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Study of Various Physical Forces Acting on the Mega Structure-Gravity Dam

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Abstract: ***This paper presents a detailed study of the physical forces acting on gravity dams. Various types of dams were studied to understand their structural behavior and force-resisting mechanisms. Their basic forces balancing technique, their usage and functionality was understood. Out of all the various types of dams, gravity dam was taken as core mega structure. The main purpose of this study is to understand various forces acting on the gravity dam. The physical forces were seen physically by visiting dam site i.e., Dharoi Dam which is gravity dam on the Sabarmati River near Dharoi, Satlasna taluka, Mehsana district, northern part of Gujarat, India.***

Keywords: Gravity dam, forces acting on gravity dam, dharoi dam

1. Introduction

A dam is a physical structure used for the confinement of water serving various other purposes. A major component of the dam is the reservoir that holds a large amount of water. The structure of the dam includes storing water at a higher altitude and forcing it to flow along the direction of gravity. The gravitational energy being harnessed to convert it into electrical energy. A major purpose for creating dams is moderating the amount of rainwater to control floods and using the same extra water for generate electricity. There are various types of dams based upon purpose, structure etc. In the paper presented we will see what are the various types of dams along with their structural part, forces acting on it and how we can analyze the forces.

2. Types of Dams

2.1 Based upon purpose

- Storage dam - It is constructed to create a reservoir to store water during periods when there is huge flow in the river (in excess of demand) for utilization later during periods of low flow (demand exceeds flow in the river). Water stored in the reservoir is used for irrigation, power generation, water supply etc. By suitable operation, it can also serve as a detention dam.
- Detention dam - It is primarily constructed to temporarily detain all or part of the flood water in a river and to gradually release the stored water later at controlled rates so that the entire region on the downstream side of the dam is protected from possible damage due to floods. It may also be used as a storage dam.
- Diversion dam - It is constructed to divert part of or all the water from a river into a conduit or a channel. For diverting water from a river into an irrigation canal, mostly a diversion weir is constructed across the river.
- Cofferdam - It is a temporary dam constructed to exclude water from a specific area. It is constructed on the u/s side of the site where a dam is to be constructed so that the site is dry. In this case, it behaves like a diversion dam.
- Debris dam - It is constructed to catch and retain debris flowing water
- Overflow and non-overflow dams - An overflow dam is constructed to permit the flow of overflowing water. A part of the dam is generally an overflow while the other is not
- Rigid and non-rigid dams - Rigid dams are constructed with concrete, stone and steel while non rigid dams are constructed with sand, silt, etc

2.2 Based upon structure

- Gravity Dams: These dams rely on their own weight and mass to resist the forces of water pressure. They are usually made of concrete or masonry and are constructed across valleys or rivers. Gravity dams are known for their stability and are commonly used for largescale projects.



Figure 1: Sardar Sarovar Dam, Gravity Dam

- Arch Dams: Arch dams are curved structures that transfer the water pressure to the abutments or sides of the valley. They are designed to resist the horizontal thrust of water by redirecting it into the surrounding rock or soil. Arch dams are often made of concrete and require a solid foundation.



Figure 2: Idduki Dam, Arch Dam

- Embankment Dams: Also known as earth dams, these dams are constructed using compacted soil, clay, rock, or other materials. They are built by placing a barrier across a river or valley and then compacting layers of material on both sides. Embankment dams can be further classified into three types: a. Homogeneous Embankment Dams: These dams are constructed using a single type of material, such as compacted earth or rock fill. b. Zoned Embankment Dams: Zoned dams have different zones or sections composed of different materials with varying properties. This allows for better stability and seepage control.
- Rockfill Dams: Rockfill dams are constructed using a combination of rock fragments and soil. They are designed to withstand the forces of water and often have an impervious core or membrane to control seepage.



