International Journal of Science and Research (IJSR)
ISSN: 2319-7064
ResearchGate Impact Factor (2018): 0.28 | SJIF (2018): 7.426

Seismic Forces and Stability Analysis of Gravity Dam

Venkata Raju Badanapuri

Executive Engineer, Water Resources Department, Government of Andhra Pradesh, India

Abstract: ***A gravity dam is a solid structure, made of concrete or masonry, constructed across a river to create a reservoir on its upstream. The section of the gravity dam is approximately triangular in shape, with its apex at its top and maximum width at bottom. The section is so proportioned that it resists the various forces acting on it by its own weight. Most of the gravity dams are solid, so that no bending stress is introduced at any point and hence, they are sometimes known as solid gravity dams to distinguish them from hollow gravity dams in those hollow spaces are kept to reduce the weight. Early gravity dams were built of masonry, but now-a-days with improved methods of construction, quality control and curing, concrete is most commonly used for the construction of modern gravity dams. A gravity dam is generally straight in plan and, therefore, it is also called straight gravity dam. However, in some cases, it may be slightly curved in plan, with its convexity upstream. When the curvature becomes significant, it becomes on arch dam. The gravity dams are usually provided with an overflow spillway in some portion of its length. The dam thus consists of two sections; namely, the non-overflow section and the overflow section or spillway section. The design of these two sections is done separately because the loading conditions are different. The overflow section is usually provided with spillway gates. The ratio of the base width to height of most of the gravity dam is less than 1.0. The upstream face is vertical or slightly inclined. The slope of the downstream face usually varies between 0.7: 1 to 0.8: 1. Gravity dams are particularly suited across gorges with very steep side slopes where earth dams might slip. Where good foundations are available, gravity dams can be built upto any height. Gravity dams are also usually cheaper than earth dams if suitable soils are not available for the construction of earth dams. This type of dam is the most permanent one, and requires little maintenance. The most ancient gravity, dam on record was built in Egypt more than 400 years B.C. of uncemented masonry. Archaeological experts believe that this dam was kept in perfect condition for more than 45 centuries. The highest gravity dam in the world is Grand Dixence Dam in Switzerland, which is 285 m high. The second highest gravity dam is Bhakra Dam in India, which has a height of 226 m. The aim of the study is to analyse the dam for stability and seismic forces. Dam being one of the mega structures it becomes prime important to design and analyse such structure with keen observation considering various factors affecting them. As it is one of the lifesaving structures, it is again important to analyse such structure for major forces like earthquake. Keeping this in mind, in this paper the study is done for finding out the result that makes dam stable against forces acting on it with and without considering seismic forces. The study is done considering the hypnotically dam subjected to pre decided geographical factors like type of soil, its density, seismic zone etc. further this experimental work is done for dam full (with and without considering uplift pressure) and empty condition. This designing is done following IS code criteria. Further in paper work various such gravity dams subjected to different factors are analysed. The results of analysis are tabulated over here and the various forces responsible for failure of dam are highlighted in conclusion.***

Keywords: Gravity Dam, Seismic Forces, Sliding, Stability, Analysis

1. Introduction

A concrete dam must be able to safely withstand the static forces that tend to cause sliding or overturning, as well as the additional dynamic forces induced by the ground motions of the design earthquake. If you are an owner or otherwise have responsibility for a concrete dam, you should know whether that dam is stable under all potential loading conditions. To verify a dam's stability, investigations and analyses may be necessary. This paper provides background information about types of concrete dams and the significance of static and seismic stability of concrete dams. It also describes modes of static and seismic stability failure.A concrete dam is a dam constructed mainly of cast-in-place or roller-compacted concrete. There are three major types of concrete dams, 1. gravity dams, 2. arch dams, and 3. buttress dams.

1) A gravity dam is a massive concrete structure, roughly triangular in shape, and designed so that its weight ensures structural stability against the hydrostatic pressure of the impounded water and other forces that may act on the dam. Gravity dams may be classified by plan as straight gravity dams and curved gravity dams, depending upon the axis alignment.
2) An arch dam is a solid concrete structure, usually thinner than a gravity dam, that is arched upstream. An arch dam obtains most of its stability by transmitting the reservoir load into the canyon walls by arch action.
3) A buttress dam, a form of gravity dam, is comprised of two or three basic structural elements: a watertight upstream face, buttresses that support the face and transfer the load from the face to the foundation, and sometimes a concrete apron. Buttress dams depend on their own weight and the weight of the water acting on the upstream face to maintain stability.

Another type of dam that may require evaluation is the masonry dam. A masonry dam is constructed mainly of stone, brick, rock, or concrete blocks joined with mortar. Most masonry dams are older gravity dams, although a few are arch dams. Each type of dam may fail due to static or seismic instability, and an evaluation should be made of a particular dam's susceptibility to such instability.

2. Historical Perspective

Concrete (or masonry) dams have some inherent advantages over embankment dams. They require less, albeit more expensive, construction material, and they are resistant to overtopping and to internal erosion by seepage. On the other hand, they generally require more competent foundations and abutments because of their rigidity. Historically concrete dams are relatively safe when compared to their earth fill and rockfill counterparts. This is because of their inherent durability and high resistance to erosion. Seepage and overtopping situations that would cause failure in an earth fill or rockfill dam would not, in most cases, cause a concrete dam to fail. Nevertheless, there still have been significant failures of all types of concrete dams continuing into recent times. Most failures can be traced to overstress of foundations or abutments because the in-situ materials were not adequate to sustain the applied loads or deteriorated as seepage developed. Deterioration of concrete and particularly of the mortar in older masonry structures has also resulted in several failures.

3. Gravity Dam Basic Definitions

Terminology relating to the design and analysis of gravity dams and definitions of the parts of gravity dams as used in this paper are as follows:

A plan is an orthographic projection on a horizontal plane, showing the main features ofa dam and its appurtenant works with respect to the topography and available geological data. A plan should be oriented so that the direction of stream flow is toward the top or toward the right of the drawing. A profile is a developed elevation of the intersection of a dam with the original ground surface, rock surface, or excavation surface along the axis of the dam, the upstream face, the downstream face, or other designated location. The axis of the dam is a vertical reference plane usually defined by the upstream edge of the top of the dam. A section is a representation of a dam as it is taken horizontally through the dam. A cantilever section is a vertical section taken normal to the axis and usually oriented with the reservoir to the left. A beam element, or beam, is a portion of a gravity dam bounded by two horizontal planes 0.3m apart. For purposes of analysis the edges of the elements are assumed to be vertical. A cantilever element, or cantilever, is a portion of a gravity dam bounded by two vertical planes normal to the axis and 0.3 m apart, A twisted structure consists of vertical elements with the same structural properties as the cantilevers, and of horizontal elements with the same properties as the beams. The twisted structure resists torsion in both the vertical and horizontal planes. The height of a cantilever is the vertical distance between the base elevation of the cantilever section and the top of the dam. The thickness of a dam at any point is the distance between upstream and downstream faces along a line normal to the axis through the point. The abutment of a beam element is the surface, at either end of the beam, which contacts the rock of the canyon wall. The crest of a dam is the top of the dam.

1) Axis of the dam: The axis of the gravity dam is the line of the upstream edge of the top (or crown) of the dam. If the upstream face of the dam is vertical, the axis of the dam coincides with the plan of the upstream edge. In plan, the axis of the dam indicates the horizontal trace of the upstream edge of the top of the dam. The axis of the dam in plan is also called the baseline of the dam. The axis of the dam in plan is usually straight. However, in some special cases, it may be slightly curved upstream, or it may consist of a combination of slightly
2) Curved RIGHT portions at ends and a central ABUTMENT straight portion to take the best advantages of the topography of the site.
3) Length of the dam: The length of the dam is the distance from one abutment to the other, measured along the axis of the dam at the level of the top of the dam. It is the usual practice to mark the distance from the left abutment to the right abutment. The left abutment is one which is to the left of the person moving along with the current of water.
4) Structural height of the dam: The structural height of the dam is the difference in elevations of the top of the dam and the lowest point in the excavated foundation. It, however, does not include the depth of special geological features of foundations such as narrow fault zones below the foundation. In general, the height of the dam means its structural height.
5) Maximum base width of the dam: The maximum base width of the dam is the maximum horizontal distance between the heel and the toe of the maximum section of thedam in the middle of the valley.
6) Toe and Heel: The toe of the dam isthe downstream edge of the base, and the heel is the upstream edge of thebase. When a person moves along with water current, his toe comes first and heel comes later.
7) Hydraulic height of the dam: The hydraulic height of the dam is equal to the difference in elevations of the highest controlled water surface on the upstream of the dam (i. e. FRL) and the lowest point in the river bed.

4. Static and seismic stability

Concrete dams are subject to various loads, including external and internal water pressures, earth pressures due to siltation, ice pressures, and earthquake forces. Stability analyses are performed to ensure that the dam and its foundation are capable of safely accommodating these loads. Two major classifications of stability are discussed in this paper static stability and seismic stability.

Static Stability
Ability of a dam to resist the static forces that tend to induce sliding or overturning.

Seismic Stability: Ability of a dam to resist the additional dynamic forces induced by the ground motions of an earthquake.

5. Scope

A concrete gravity dam, as discussed in this paper, is a solid concrete structure so designed and shaped that its weight is sufficient to ensure stability against the effects of all imposed forces. Other types of dams exist which also maintain their stability through the principle of gravity, such as buttress and hollow gravity dams, but these are outside the scope of this paper. Further, discussions in this paper are limited to damson rock foundations and do not include smaller

International Journal of Science and Research (IJSR)
ISSN: 2319-7064
ResearchGate Impact Factor (2018): 0.28 | SJIF (2018): 7.426

dams generally less than 15 m high which are discussed in the Bureau of Reclamation publication "Design of Small Dams".

The complete design of a concrete gravity dam includes not only the determination of the most efficient and economical proportions for the water impounding structure, but also the determination of the most suitable appurtenant structures for the control and release of the impounded water consistent with the purpose or function of the project. This paper presents the basic assumptions, design considerations, methods of analysis, and procedures used by designers within the Engineering and Research Centre, Bureau of Reclamation, for the design of a gravity damand its appurtenances.

6. Classifications

Gravity dams may be classified by plan as straight gravity dams and curved gravity dams, depending upon the axis alignment. The principal difference in these two classes is in the method of analysis. Whereas a straight gravity dam would be analysed by one of the gravity methods discussed in this paper, a curved gravity dam would be analysed as an arch dam structure. For statistical purposes, gravity dams are classified with reference to their structural height. Dams up to30 m high are generally considered as low dams, dams from 30 m to 90 m high as medium-height dams, and dams over 90 m high as high dams.

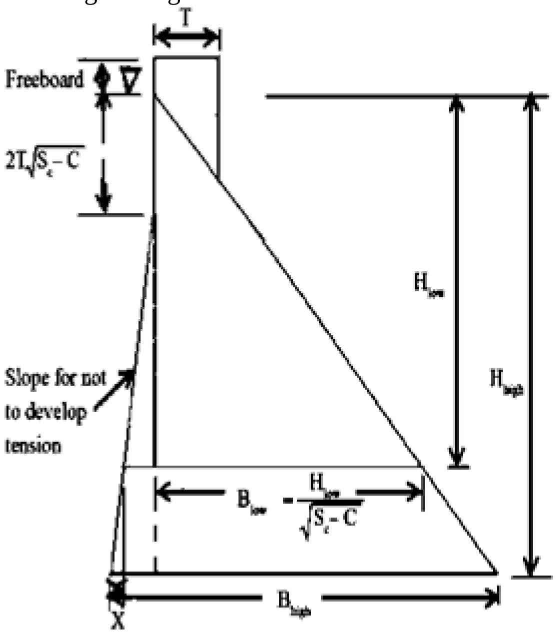

Fig.1 Elementary profile of Concrete Gravity Dam

7. Design Philosophy

The Bureau of Reclamation's philosophy of concrete dam design is founded on rational and consistent criteria which provide for safe, economical, functional, durable, and easily maintained structures. It is desirable, therefore, to establish, maintain, and update design criteria. Under special conditions, consideration can be given to deviating from these standards. In those situations, the designer bears the responsibility for any deviation and, therefore, should be careful to consider all ramifications. Accordingly, each of the criteria definitions in this monograph is preceded by a discussion of the underlying considerations to explain the basis of the criterion. This serves as a guide in appraising the wisdom of deviating from a particular criterion for special conditions.

The line of the upstream side of the dam or the line of the coronet of the dam if the upstream side in slanting, is considered as the orientation line for plan purposes, etc. and is known as the "Base line of the Dam" or the "Axis of the Dam". When appropriate circumstances are on hand, such dams can be constructed up to immense heights. The ratio of base width to height of high gravity dams is generally less than 1:1. A typical cross-section of a high concrete gravity dam is shown in figure alongside. The upstream face may be kept throughout perpendicular or partially slanting for some of its length. A drainage passage is usually provided in order to lessen the uplift pressure formed by the seeping water. Purposes valid to dam creation may include routing, flood damage reduction, hydroelectric power creation, fish and wildlife improvement, water superiority, water supply, and amusement. Several concrete gravity dams have been in use for more than five decades, and over this phase significant advances in the methodologies for assessment of natural phenomena hazards have caused the design-basis events for these dams to be revised upwards. Older existing dams may fail to meet revised safety criteria and structural rehabilitation to meet such criteria may be costly and difficult.

8. Causes of Dam Failures

The incident of failures demonstrates that depending on the type of dam, the cause of failure may be classified as:

a) Hydraulic failures; (for all types of dams)
b) Failures due to seepage.
   (i) Through foundation, (all except arch dams)
   (ii) Through body of dam (embankment dam)
c) Failures due to stresses developed within structure.

Arch dams fail instantaneously, whereas the gravity dams take some multiples of 10minutes. A study of dam failures in the world has revealed the percentage distribution ofdam breaks and its attributes cause of failure.

1. Foundation problems 40 %
2. Inadequate spillway 23 %
3. Poor construction 12 %
4. Uneven settlement 10 %
5. High pore pressure 5 %
6. Acts of war 3 %
7. Embankment slips 2 %
8. Defective materials 2 %
9. Incorrect operations 2 %
10. Earthquakes 1 %

Other surveys of dam failure have been cited by, who estimated failure rates from 2×10^{-4} to 7×10^{-4} per dam year based on these surveys.

9. Sliding Failures

Sliding failures more often result from deficiencies in the foundation. Various foundation conditions can make a concrete dam vulnerable to sliding failure:

Low foundation shear strength
Bedding planes and joints containing weak material, such as clay or bentonite Seams of pervious material, if seepage through them is not controlled to prevent detrimental uplift
Faults and shear zones

Bedding planes and joints frequently have caused problems at dam sites and therefore warrant close examination. Two common types that have been troublesome are bedding plane zones in sedimentary rocks and foliation zones in metamorphic.

For a gravity dam, the potential for sliding may be greatest when the foundation rock is horizontally bedded, particularly where there is low shear strength along the bedding planes. Consideration also must be given to zones within the foundation rock that are especially susceptible to the development of unacceptable seepage uplift forces.

A situation that can lead to detrimental uplift is the dam tends to move downstream, tensile stresses are created in the foundation which may cause upstream joints and cracks to open and allow seepage to enter. The resulting uplift can lead to sliding or overturning.

10. Overturning Failures

Overturning failures have various causes:

Insufficient weight or improper distribution of weight in the dam cross section to resist the applied forces. This situation can cause high compressive stresses at the toe of the structure and/or high tensile stresses at the heel. Crushing of the concrete or foundation material at the toe may occur as a result of the high compressive stresses.

Tensile cracking over portions of the base of the structure which is not in compression, resulting in high uplift forces and a loss of resistance to overturning.

Erosion of the rock foundation at the toe of the dam due to overtopping or rock deterioration.

High uplift pressures caused by inadequate seepage control or pressure relief.

Excessive hydrostatic pressures due to severe flood conditions, resulting in higher reservoir levels than the dam was designed to accommodate.

11. Defective or Inferior Concrete

Substandard concrete may result from using inferior materials or procedures in preparing or placing the concrete. Inferior concrete may result from many causes, including:
Poor consolidation and curing Poor bond at lift lines
Weak aggregates Mineral-laden water
Highly absorptive aggregates, which may be susceptible to freeze-thaw damage Aggregates contaminated by soils, salts, mica, or organic material

High cement content, leading to high internal temperatures due to hydration Insufficient pre or post cooling of concrete
High water/cement ratios in concrete mix
Lack of entrained air
Reactive aggregates

Many gravity dams built in the nineteenth century were constructed of stone masonry with lime mortar. Lime mortar is susceptible to deterioration and loss of strength over long periods of exposure to seeping water. Once the bond between stones created by the mortar has been broken, water may enter the joints and the resulting pressure can cause a sliding or overturning failure.

12. Concrete Distress

Cracking of concrete structures may result from excessive tensile or compressive stresses, high impact loads such as barges or ice, or differential movements of foundation and abutment materials. In spillways or outlet works conveying high velocity flows, offsets in the concrete surfaces may cause cavitation. Vibration of structures by earthquake, water surges, or equipment operation may also damage concrete.

13. Foundation Failures

A seismic analysis must consider not only the effects of ground motions on the structure, but also their impact upon the strength of the foundation and abutments. Two main types of foundation failure need to be considered: Deformation, settlement, and fault movement Liquefaction
The dynamic strength of bedding planes and shear zones in the foundation is usually lower than their static strength. During earthquakes, movements can occur along faults or other weak zones in the foundation and abutments. These movements can cause a variety of problems:

1) Excessive movements can cause tensile cracking in the dam, which could possibly lead to dam failure.
2) Excessive movements can open up faults and cracks in the foundation, which may result in increased seepage and a corresponding rapid increase in uplift pressures.
3) Infiltration of water along bedding planes due to open cracks and fissures can cause reduced foundation shear strength. For gravity dams, the potential for sliding is greatest when the bedding planes are horizontal or they dip in the upstream direction.
4) Infiltration of water along bedding planes can lead to erosion of joint filler or shear zone material by piping.
5) This process can cause strength reduction as well as lead to large settlements or undermining of the dam.

14. Uplift Pressures

Modern dams are designed assuming full uplift over 100 percent of the base area. Some older dams were designed assuming that full uplift acted over only a percentage of the base area, and this assumption has been found to be in error. However, many dams designed under the older criteria have performed satisfactorily, for several reasons:

Pressure levels may be less than assumed in the original design because of good drainage or permeability of the foundation.

It takes many years to saturate concrete and dense foundation rock.

The reservoir may be at full pool conditions only for short periods.

The fact that the resultant falls outside the middle one-third of the base may not mean the dam is unstable.

There are sufficient uplift data to ensure that the uplift (magnitude and distribution) used in the stability analysis is representative of actual conditions for both the long and short term.

High hydrostatic pressures are not present in rock zones below the dam.

The instrumentation is functioning properly.

15. General Dimensions

For uniformity within the Bureau of Reclamation, certain general dimensions have been established and are defined as follows:

The structural height of a concrete gravity dam is defined as the difference in elevation between the top of the dam and the lowest point in the excavated foundation area, exclusive of such features as narrow fault zones. The top of the dam is the crown of the roadway if a roadway crosses the dam, or the level of the walkway if there is no roadway. Although curb and sidewalk may extend higher than the roadway, the level of the crown of the roadway is considered to be the top of the dam. The hydraulic height, or height to which the water rises behind the structure, is the difference in elevation between the lowest point of the original streambed at the axis of the dam and the maximum controllable water surface. The length of the dam is defined as the distance measured along the axis of the dam at the level of the top of the main body of the dam or of the roadway surfaces, on the crest, from abutment contact to abutment contact, exclusive of abutment spillway; provided that, if the spillway lies wholly within the dam and not in any area especially excavated for the spillway, the length is measured along the axis extended through the spillway to the abutment contacts. The volume of a concrete dam should include the main body of the dam and all mass concrete appurtenances not separated from the dam by construction or contraction joints. Where a power plant is constructed on the downstream toe of the dam, the limit of concrete in the dam should be taken as the downstream face projected to the general excavated foundation surface.

Forces Acting on a Gravity Dam

Fundamentally a gravity dam should satisfy the following criteria:

1) It shall be safe against overturning at any horizontal position within the dam at the contact with the foundation or within the foundation.
2) It should be safe against sliding at any horizontal plane within the dam, at the contact with the foundation or along any geological feature within the foundation.
3) The section should be so proportional that the allowable stresses in both the concrete and the foundation should not exceed.

Safety of the dam structure is to be checked against possible loadings, which may be classified as primary, secondary or exceptional. The classification is made in terms of the applicability and/or for the relative importance of the load.

1) Primary loads are identified as universally applicable and of prime importance of the load.
2) Secondary loads are generally discretionary and of lesser magnitude like sediment load or thermal stresses due to mass concreting.
3) Exceptional loads are designed on the basis of limited general applicability or having low probability of occurrence like inertial loads associated with seismic activity.

Technically a concrete gravity dam derives its stability from the force of gravity of the materials in the section and hence the name. The gravity dam has sufficient weight so as to withstand the forces and the overturning moment caused by the water impounded in the reservoir behind it. It transfers the loads to the foundations by cantilever action and hence good foundations are pre requisite for the gravity dam.

The forces that give stability to the dam include:

1) Weight of the dam
2) Thrust of the tail water

The forces that try to destabilize the dam include:

1) Reservoir water pressure
2) Uplift
3) Forces due to waves in the reservoir
4) Ice pressure
5) Temperature stresses
6) Silt pressure
7) Seismic forces
8) Wind pressure

The forces to be resisted by a gravity dam fall into two categories as given below:

1) Forces, such as weight of the dam and water pressure which are directly calculated from the unit weight of materials and properties of fluid pressure and
2) Forces such as uplift, earthquake loads, silt pressure and ice pressure which are assumed only on the basis of assumptions of varying degree of reliability. In fact, to evaluate this category of forces, special care has to be taken and reliance placed on available data, experience and judgement.

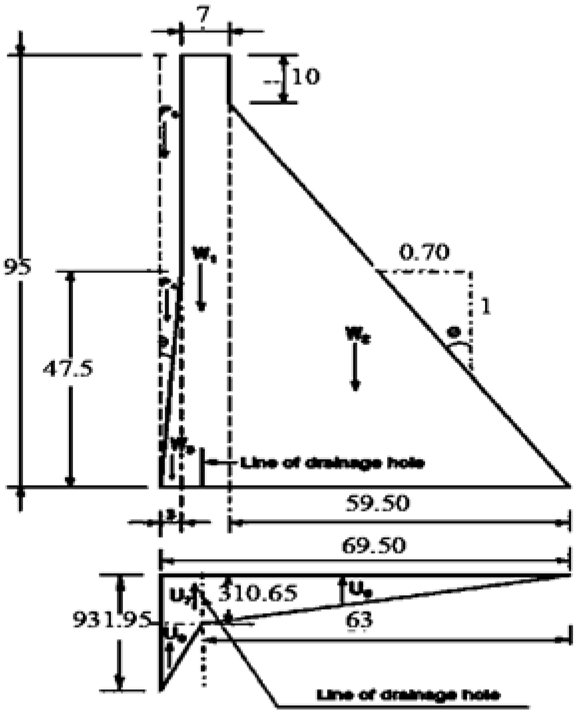

Fig 2. Typical Section of Concrete Gravity Dam

For consideration of stability of a concrete dam, the following assumptions are made:

1) That the dam is composed of individual transverse vertical elements each of which carries its load to the foundation without transfer of load from or to adjacent elements. However, for convenience, the stability analysis is commonly carried out for the whole block.
2) That the vertical stress varies linearly from upstream face to the downstream face on any horizontal section.

The Bureau of Indian Standards code IS 6512-1984 "Criteria for design of solid gravity dams" recommends that a gravity dam should be designed for the most adverse load condition of the seven given type using the safety factors prescribed. Depending upon the scope and details of the various project components, site conditions and construction programme one or more of the following loading conditions may be applicable and may need suitable modifications. The seven types of load combinations are as follows:

1) Load combination A (construction condition): Dam completed but no water in reservoir or tailwater
2) Load combination B (normal operating conditions): Full reservoir elevation, normal dry weather tail water, normal uplift, ice and silt (if applicable)
3) Load combination C: (Flood discharge condition) - Reservoir at maximum flood pool elevation, all gates open, tailwater at flood elevation, normal uplift, and silt (if applicable)
4) Load combination D: Combination of A and earthquake
5) Load combination E: Combination B, with earthquake but no ice
6) Load combination F: Combination C, but with extreme uplift, assuming the drainage holes to be Inoperative
7) Load combination G: Combination E but with extreme uplift (drains inoperative)

It would be useful to explain in a bit more detail the different loadings and the methods required to calculate them.

16. Methodology and Design of High Gravity Dam

Check the stability of Typical section of gravity dam as shown in fig.2. For reservoir empty and full condition considering seismic forces assume reasonable value of uplift and a line of drain holes 6m downstream of the upstream face for the purpose of this check assume water level at the top of dam and no tail water. Also find principal and shear stresses at the toe & heel of dam. Take unit weight of concrete23.5kN/m³ shear strength of concrete as 2200 kN/m² and μ=0.7.The Specific Weight of Water is 9.81 kN/m³.

The allowable compressive stress 3000 kN/m² of dam material is exceeds for concrete, the dam may crush and fail by crushing. The maximum permissible tensile stress for high concrete gravity dam under worst loadings may be taken as 500 kN/m².

(i) Stability check of Concrete Gravity dam without considering seismic forces

Case I: Reservoir Empty Condition

Calculation of stresses

When reservoir is empty only self-weight of dam will be acting as force. Other forces such as water pressure & uplift forces will be zero. The resulting force ΣV_1 and resulting moment ΣM_1 for this case has worked out as follows:

Position of resultant from toe

$$X = \left(\frac{\sum M_1}{\sum V_1}\right) = \frac{3454769.8}{76727.51} = 45.03 \text{ m}$$

Position of resultant from the centre of the base is

$$e = \left(\frac{B}{2} - X\right) = \left(\frac{69.5}{2} - 45.03\right) = -10.28 \text{ m}$$

(i.e. The Resultant acts nearer the heel and slight tension will develop at the toe.)

Normal compressive stress

$$P_{max/min} = \frac{\sum V_1}{B}\left(1 \pm \frac{6e}{B}\right)$$
$$= \frac{76727.51}{69.5}\left(1 \pm \frac{6x(-10.28)}{69.5}\right)$$

Normal compressive stress at heel

$P_v at\ heel = 2083.77 \text{ kN/m}^2 < 3000\ kN/\text{m}^2 (\text{safe})$

Normal compressive stress at toe

$P_v at\ toe = 124.22 \text{ kN/m}^2 < 500\ kN/\text{m}^2 (\text{safe})$

Average vertical stress

$$= \frac{\sum V}{B} = \frac{76727.51}{69.5} = 1103.99 \text{ kN/m}^2$$

Which is $< 3000\ kN/\text{m}^2\ (safe)$

Principal stress at toe

$$\sigma_t = P_v \sec^2 \emptyset; \ (\tan \emptyset = 0.7)$$
$$= 124.22(1 + 0.49) = 185.09 \text{ kN/m}^2$$

Which is $< 500\ kN/\text{m}^2$ (safe)

Principal stress at heel

$$\sigma_h = P_v \sec^2\theta; \ (\tan\theta = 0.063)$$
$$\sec^2\theta = 1 + \tan^2\theta = 1 + 0.0039 = 1.0039$$
$$= 2083.77x1.0039 = 2091.89 \text{ kN/m}^2$$

Which is $< 3000 \ kN/\text{m}^2 \ (safe)$

Shear stress at toe

$$\tau = P_v \tan\emptyset = 124.22 \times 0.70 = 86.95 \text{ kN/m}^2$$

Shear stress at heel

$$\tau = P_v \tan\theta = 2083.77x\,0.063 = 131.28 \text{ kN}/m^2$$

Case II: - Reservoir Full with No Uplift

Calculation of stresses

When reservoir is full, self-weight of dam and water pressure will be acting as force. Other force such as uplift forces will be zero. The resulting force ΣV_2 and resulting moment ΣM_2 for this case has worked out as follows:

Position of resultant from toe

$$X = \left(\frac{\Sigma M_2}{\Sigma V_2}\right) = \frac{2195899.52}{78824.40} = 27.86 \text{ m}$$

Position of resultant from the centre of the base is

$$e = \left(\frac{B}{2} - X\right) = \left(\frac{69.5}{2} - 27.86\right) = 6.89 \text{ m}$$

(i.e. The Resultant acts nearer the toe and tension will develop at the heel.)

Normal compressive stress

$$P_{max\,/min} = \frac{\Sigma V_2}{B}\left(1 \pm \frac{6e}{B}\right)$$
$$= \frac{78824.40}{69.5}\left(1 \pm \frac{6x6.89}{69.5}\right)$$

Normal compressive stress at toe

$P_v at\ toe = 1808.79 \text{ kN/m}^2 < 3000 \ kN/\text{m}^2$(safe)

Normal compressive stress at heel

$P_v at\ heel = 459.54 \text{ kN/m}^2 < 500 \ kN/\text{m}^2$(safe)

Principal stress at toe

Table 1.0

Sl No	Designation if any	Magnitude of force in kN		Lever arm in m	Moments about the toe ant-clockwise (+ve) in kN m
		Vertical	Horizontal		
	Weight of Dam				
1	W_1	95x7x23.5= 15627.5	-	63	984532.50
2	W_2	1/2x59.5x 85x23.5 = 59425.63	-	39.66	2357216.65
3	W_3	1/2x 3x 47.5x23.5 = 1674.38	-	67.5	113020.65
		ΣV_1= 76727.51			ΣM_1=3454769.80
	Water Pressure				
4	P_4	1/2x3x47.5x9.81 = 698.96	-	68.5	47878.76
5	P_5	3x47.5x9.81 =1397.93	-	68	95059.24
6	H	-	1/2x95²x9.81 =44267.63	95/3	(-)1401808.28
		ΣV_2= 78824.40			ΣM_2= 2195899.52
	Uplift Forces				
7	U_6	931.95/3x63x1/2 = -9785.48		42	(-)410990.16
8	U_7	931.95/3x8x1 = -2485.2		66.5	(-)165265.8
9	U_8	2x931.95/3x8x1/2x1 = -2485.2		67.5	(-)167751
		ΣV_3=64068.52			ΣM_3=1451892.56

$$\sigma_t = P_v \sec^2\emptyset; \ (\tan\emptyset = 0.7)$$
$$= 1808.79(1 + 0.49) = 2695.09 \text{ kN/m}^2$$

