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Stability Analysis of Gravity Dam Structures in India: Calculation Methods and Procedures

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ABSTRACT
Gravity dams play a crucial role in India's water resource management and hydropower generation. The stability of these structures is of utmost importance to ensure their safe and reliable operation. This review paper focuses on the calculation methods and procedures employed in the stability analysis of gravity dam structures in India. The study aims to provide an overview of the design considerations, loading conditions, failure mechanisms, and analysis techniques specific to Indian gravity dams. Additionally, relevant case studies and practical aspects of stability analysis are discussed to highlight the current practices in the country.

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I. INTRODUCTION

Gravity dams in India serve as essential infrastructure for water storage, irrigation, and power generation. This section introduces the significance of stability analysis and the importance of understanding the specific considerations for gravity dams in the Indian context.

1. Design Considerations for Indian Gravity Dams

Geometry and Layout: This refers to the design aspects related to the dam's cross-sectional shape, crest length, upstream and downstream slopes, and spillway arrangement. The geometry and layout should be optimized to ensure stability and efficient water management.

Foundation Conditions: The foundation plays a critical role in the stability of a gravity dam. This sub-point focuses on evaluating the geological and geotechnical characteristics of the foundation, including soil properties, rock mass quality, and potential for seepage or sliding.

Foundation Conditions: The foundation plays a critical role in the stability of a gravity dam. This sub-point focuses on evaluating the geological and geotechnical characteristics of the foundation, including soil properties, rock mass quality, and potential for seepage or sliding.

Material Selection and Properties: The choice of construction materials and their properties significantly impact the stability of a dam. This sub-point discusses the selection of suitable materials, such as concrete or masonry, and considerations related to strength, durability, and construction techniques**.**

Structural Design Codes and Guidelines: Indian gravity dams are designed according to specific design codes and guidelines provided by organizations such as the Central Water Commission (CWC). This sub-point outlines the key design criteria and safety factors incorporated into the structural design process [1]

2. Loading Conditions for Indian Gravity Dams

Water Pressure and Reservoir Characteristics: The hydrostatic pressure exerted by water in the reservoir is an important factor in dam stability. This sub-point emphasizes the estimation of water pressure and considerations related to reservoir characteristics, including water level fluctuations and sedimentation.

Seismicity and Earthquake Loads: India is prone to seismic activity, making earthquake considerations crucial in dam design. This sub-point discusses the assessment of seismic hazards, ground motion analysis, and the determination of seismic loads acting on gravity dams.

Temperature Effects: Temperature variations can cause thermal stresses in the dam structure, affecting its stability. This sub-point addresses the evaluation of temperature effects, including the differential thermal expansion of materials and resulting internal forces.

Flood and Spillway Design Considerations: Gravity dams must be designed to safely handle flood events and accommodate spillway discharges. This sub-point highlights the importance of assessing flood characteristics, designing spillways, and managing potential flood-related risks [2]

3. Failure Mechanisms in Indian Gravity Dams:

Sliding and Overturning Failure: This sub-point explores the potential for sliding and overturning of the dam structure due to inadequate foundation support or excessive horizontal forces. Measures to prevent or mitigate these failures are discussed.

Structural Failure and Cracking: Structural failure may occur due to inadequate design, poor construction quality, or material deterioration. This sub-point examines the causes and consequences of structural failures, including cracking, and emphasizes the need for structural monitoring and maintenance.

Erosion and Piping Failure: Erosion and piping can lead to the formation of internal pathways for water flow, weakening the dam's foundation and structure. This sub-point discusses erosion and piping mechanisms and highlights preventive measures, such as suitable filters and grouting techniques.

Seismic Vulnerabilities: Considering India's seismicity, gravity dams must be designed to resist seismic forces. This sub-point explores the specific vulnerabilities of gravity dams to earthquakes, including the risk of foundation failure and the potential for liquefaction [3]

4. Calculation Methods for Stability Analysis:

Limit Equilibrium Analysis: Limit equilibrium methods, such as the Bishop and Janbu methods, are widely used for stability analysis. This sub-point explains the principles behind these methods and their application in assessing the stability of Indian gravity dams.

Finite Element Analysis: Finite element analysis (FEA) is a numerical method used to simulate the behavior of complex dam structures under various loading conditions. This sub-point discusses the application of 2D and 3D FEA techniques, material modeling, and boundary conditions for stability analysis [4].

Forces and Moments Analysis : The acting forces and moments are summarized in the tables below. See Table 1.1 for horizontal and vertical loads and Table 1.2 for positive and negative moments acting on the dam.

Table 1. Summarized horizontal and vertical design loads.

	ΣF_H [MN]	ΣF_V [MN]
Normal	200.6	290.8
Critical	174.5	287.5

Table 1.2. Summarized positive and negative moments.

	$\Sigma M+$ [MNm]	$\Sigma M-$ [MNm]
Normal	8348.8	-13789.7
Critical	9224.1	-13922.3

The arm of force in both *X*- and *Y*-direction from dam center are calculated and presented in Table 1.3

Table 1.3 Center of mass for the arm of force in *X*- and *Y*-direction.

	X [m]	*Y* [m]
Normal	23.1	56.6
Critical	18.7	54.3

Limit States

The factor of safety against sliding is presented in Table. 1.4

Table 1.4. Factory of safety against sliding

Calculation Condition	δδ0 *T S* [MN]	1/ δδ0 *R* [MN]	SF
Normal	202.6	256.0	1.26
Critical	163.1	253.7	1.56
Normal + Earthquake	187.6	256.0	1.37

The induced compressive stress compared to the concrete's compressive strength is listed in Table 1.5

Table. 1.5Factor of safety against compressive stress.

Calculation Condition	*δδ0 T S* [MPa]	*1/ δδ0 R* [MPa]	SF
Normal	5.2	14.1	2.73
Critical	4.5	14.1	3.13
Normal + Earthquake	4.8	14.1	2.93

Table 4.7 shows the tensile stress induced on the dam heel, where values < 0 indicates ten-sile failure.

Table 1.6. Design tensile stress at dam heel.

Calculation Condition	*δδ0 T S* [MPa]
Normal	0.9
Critical	0.6
Normal + Earthquake	0.5

SLOPE/W

Numerical calculations of the slope stability of the dam show 55 possible slippery surfaces where all show stable results. The most important slip surfaces are shown in Fig.1.7. The results show that the lowest safety factor is 2.26. It is observed that all the possible slippery surfaces in the base layer are very shallow.

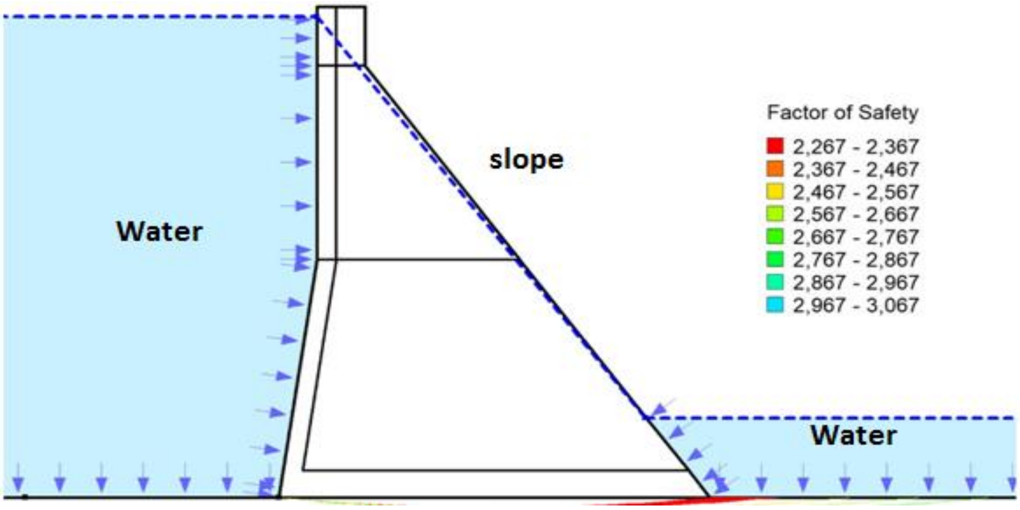

Figure 1.7. Factor of safety against sliding, normal water case.

A similar result is observed when applying the critical water case. Specifically, the safety factor of the most critical surface increases from 2.26 to 2.36. The same potential slip surfaces as normal apply to the critical case, although the safety factor is slightly higher.

SEEP/W

The total head of water for a normal water level shows the head pressure interval after the defined upstream and downstream levels, namely 182.1 m and 30.5 m, see Figure 1.8. The equipotential lines of the flow net are adjusted after the structure of the dam, where the effect of a drainage curtain can be seen in Fig.