Figure 3: Tehri Dam, Embankment Dam

- Buttress Dams: Buttress dams consist of a series of supports or buttresses on the downstream side of the dam. These buttresses are used to counteract the water pressure and transfer it to the foundation. Buttress dams are commonly made of reinforced concrete and are suitable for sites with wide valleys and deep foundations.
- Arch-Gravity Dams: These dams combine the features of arch dams and gravity dams. They have a curved upstream face like an arch dam, but also rely on their weight to resist the water pressure. Arch-gravity dams are commonly used for large-scale projects where both arch action and gravity action are necessary.
- Composite Dams: Composite dams are constructed using a combination of different materials. For example, they may have a concrete base with an embankment section built on top. These dams are designed to take advantage of the benefits of multiple materials and are often used in complex geological conditions

3. Various Parts of Gravity Dam

- Heel: It is in contact with the ground on the upstream side.
- Toe: It is in contact with the bottom part of dam in downstream side.
- Abutments: It is the sides of the valley where the structure rests
- Galleries: They are small rooms for maintenance which gives access to the inside of the dam.
- Diversion tunnels: They are used for diverting excess water.
- Spillways: They are used to release excess water also acts as the safety structure of the dam.
- Sluiceway: It is an opening in the dam

4. Elementary Profile of the Gravity Dam

To understand various forces acting on gravity dam, first we need to understand the elementary profile of the gravity dam. Basically, elementary profile is the theoretical shape of the gravity dam in which there is no width at the top and no free board, and only three major forces are taken into consideration i.e., gravity force also termed as self-weight, water pressure and uplift pressure. The elementary profile of a gravity dam is represented by a right-angled triangular section.

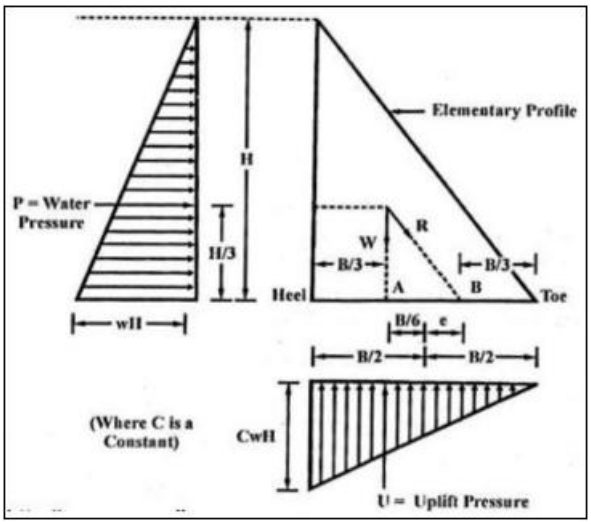


Figure 4: Elemental shape of the Gravity Dam

(a) Self weight of the dam

Weight of dam (W) $= \frac{1}{2} \times B \times H \times Y$

where, Y = Density of the material which is used for construction of gravity dam, majorly Y of concrete is used in kN/m^3.

B = Base width of elementary profile

H = height of elementary profile.

The weight (W) force acts vertically through the centroid of the triangle (i.e., center of mass of the triangular shape) at a distance of B/3 from the heel as mentioned in the figure 4.

(b) Hydrostatic pressure/ water pressure
$P = 1/2 \times Y_w \times H^2$
Y_w = Density of the water (taken as $9.81 kN/m^3$)
H = Height of elementary profile.
This is acting at height of H/3 from base as shown in figure 4.

(c) Uplift Pressure
U = 1/2CwBH
C= coefficient of uplift pressure intensity.
w = unit weight of water
B = Base of width of elementary profile
H = Height of the elementary profile

This is acting at base width of B/3 from heel of the elementary profile.

Now the base width of the elementary profile is to be analyzed into two major criteria
1) Reservoir is empty
2) Reservoir is full

5. Forces Acting on Gravity Dam

Generally, the most significant force acting on a gravity dam is the gravitational force itself. The most significant factor for determining the overturning of a dam is to consider if the weight of the dam is capable of withstanding all the force. Another force that tries to stabilize the dam is the thrust force exerted by the water. On the other hand, the forces trying to destabilize the dam are:

- Reservoir water pressure
- Uplift
- Forces due to waves in the reservoir
- Ice pressure
- Silt pressure
- Seismic forces
- Self-weight

(a) Water pressure: This is the most elementary forces which is explained in elementary profile of the dam. Hydrostatic force can be used to measure horizontal water pressure caused by water that is held dam's upstream side.

(b) Uplift pressure: Water seeping through the foundation material's pores as well as the dam's body and down to the bottom through the joints where the body of the dam meets the foundation at the base causes an uplift strain on the base of the dam. This is considered one of the most critical forces acting on the elementary profile of Gravity dam that can potentially lead failure of gravity dam

This type of uplift pressure effectively lessens the downward weight of the dam's body and undermines its stability. It is given that the forces of an earthquake have no impact on uplift pressure.

Construction of weighted walls beneath the upstream face, drainage channels between the dam and its foundation, and pressure grouting of the foundation can all be used to regulate it. Its calculation is explained in the elementary profile of the gravity dam.

(c) Forces due to waves in the reservoir: The blowing winds create waves to form on the reservoir's surface, and depending on the wave height, these waves may push pressure to the downstream side. The equation below can be used to determine wave height:

$$h_w = 0.032\sqrt{\ } vf + 0.763 - 0.271f\frac{3}{4}$$

where, h_w = height of water from top of crest to bottom of trough in meters.
v = wind velocity in km/h.
f = fetch or straight length of water expanse in km.

The maximum pressure intensity due to wave action may be given by,

Pw $= 2.4\gamma$ h and acts at $h_w/2$ meter above the silt water surface.

The pressure distance is assumed to be triangular of height 5hw/3. The total force due to wave action, $= 19.62wh^2$.

This force acts at a distance $3/8\ h_w$ above the reservoir surface.

(d) Ice pressure: In colder climates, the ice that forms on the water surface of the reservoir occasionally melts and consequently expands. The increasing ice must then be resisted by the dam face. Over the dam's length and at the reservoir's level, this force behaves linearly. In Indian topographical condition, ice pressure is least considered in the calculation.

(e) Silt pressure: The force exerted by the silt in addition to the external water pressure may be described by Rankine's formula if " h " is the height of the silt deposit.

Psilt $= 0.5ph^2$ Ka and it acts at h/3 from base. where, Ka $= \frac{1-\sin\Phi}{1+\sin\Phi}$

$\gamma(s)$ = submerged unit weight of silt material, h = height of silt deposited

(e)Seismic forces: An earthquake generates waves that have the power to shake the dam in all directions. Failure of gravity dam can be incited by an earthquake of strong magnitude. The effect of an earthquake is the same as giving the dam's foundation an acceleration in the direction of the wave. One may divide acceleration into two parts:

Horizontal Acceleration = Kh × g
Vertical Acceleration = K × g

The values of these accelerations are generally expressed as % of acceleration due to gravity (g).

Effect of Vertical Acceleration
There can be upward or downward vertical acceleration. The foundation of the dam will be elevated higher and drawn

closer to the dam body as it acts upward, increasing the effective weight of the dam and raising the created stress. The foundation will attempt to slide downhill from along the dam's body while the acceleration is operating downward, which will lessen the dam's stability and effective weight. Thus, this sort of acceleration will produce the following inertia force:

$= W(1 - Kv)$

- Effect of Horizontal Acceleration

It causes the following two forces:
Hydrodynamic pressure.
Horizontal inertia force.

(f) Self-weight: The main opposing force is the weight of the dam body and its base. The unit length of the gravity dam is taken into account in the study in two dimensions. The c/s can then be split up into triangles and rectangles. The sum of all these downward pressures pushing on the dam's center of gravity will be the overall weight of the dam. Weight of the dam is the major resisting force against failure of gravity dam. Its detail analysis is done in the elementary profile of the gravity dam.

6. Types of Failure of Gravity Dam

Gravity dams may experience several types of structural failure. They include:

1) Overturning of the dam about the toe
2) Sliding failure which is also known as shear failure of dam.
3) Compression failure which is majorly materialistic property of the dam.
4) Tension failure which is important as it develops cracks in the dam.

6.1 Overturning failure

Horizontal forces acting on a dam such as water pressure, silt pressure, wave pressure creates the overturning moments in the dam. Only resisting moment is developed by the self-weight of the dam. If take the submission of all the moments (about toe) created by horizontal forces it will always try to rotate and overturn the dam about the toe, this is why it is known as overturning failure. Ratio of resisting moment to the overturning moment is factor of safety (FOS) for the dam against overturning failure. Generally, FOS is kept between 2-3.

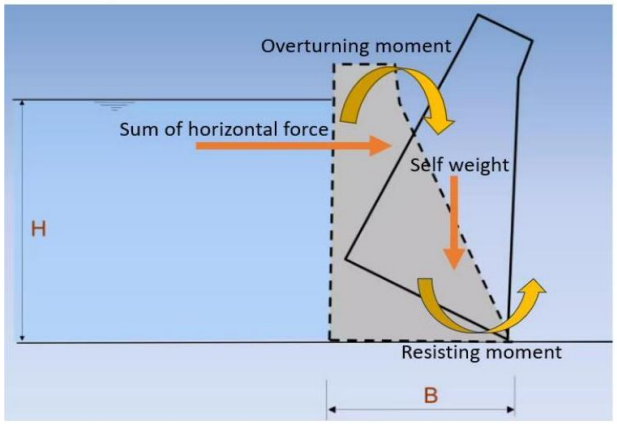


Figure 5: Illustration of overturning of dam

6.2 Sliding failure

Horizontal forces which are acting on the dam is counteracted by the frictional forces which is produced at the base of the dam and acts between base of the dam and foundation. Its factor of safety is calculated on the very simple basis as explained below:

$$\text{Fos (Factor of safety)} = \frac{\mu \sum H}{\sum V}$$

$\sum H$ = sum of all the horizontal forces
$\sum V$ = sum of all the vertical forces
μ = coefficient of friction

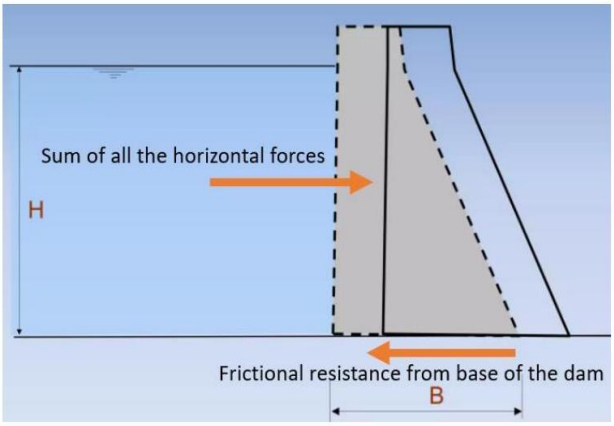


Figure 6: Illustration of sliding failure of dam

6.3 Compression failure

A gravity dam may be failed by failure of its construction material especially concrete or masonry which are good in compression. If the compressive stresses produced in the dam exceeds the allowable compressive stresses the dam fails in compression also known as crushing failure.

6.4 Tension failure

Construction material which is used in construction of the gravity dam is majorly masonry and concrete which are weak in tension. This is the reason why gravity dam is designed in such a way that no tension is developed anywhere in the dam. If tension cracked is developed it will result in the tension crack. Tension crack always leads to progressive failure of the dam.

7. Site Visit to Dharoi Dam

7.1 Dam information

- Dam type: Gravity dam
- Maximum height above the lowest point of foundation: 45.87 m
- Length at top of the dam: 1207 m
- Location: Vill Dharoi, Taluka - Kheralu, DistMehsana, State- Gujarat, India
- River: Sabarmati river
- Area of catchment: 5475 km^2
- Gross storage capacity: 907.88Mm^3
- Total concrete volume: 0.07Mm^3
- Total masonry volume: 0.24Mm^3
- Total earthwork volume: 1.58Mm^3



Figure 7: Dharoi dam

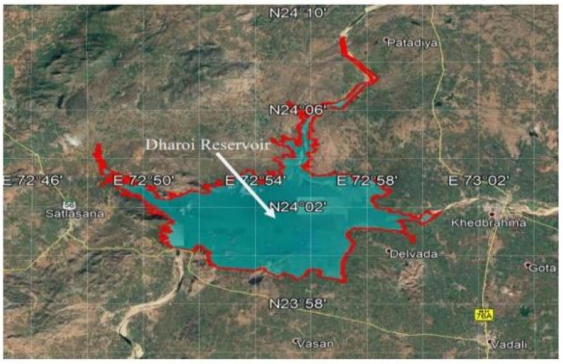


Figure 8: Location of Dharoi dam

Table 1: Silent feature of Dharoi Dam

Date	Crest R.L. (M.)	F.R.L. (M)	H.F.L. (M)	Top of Dam R.L.(M)	Gross Capacity at F.R.L. (MCM)	Dead storage (MCM)	Live storage (MCM)	Length of Spillway (M)
02-09-1973	178.92	189.59	192.24	195.07	823.1	88.06	735.04	219.46