Which is $< 3000 \ kN/\text{m}^2$ (safe)

Principal stress at heel

$$\sigma_h = P_v \sec^2\theta - P\,tan^2\theta$$

$(tan\ \theta = 0.063)$;

$$\sec^2\theta = 1 + \tan^2\theta = 1 + 0.0039 = 1.0039$$
$$= 459.54x1.0039 - (9.81x95)x0.0039$$

$= 455.84 \text{ kN/m}^2$Which is $< 500 \ kN/\text{m}^2 \ (safe)$

Shear stress at toe

$$\tau = P_v \tan\emptyset = 1808.79 \times 0.70 = 1266.15 \text{ kN/m}^2$$

Shear stress at heel

$$\tau = -(P_v - \text{P})\tan\theta$$
$$= -\{459.54 - (9.81x95)\}x\,0.063$$
$$= 29.76 \text{ kN}/m^2$$

The factor of safety against sliding and overturning should be found out only when reservoir is full &Full uplift acts, since the condition of sliding & overturning will be more critical in that case.

Case III: Reservoir Full with Uplift

Calculation of stresses

When reservoir is full, including self-weight of dam and water pressure, &uplift forces will be acting as forces. The resulting force ΣV_3 and resulting moment ΣM_3 for this case has worked out as follows:

Position of resultant from toe

$$X = \left(\frac{\Sigma M_3}{\Sigma V_3}\right) = \frac{1451892.56}{64068.52} = 22.66 \text{ m}$$

Position of resultant from the centre of the base is

$$e = \left(\frac{B}{2} - X\right) = \left(\frac{69.5}{2} - 22.66\right) = 12.09 \text{ m}$$

(i.e. The Resultant acts nearer the toe and tension will develop at the heel.)

Normal compressive stress

$$P_{max\,/min} = \frac{\Sigma V_3}{B}\left(1 \pm \frac{6e}{B}\right)$$
$$= \frac{64068.52}{69.5}\left(1 \pm \frac{6x12.09}{69.5}\right)$$

Normal compressive stress at toe

$P_v at\ toe = 1884.02 \text{ kN/m}^2 < 3000 \ kN/\text{m}^2$(safe)

Normal compressive stress at heel

$P_v at\ heel = -40.32 \text{ kN/m}^2 < 500 \ kN/\text{m}^2$(safe)

Principal stress at toe

$$\sigma_t = P_v \sec^2\emptyset; \ (\tan\emptyset = 0.7)$$
$$= 1884.02(1 + 0.49) = 2807.19 \text{ kN/m}^2$$

Which is $< 3000 \ kN/\text{m}^2$ (safe)

Principal stress at heel

$$\sigma_h = P_v \sec^2\theta - P\,tan^2\theta$$

$(tan\ \theta = 0.063)$;

$$\sec^2\theta = 1 + \tan^2\theta = 1 + 0.0039 = 1.0039$$
$$= 40.32x1.0039 - (9.81x95)x0.0039$$

$= 36.84 \text{ kN/m}^2$Which is $< 500 \ kN/\text{m}^2 \ (safe)$

Shear stress at toe

$$\tau = P_v \tan\emptyset = 1884.02 \times 0.70 = 1318.81 \text{ kN/m}^2$$

Shear stress at heel

$$\tau = -(P_v - \text{P})\tan\theta$$
$$= -\{40.32 - (9.81x95)\}x\,0.063$$
$$= 56.17 \text{ kN}/m^2$$

Calculation of Factor of Safety

(i) Factor of safety against overturning

$$= \frac{\sum M(+)}{\sum M(-)} = \left(\frac{3597707.80}{2145815.24}\right) = 1.68 > 1.5$$

Hence safe

(ii) Factor of safety against sliding

$$= \frac{\mu(\sum V_3)}{\sum H} = 0.7x\left(\frac{64068.52}{44267.63}\right) = 1.01 > 1.0$$

Hence safe

(iii) Shear friction factor

$$SFF = \frac{\mu \sum V_3 + \tau_c B}{\sum H}$$

$$= \frac{(0.7x64068.52 + 69.5x2200)}{44267.63}$$

$$= 4.47 > 4 \text{ to } 5 \quad \textit{Hence safe}$$

(iv) Safety against sliding as per IS 6512-1984

Taking f_ϕ =1.5 & f_c =3.6 for loading combination B,

$$F = \left\{\frac{\left(\frac{\mu \sum V_3}{f_\phi}\right) + \left(\frac{\tau_c B}{f_c}\right)}{\sum H}\right\}$$

$$= \left\{\frac{\left(\frac{0.7x64068.52}{1.5}\right) + \left(\frac{2200x69.5}{3.6}\right)}{44267.63}\right\}$$

$$= 1.64 > 1.0 \quad \text{Hence safe}$$

(ii) Stability check of Concrete Gravity dam by considering seismic forces:

For worst condition consider that,

i) Horizontal earthquake acceleration acts upstream.

ii) Vertical earthquake acceleration acts downwards.

Hydrodynamic pressure due to water caused by earthquake can be found out from zangers formula. Since the slope is upto middle depth, approximate value of θ can be found out by joining heel to the upstream edge.

