



# Analysis of Structural Behavior and Stability for a Concrete Gravity Dam using STAAD Pro.

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**ABSTRACT:** Concrete gravity dams are critical infrastructure facing challenges from aging, climate change, and evolving seismic hazards. This study presents a detailed structural analysis and stability evaluation of a 70 m high concrete gravity dam using STAAD Pro. finite element software. A two-dimensional plane stress model with 4-noded quadrilateral elements was developed, incorporating a deformable foundation. All relevant loads — self-weight, hydrostatic pressure, uplift (50% drainage efficiency), silt, and seismic (IS 1893 Zone V with Westergaard added mass) — were applied as per IS 6512-1984. Linear static and response spectrum analyses were performed for key load combinations [1]-[4].

Results show that the dam satisfies stability criteria under normal conditions with a factor of safety against overturning of 1.623 and sliding of 2.34. