MODULE 3: GRAVITY DAMS

Introduction to Gravity Dams

A **gravity dam** is a solid structure designed to hold back large volumes of water primarily by using its own weight to resist the horizontal forces exerted by the water body. The stability of the structure is ensured by the force of gravity acting downward on the mass of the dam itself. Unlike other types of dams that rely on arch action or buttresses, a gravity dam resists loads through sheer mass and geometry. Typically constructed from concrete or masonry, gravity dams are suited for narrow gorges with strong and stable foundations capable of withstanding the massive weight and pressures involved.

Gravity dams are often used for purposes such as water storage for irrigation, drinking water supply, hydroelectric power generation, flood control, and recreational activities.

Forces Acting on a Gravity Dam

A gravity dam is subjected to multiple forces that act in different directions. Proper analysis of these forces is critical for a safe and economical design. The forces include:

1. **Water Pressure (Hydrostatic Pressure):**
    - The main horizontal force acts from upstream to downstream.
    - It varies linearly with depth, being zero at the surface and maximum at the base.
2. **Uplift Pressure:**
    - Water seeping through the foundation and body of the dam exerts upward pressure at the dam base.
    - Reduces the effective downward weight, decreasing stability.

- Uplift pressure is usually assumed to vary linearly from full water pressure at the upstream face to zero at the downstream toe (though actual distribution depends on drainage effectiveness).

3. **Self-Weight of the Dam (Dead Load):**
   - The major stabilising force.
   - Acts vertically downwards through the centre of gravity of the dam section.
   - Depends on the density and volume of dam material (e.g., concrete or masonry).
4. **Silt Pressure:**
   - Fine particles settle against the upstream face.
   - Silt imposes both horizontal and vertical pressures similar to water but with different magnitudes and characteristics.
5. **Wave Pressure:**
   - Waves generated by wind or seismic activity impact the upstream face.
   - Generally adds additional short-term horizontal force near the water surface.
6. **Earthquake Forces:**
   - Seismic action induces additional horizontal and vertical inertial forces on both dam and water body.
   - Hydrodynamic pressure during earthquakes is a critical factor in dam design in seismically active regions.
7. **Ice Pressure:**
   - In colder regions, expansion of freezing water imposes significant lateral forces on the upstream face.
8. **Temperature Stresses:**
   - Seasonal variations cause expansion and contraction of the dam body, generating internal stresses.

- Proper design and provision for expansion joints are necessary to manage temperature effects.

Each of these forces must be calculated and incorporated into the stability analysis to ensure a safe dam design.

Causes of Failure of a Gravity Dam

Gravity dams may fail due to a number of reasons if improperly designed, constructed, or maintained. The major causes of failure are:

Overturning:

When the resultant force of water pressure and other forces shifts beyond the base's middle third, creating tensile stresses at the toe, causing the dam to rotate and eventually topple.

Sliding:

If the horizontal forces exceed the frictional and cohesive resistance between the dam base and its foundation, the dam may slide downstream.

Excessive Base Pressure:

If the stresses at the dam-foundation contact exceed the bearing capacity of the foundation material, it may cause crushing, shear failure, or differential settlement.

Uplift Pressure:

Excessive seepage water under the dam can reduce its effective weight, making it prone to sliding or overturning.

Seepage and Piping:

Seepage water can erode foundation materials, leading to the creation of channels (piping) and possible collapse of the structure.

Structural Failure:

Poor quality of concrete or masonry, improper compaction, inadequate curing, or incorrect reinforcement may cause cracking, leakage, or even sudden collapse.

Foundation Instability:

Weak or fractured foundation rock may lead to settlement, tilting, or sliding of the entire dam body.

Prevention of these failures involves careful design, high-quality construction practices, thorough site investigation, proper drainage arrangements, and regular inspection and maintenance.

Elementary Profile of a Gravity Dam

The **elementary profile** is a theoretical, idealised design of a gravity dam, assuming perfect conditions with simplified assumptions:

Triangular Shape:

The dam cross-section is triangular — vertical on the upstream side and sloping downstream.

Conditions Assumed:

- Only water pressure and self-weight are considered.
- Uplift, silt, earthquake, and other forces are ignored.
- No tensile stresses are allowed in the dam body.
- The resultant force must pass through the middle third of the base.