From the data shown in section 7.1, total height of dam from foundation is 45.87 m and from table 1 top of dam has RL (Reduced level, measured from the mean sea level) is 195.07 m . We can calculate the RL of the RL of the bottom of the dam by subtracting height of the dam from top of the dam. Thus, it will result in the following information:

Top of the dam RL - height of the dam from bottom = RL of the bottom of the dam,
Thus $195.07\ \text{m} - 45.87\ \text{m} = 149.2\ \text{m}$

7.2 Site data collection

Following data were collected on dam site for calculation of horizontal thrust

Table 2: Data of the water levels at Dharoi dam site

Date	Site	District	State	Type	Category	Rule Level (m)	FRL (m)	Actual height of water	OSL (m)
29/08/23	Dharoi	Mehsana	Gujarat	G	Major	188.67	189.59	39.47	175.87
30/08/23	Dharoi	Mehsana	Gujarat	G	Major	188.67	189.59	39.47	175.87
31/08/23	Dharoi	Mehsana	Gujarat	G	Major	188.67	189.59	39.47	175.87
01/09/23	Dharoi	Mehsana	Gujarat	G	Major	188.67	189.59	39.47	175.87
02/09/23	Dharoi	Mehsana	Gujarat	G	Major	189.28	189.59	40.08	175.87
03/09/23	Dharoi	Mehsana	Gujarat	G	Major	189.28	189.59	40.08	175.87
04/09/23	Dharoi	Mehsana	Gujarat	G	Major	189.28	189.59	40.08	175.87
05/09/23	Dharoi	Mehsana	Gujarat	G	Major	189.28	189.59	40.08	175.87
06/09/23	Dharoi	Mehsana	Gujarat	G	Major	189.28	189.59	40.08	175.87

The above data that was collected from the dam site, our main primarily data which is important for the calculation of water horizontal thrust is "Actual height of water", which is calculated by subtracting Rule level from RL of the bottom of the dam which is 149.2 m as calculated earlier. If we take average of that column is 39.808 m which can be considered as average rule level of the water during the visited tenure. The typical dam spillway cross section diagram was also provided, based upon the diagram one illustrative dam cross section was drawn which is shown in further sections.

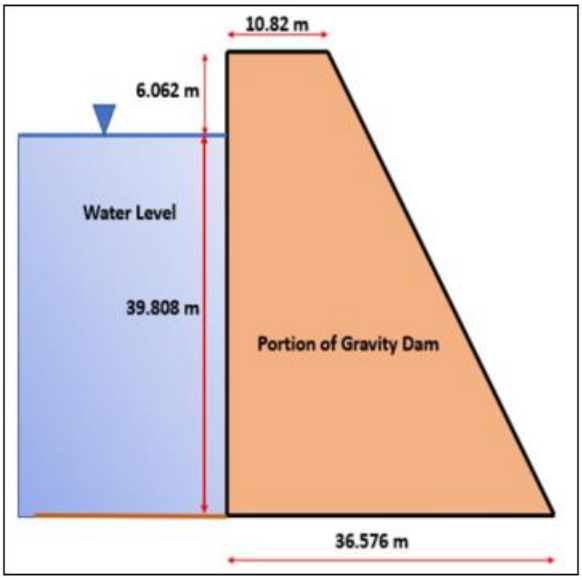


Figure 9: Illustrative diagram of cross section of Dharoi Dam

7.3 Calculation of the known forces on the dam

- Hydrostatic force: As stated earlier, hydrostatic force can be calculated as follows:
  Hydrostatic force $= 1/2 \times Y_w \times H^2$
  $= 1/2 \times 1000 \times 9.81 \times 39.808^2 = 7{,}772 \text{kN/m}$
  Total force $= 7{,}772 \times 1{,}207$ m (length of dam) = 93,80,804 kN
  39.808 m is the height of the water from fig 9.
  The force of application is $H/3$ from base which is $39.808/3 = 13.269$ m from base.
- Gravity force: As we can see that Dharoi gravity dam is made up of 3 material concrete, masonry and earthwork. We had the volume, we will calculate the total weight of each material by multiplying the volume with their respective unit weight (density)