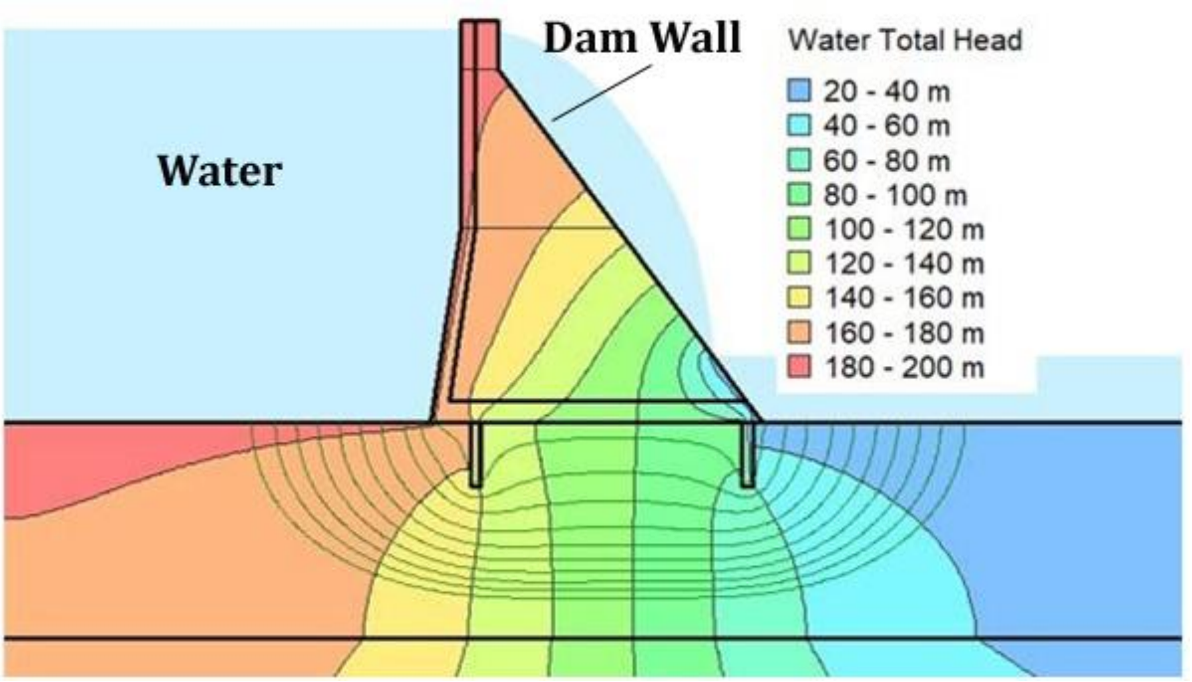

Figure 1.8. Water Total Head, normal water case.

Comparing with the critical case, similar flux nets and equipotential lines can be observed in the base layer. However, an increase in water levels both upstream and downstream results in an increase in the total water pressure in the main body of the dam. In particular, towards the downstream where the water level doubles in the severe scenario, see Figure

5. Stability Analysis Procedures for Indian Gravity Dams:

Initial Stability Assessment: This sub-point outlines the initial steps involved in assessing dam stability, including the collection of geological and geotechnical data, evaluation of loading conditions, and preliminary analysis to identify potential stability issues.

Deterministic and Probabilistic Approaches: Stability analysis can be performed using deterministic or probabilistic methods. This sub-point discusses the advantages and limitations of both approaches and their application to Indian gravity dams.

Sensitivity Analysis and Parametric Studies: Sensitivity analysis involves examining the effects of variations in input parameters on dam stability. Parametric studies focus on evaluating the impact of key design variables. This sub-point explains the importance of these analyses in understanding the behavior of gravity dams.

Consideration of Environmental Effects: Environmental factors, such as reservoir sedimentation, water quality, and climate change, can affect the stability of dams. This sub-point emphasizes the need to consider long-term environmental effects during stability analysis and dam design [4]

6. Practical Aspects and Challenges in Stability Analysis:

Field Investigations and Data Collection: Adequate field investigations and data collection are crucial for accurate stability analysis. This sub-point addresses the practical aspects of site investigations, instrumentation, and data interpretation.

Instrumentation and Monitoring: Continuous monitoring of dam behavior and performance is essential to ensure its ongoing stability. This sub-point discusses the instrumentation techniques used for monitoring various parameters, including stress, deformation, and seepage.

Risk Assessment and Safety Factors: Risk assessment involves evaluating the potential hazards and consequences associated with dam failure. This sub-point emphasizes the importance of incorporating appropriate safety factors into stability analysis to mitigate risks effectively.

The explanations provided above aim to give you a general understanding of each sub-point. For a more comprehensive understanding, it is recommended to refer to the cited references for in-depth information on specific topics [5].

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