Design Considerations:

- Base width is determined solely to resist hydrostatic pressure.
- Top width is minimised (just enough for service needs).

This profile provides the most economical use of material theoretically, but real-life conditions demand modifications.

Practical Profile of a Gravity Dam

The **practical profile** of a gravity dam accounts for real-world conditions and additional forces:

Top Width Adjustment:

Practical needs like roadways, inspection pathways, and parapet walls require a minimum top width (often 4 to 6 metres).

Inclusion of Uplift Pressure:

Uplift reduces the effective stabilising force; thus, additional thickness is provided, and drainage systems are introduced.

Seismic and Hydrodynamic Forces:

In earthquake-prone regions, additional forces must be resisted by making the structure more massive or by modifying slopes.

Provision of Freeboard:

Additional height above the maximum reservoir level ensures protection against waves and sudden rises in water level.

Modified Upstream and Downstream Faces:

Gentle slopes on the faces are provided instead of vertical walls to reduce stress concentration and improve stability.

The practical profile optimises between economy and safety under realistic conditions.

Limiting Height of a Low Gravity Dam

The **limiting height** is the maximum height up to which a simple triangular-section gravity dam can be designed without developing tensile stresses at the base:

- For heights up to approximately **30 metres**, the gravity dam section can be designed economically without high complexity.
- Beyond this height:
    - Additional stresses due to higher hydrostatic pressure,
    - Need for thicker sections,
    - Consideration of seismic forces,
    - Complicated analysis for thermal and structural stresses arise.

Thus, a more careful, detailed design is needed for high dams, and different profiles or construction materials might be adopted to manage forces efficiently.

Factors of Safety – Stability Analysis

To ensure the safety of the dam under all possible load combinations, specific **factors of safety** (FoS) are maintained:

1. **Against Overturning:**
   - Stabilising moments (due to weight) must be greater than overturning moments (due to water pressure).
   - Typically, a minimum FoS of **1.5** is used.
2. **Against Sliding:**
   - Resisting forces (friction and cohesion) must be greater than driving horizontal forces.
   - A minimum FoS of **1.5** is recommended.
3. **Against Excessive Base Pressure:**
   - Maximum compressive stress at the foundation contact must be less than the allowable stress of the foundation material.
   - Stress distribution should be compressive across the entire base; no tensile stress should be allowed.
4. **Against Uplift Pressure:**
   - Adequate drainage and cut-off walls are provided to reduce uplift pressures, maintaining stability.

Comprehensive stability analysis includes checking all these conditions for both normal operating conditions and extreme events like floods and earthquakes.

Foundation for a Gravity Dam

A strong, impermeable foundation is a basic requirement for the safe performance of a gravity dam:

Preferred Foundation Materials:

Massive igneous rocks (e.g., granite, basalt) are ideal due to their high strength and low permeability.

Undesirable Conditions:

Presence of fractured, jointed, or weak rocks, loose alluvium, or highly permeable soils are unfavourable.

Foundation Treatments:

  - **Grouting:** Injection of cementitious material into fissures and joints to seal and strengthen the rock.
  - **Cut-off Walls:** Deep vertical barriers constructed beneath the dam to prevent seepage.
  - **Drainage Galleries:** Horizontal passages that collect seepage and relieve uplift pressures.

Foundation Preparation:

  - Excavation down to sound rock.
  - Removal of loose or weathered material.
  - Cleaning and levelling before starting dam construction.

A properly treated and prepared foundation significantly enhances the stability and lifespan of the dam.

Drainage and Inspection Galleries

Drainage galleries and **inspection galleries** are key features integrated into large gravity dams:

- **Drainage Galleries:**
  - Run horizontally or slightly inclined through the lower part of the dam.
  - Collect seepage water and discharge it safely.
  - Reduce uplift pressures acting at the base.
- **Inspection Galleries:**
  - Allow access for visual inspection and maintenance.
  - Used for installing and reading instruments like piezometers, strain gauges, and thermometers.

    - Help detect and address problems early (like abnormal seepage or movement).

Their placement is determined based on seepage patterns and the need for easy access. Galleries are connected with surface drains and inspection shafts to facilitate maintenance activities.