Weight of concrete (W_1) = volume x unit weight of concrete
$W_1 = 0.07 \times 10^6 \times 2500 \times 9.81 = \mathbf{17,16,750\ kN}$
(Density of concrete as per IS Code 456:2000 is 2500 kg/m^3)
Weight of the masonry (W_2) = volume x unit weight of masonry

$W_2 = 0.24 \times 10^6 \times 2600 \times 9.81 = 61{,}21{,}440\text{kN}$
(Density of stone masonry is 2600 kg/m^3)
Weight of earthwork (W_3) = Volume x unit weight of earthwork

$W_3 = 1.58 \times 10^6 \times 1800 \times 9.81 = \mathbf{2,78,99,640\ kN}$
(Density of stone masonry is 1800 kg/m^3)
Total weight for the gravity dam$(W) = W_1 + W_2 + W_3$
$W = 2{,}78{,}99{,}640\text{kN} + 61{,}21{,}440\text{kN} + 17{,}16{,}750\text{kN}$
$\mathbf{W = 3,57,37,830\ kN}$

Acting at $B/3$ of the base i.e. $36.576/3 = 12.192$ m from heel end.

All the remaining forces like silt force, earthquake forces, wave forces were unable to calculate due to lack of the information and confidential data of the site.

7.4 Analysis of forces on the dam

a) Safety against overturning
Total horizontal forces = 93,80,804 kN
Moment of horizontal forces about toe = $93{,}80{,}804\text{kN} \times 13.269$ m
Overturning Moment $M_o = 12{,}44{,}73{,}888\text{kN.m}$
Total vertical forces = $3{,}57{,}37{,}830\text{kN}$
Moment of vertical forces about toe = $3{,}57{,}87{,}830\ \text{kNx}(36.576 - 12.192)\text{m}$
Resisting Moment $(M_R) = 87{,}26{,}50{,}446\text{kN.m}$
Factor of safety against overturning $= \frac{M_R}{M_o}$
$\text{FOS} = \frac{87{,}26{,}50{,}446}{12{,}44{,}73{,}888} = 7.01$
As FOS ≥ 1, dam is safe against overturning failure.

b) Safety against sliding
As we mentioned earlier, gravity dam should be checked against the sliding failure. For sliding failure factor of safety is stated as below
Factor of safety $= \frac{\mu \Sigma V}{\Sigma H}$
Factor of safety $= \frac{0.35 * 3{,}57{,}87{,}830}{93{,}80{,}804} = 1.3$
As FOS ≥ 1, dam is safe against sliding failure.

7.5 Limitations and assumptions made for the analysis

- Actual data may vary due to restriction of availability of confidential government's data. However, we had tried our best to match the data with the actual site conditions.
- In practical conditions there are various forces which acts on gravity dam but for the analysis purpose all the data were not available for the calculation part hence other forces calculations such as silt pressure, earthquake pressure, wave pressure etc. were not done.
- The rule level of the water is time dependent. The represented data is only data which was collected during the visit tenure.
- For calculation purpose homogenous section was assumed but in actual the material compositions are going to vary.

8. Conclusions and Discussion

- The main purpose was to study the physical forces acting on mega structure which is completely understood by both theoretical and practical means.
- Various reasons for the failure of the gravity dam are completely understood and respective analysis with actual site conditions were done.
- The analyzed FOS for overturning failure comes out to be 7.01 which is very high compared to the actual FOS i.e., 1.5-2. This is because various assumptions were made and all the forces actually coming on the mega structure were not considered due to lack of availability of the data. But what is the effect of resisting moment vs overturning moment was understood.
- The analyzed FOS for sliding failure comes out to be more than 1 which should be in range of 1.5-2, the variation is because of the same reasons which are mentioned above.
- Both horizontal and vertical forces play important roles in the structural stability of gravity dams.
- We took suitable assumptions wherever it was required to make the analysis more in generalized manner.

References

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[2] Reservoir data management system, Government of Gujarat.
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