface of the reservoir by the blowing winds, which exert pressure on the downstream side. Wave pressure depends upon wave height



The maximum pressure intensity due to wave action may be given by **$P_w = 2.4\gamma_w h_w$** and acts at **$h_w/2$** meters above the still water surface.

The pressure distribution may be assumed to be triangular of height **$5h_w/3$,** as shown in the figure.

Hence total force due to wave action acting at **$3h_w/8$** above the reservoir surface and given by

$$P_w = \frac{1}{2} \times (2.4\,\gamma_w h_w) \times 5h_w/3$$

5. Ice Pressure

The ice that may be formed on the reservoir's water surface in cold countries may sometimes melt and expand. The dam face is subjected to the thrust exerted by the expanding ice. This force acts linearly along the length of the dam and at the reservoir level. The magnitude of this force varies from 250 to 1500 kN/sq.m depending upon the temperature variations. On average, a value of 500 kN/sq.m may be taken under ordinary circumstances.

6. Weight of dam

The weight of the dam and its foundation is a major resisting force. In two dimensional analysis of the dam, unit length is considered.

Causes of Failure of a Gravity Dam

Failure of the gravity dam occurs due to overturning, sliding, tension and compression. A gravity dam is designed to resist all external forces acting on the dam, like water pressure, wind pressure, wave pressure, ice pressure, and uplift pressure, by its own self-weight. Gravity dams are constructed from masonry or concrete. However, concrete gravity dams are preferred these days and are mostly constructed. The advantage of a gravity dam is that its structure is most durable and solid and requires very less maintenance.

A gravity dam may fail in the following modes:

1. Overturning of a dam about the toe
2. Sliding–shear failure of gravity dam
3. Compression – by crushing the gravity dam
4. Tension – by the development of tensile forces, which results in the crack in the gravity dam.

Overturning Failure of Gravity Dam

The horizontal forces, such as water pressure, wave pressure, and silt pressure, which act against the gravity dam, cause overturning moments. To resist this, resisting moments are generated by the self-weight of the dam.

If the resultant of all the forces acting on a dam at any of its sections passes through the toe, the dam will rotate and overturn about the toe. This is called the overturning failure of a gravity dam and is to create MSQ-based questions in the GATE CE question paper. But, practically, such a condition does not arise, and the dam will fail much earlier by compression.

The ratio of the resisting moments about the toe to the overturning moments about the toe is called the safety factor against overturning. Its value generally varies between 2 and 3.

The factor of safety against overturning is given by

FOS = sum of overturning moments/ sum of resisting moments

Sliding Failure of Gravity Dam

When the net horizontal forces acting on the gravity dam at the base exceed the frictional resistance (produced between the body of the dam and the foundation), The failure is known as a sliding failure of the gravity dam.

In low dams, the safety against sliding should be checked only for friction, but in high dams, for economical, precise design, the shear strength of the joint is also considered.

The factor of safety against sliding can be given based on

- Frictional resistance
- Frictional resistance and shear strength of the dam

Gravity Dam Failure due to Tension Cracks

Masonry and concrete are weak in tension. Thus masonry and concrete gravity dams are usually designed so that no tension is developed anywhere. Materials may develop tension cracks if these dams are subjected to tensile stresses. Thus the dam loses contact with the bottom foundation due to this crack and becomes ineffective and fails. Hence, the effective width B of the dam base will be reduced. This will increase p_{max} at the toe. Hence, a tension crack by itself does not fail the structure but leads to the failure of the structure by producing excessive compressive stresses.

For high gravity dams, a certain amount of tension is permitted under severest loading conditions to achieve economy in design. This is permitted because the worst condition of loads may occur only momentarily and not frequently.

Gravity Dam Failure Due to Compression

A gravity dam may fail by the failure of its material, i.e., the compressive stresses produced may exceed the allowable stresses, and the dam material may get crushed.