Calculation of P_e:

P_e and the moment due to this hydrodynamic force is calculated and then all the forces and their moments are tabulated in table 1.1

Calculation of P_e from Zanger's formulas

$P_e = 0.726\, p_e H$

Where $p_e = C_m \alpha_h \gamma_w H$

tan θ = 95/3 = 31.66 or θ = 88.19°

$$C_m = 0.735x\left(\frac{88.19°}{90°}\right) = 0.72$$

At base $C = C_m$

Therefore $p_e = C_m \alpha_h \gamma_w H$

As per IS: 1893-1984, Clause 3.4.2.3

$$\alpha_h = \beta I \alpha_0$$

β = 1.00 for Dams (As per IS: 1893-1984, Clause 3.4.3, from Table 3)

I = 3.00 for dams (all types) (As per IS:1893-1984, Clause 3.4.2.3 and 3.4.4, from Table 4)

(As per IS: 1893-2002, Clause 3.4.2.1,3.4.2.3 and 3.4.5, from Table 2)

α_0=0.04for zone III in seismic coefficient method

$\therefore \alpha_h$=1.00×3.00×0.04=0.12

As per IS: 1893-1984, Clause 7.3.1.1, 7.3.1.2 Concrete or masonry inertia force due to horizontal and vertical seismic acceleration Seismic coefficient method (dams up to 100 m height)

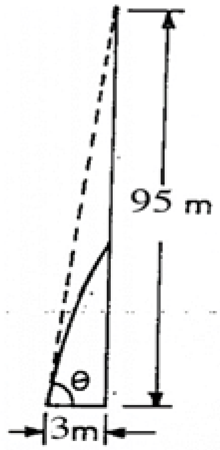

Fig .3.0

Horizontal seismic coefficient shall be taken as 1.5 times seismic coefficient α_h at the top of the damreducing linearly to zero at the base.

Vertical seismic coefficient shall be taken as 0.75 times the value of α_h at the top of the dam reducinglinearly to zero at the base.

The value of α_h (horizantal) = 1.5× 0.12 = 0.18

and α_v (vertical) = 0.75× 0.12 = 0.09

$$p_e = C_m \alpha_h \gamma_w H$$

Substitute C_m and α_h value in above equation

$$p_e = 0.72x0.18x9.81x95 = 120.78 \text{ kN/m}^2$$

Total pressure $P_e = 0.726\, p_e H$

$$P_e = 0.726x120.78x95 = 8330.20 \text{ kN}$$

Moment due to this force at base,

$$M_e = 0.412\, P_e H = 0.412 \text{ x } 8330.78 \text{ x } 95$$
$$= 326066.73 \text{ kNm}$$

When the reservoir full with all forces including uplift

Horizontal seismic forces moving towards the reservoir causing upstream acceleration, and thus producing horizontal forces towards downstream is considered, as it is the worst case for this condition. Similarly, a vertical seismic force moving downward and thus, producing forces upward, i.e., subtractive to the weight of dam is considered. Calculation of forces and moments due to inertial earthquake force is done below: -

Additional forces and their moments due to earthquake Position of resultant from toe

$$X = \left(\frac{\sum M_4}{\sum V_4}\right) = \frac{702268.08}{57163.04} = 12.29 \text{ m}$$

$$e = \left(\frac{B}{2} - X\right) = \left(\frac{69.5}{2} - 12.29\right) = 22.46 \text{ m}$$

The resultant is nearer the toe and tension is developed at the heel.

Average vertical stress

$$= \frac{\sum V_3}{B} = \frac{57163.04}{69.5} = 822.49 \text{ kN/m}^2$$

Normal compressive stress

Table 1.1

Sl No	Designation if any	Magnitude of force in kN: Vertical Downward (+ve) Upward (-ve)	Magnitude of force in kN: Horizontal Towards Upstream (-ve) Towards Downstream (+ve)	Lever arm in m	Moments about toe in Anticlock wise (-ve) and Clockwise (-ve) in kN m
1	2	3	4	5	6
Inertial force due to earthquake on weight of dam					
1	$\sum V_1$	-76727.51x 0.09 = -6905.48			
2	W_1	-	-15627.5 x 0.18 = -2812.95	47.5	-133615.13
3	W_2	-	-59425.63 x 0.18 = -10696.61	26.66	-285171.62
4	W_3	-	-1674.38 x0.18 = -301.39	15.83	-4771.00
Hydrostatic pressure					
5	P_e		8330.20		-326066.73
	Total	$\sum V_1$ = -6905.48	$\sum H$ = 22141.15		$\sum M$ = - 749624.48
Sum of forces and moments from previous Table 1.0					
6	$\sum V_3$	$\sum V_3$ = 64068.52	-		- 2145815.24
7	H	-	1/2x95²x9.81 =44267.63		+ 3597707.80
	Sum	ΣV_4= 57163.04	$\sum H$= 66408.78		ΣM_4= 702268.08

$$P_{max/min} = \frac{\sum V_4}{B}\left(1 \pm \frac{6e}{B}\right)$$

$$= \frac{57163.04}{69.5}\left[1 \pm \frac{6x\ 22.46}{69.5}\right]$$

p_v at toe = 822.49 x2.94 = 2418.12 kN/m^2
Which is <3000 kN/m^2(safe)
p_v at heel = - 822.49x 0.94 = -773.14 kN/m^2
Which is <500 kN/m^2(safe)

Since the tensile stress developed is less than the safe allowable value, the dam is safe even examined with seismic forces, under reservoir full condition.

Principal stress at toe

$\sigma_t = P_v \sec^2 \emptyset$; $(\tan \emptyset = 0.7)$
$= 2418.12(1 + 0.49) = 3602.99$ kN/m^2
Which is > 3000 kN/m^2 (unsafe)

Principal stress at heel

$\sigma_h = P_v \sec^2 \theta - P\, tan^2\theta$
$(tan\ \theta = 0.063)$;
$\sec^2 \theta = 1 + \tan^2 \theta = 1 + 0.0039 = 1.0039$
$= -773.14x1.0039 - (9.81x95)x0.0039$
$= -779.79$ kN/m^{2}Which is $< 500\ kN/m^2\ (safe)$

Shear stress at toe

$\tau = P_v\ tan\emptyset = 2418.12 \times 0.70 = 1692.68$ kN/m^2

Shear stress at heel

$$\tau = -(P_v - \mathrm{P})\tan\theta$$
$$= -\{-773.14 - (9.81x95)\}x\ 0.063$$
$$= 107.42\ kN/m^2$$

Calculation of Factor of Safety

(i) Factor of safety against overturning

$$= \frac{\sum M(+)}{\sum M(-)} = \left(\frac{3597707.80}{2895439.72}\right) = 1.24 < 1.5$$

Hence unsafe

(ii) Factor of safety against sliding

$$= \frac{\mu(\sum V_3)}{\sum H} = 0.7x\left(\frac{57163.04}{66408.78}\right) = 0.60 < 1.0$$

Hence unsafe

(iii) Shear friction factor

$$SFF = \frac{\mu \sum V_3 + \tau_c B}{\sum H}$$
$$= \frac{(0.7x57163.04 + 69.5x2200)}{66408.78}$$
$$= 2.69 < 3$$

Hence unsafe

(iv) Safety against sliding as per IS 6512-1984

Taking $f_\emptyset$ =1.5 &f_c =3.6 for loading combination B,

$$F = \left\{\frac{\left(\frac{\mu \sum V_3}{f_\emptyset}\right) + \left(\frac{\tau_c B}{f_c}\right)}{\sum H}\right\}$$
$$= \left\{\frac{\left(\frac{0.7x57163.04}{1.5}\right) + \left(\frac{2200x69.5}{3.6}\right)}{66408.78}\right\}$$
$$= 1.04 > 1.0$$

Hence unsafe

17. Observations and Results

Table 1.2 Results for Maximum Stresses
(Stability Check of Concrete Gravity Dam without considering Seismic Forces)

Sl No	Stress at toe: Max.Normal (kN/m²)	Stress at toe: Max.Principal (kN/m²)	Stress at toe: Max.Shear (kN/m²)	Stress at heel: Max.Normal (kN/m²)	Stress at heel: Max.Principal (kN/m²)	Stress at heel: Max.Shear (kN/m²)
CASE I: RESERVOIR EMPTY CONDITION						
1	124.22	185.09	86.95	2083.77	2091.89	131.28
CASE II: RESERVOIR FULL WITH NO UPLIFT						
2	459.54	2695.09	1266.15	1808.79	455.84	29.76
CASE III: RESERVOIR FULL WITH UPLIFT						
3	-40.32	2807.19	1318.81	1884.02	36.84	56.17
(Stability Check of Concrete Gravity Dam by considering Seismic Forces)						
RESERVOIR FULL WITH ALL FORCES INCLUDING UPLIFT						
4	2418.12	3602.99	1692.68	-773.14	-779.79	107.42

Table 1.3 Comparison of Design Results of Concrete Gravity Dam with and without Seismic Forces

Sl No	Action/Consideration	Magnitude	Effect	Check	Comment
1	2	3	4	5	6
IN ABSENCE OF SEISMIC FORCES					
1	F.O.S. against overturning	1.68	Overturning	Safe	Stable
2	F.O.S. against sliding	1.01	Sliding	Safe	Stable
3	Shear friction factor	4.47	Shearing	Safe	Stable
4	Safety against sliding As per IS 6512 - 1984	1.64	Sliding	Safe	Stable
SEISMIC FORCES EFFECT					
1	F.O.S. against overturning	1.24	Overturning	Unsafe	Unstable
2	F.O.S. against sliding	0.60	Sliding	Unsafe	Unstable
3	Shear friction factor	2.69	Shearing	Unsafe	Unstable
4	Safety against sliding As per IS 6512 - 1984	1.04	Sliding	Safe	Stable

18. Conclusion

The behaviour of Gravity dam for stability and response towards seismic forces are studied in this paper. With problem consideration the stability analysis of gravity dam is done in absence of seismic forces initially. Thus, analysis highlighted that in presence of various loads like dead load, water/ hydrostatic pressure, uplift pressure, total cumulative values of +ve moment and -ve moment, summation of horizontal and vertical forces are overall responsible for dam stability. Further with analysis it is clear that moment resulting due to self-weight act as resistive moment against moment produced due to water, uplift pressure etc. Which means that stability against overturning is achieved when +ve moment is greater than -ve moments. Whereas stability against sliding depends upon coefficient of friction, sum of all vertical forces and all horizontal forces. Thus, sliding is governed by uplift pressure. More friction coefficient & more summation of vertical forces results stability against sliding. However, if horizontal force increases stability against sliding decreases if vertical forces remain approximately same. Third stability of dam is on basis of shear friction factor, this depends upon coefficient of friction, summation of all vertical forces, summation of all horizontal forces, geometry of dam and materials shear strength. For same problem material shear strength, geometry friction remains unchanged, thus stability should depend upon sum of all vertical forces and all horizontal forces. For problem considered in study, dam achieves stability against all factors i.e. overturning, sliding &shearing. The dam is unsafe only sliding and S.F.F., for which shear key etc. can be provided.

References

[1] Bureau of Indian standards publication IS: 1893-1984 criteria for Earthquake Resistant design of structures.
[2] Seismic analysis for safety of dams, IOSR journal of civil engineering, vol 6, 2013.
[3] IS: 6512-1984 criteria for design of solid gravity dams.
[4] Irrigation water resources and water power engineering by B.C Punmia.
[5] Irrigation Engineering and Hydraulic Structures by Santosh Kumar Garg
[6] Dr. D.S Saini (1983), “Dams and Earthquake”. Department of civil engineering, University of Roorkee.
[7] Earthquake Tips (C.V.R. MURTHY, Dept. of Civil Engg. IIT Kanpur)
[8] H.D Sharma (1981) “concrete Dams – Criteria for Design.” University of Roorkee. Metropolitan publication New Delhi.

Author Profile

Er Venkata Raju Badanapuri, Executive Engineer, Water Resources Department, Government of Andhra Pradesh, India. His educational Qualifications includes Institute of Engineers India, C.E (India), F.I.E. He did Post-Graduation in M. Tech (Structural Engineering), J.N.T University, Hyderabad. He did B.E.(Civil), Andhra University, Vishakhapatnam. He has following Journal Publications in his name:
1. “Indian Scenario of Water Resources - An Overview, Integrated Water Management and Major Issues related to Indian Waters " in ISSN:2321-7758, Vol.6., Issue.5, 2018 Sept-Oct., PP 64-70, International Journal of Engineering Research by Venkata Raju Badanapuri
2. “An Overview of Integrated theory of Irrigation Efficiency and Uniformity and Crop Water Use Efficiency Indian Waters " in ISSN:2321-7758, Vol.6., Issue.6, 2018 Nov-Dec., PP 11-26, International Journal of Engineering Research by VenkataRaju Badanapuri
3. “Water Resources Scenario in India: Its Requirement, WaterDegradation and Pollution, Water Resources Management” ine-ISSN:2348-6848, Volume 05 Issue 23December 2018,PP 672-696,International Journal of Researchby VenkataRaju Badanapuri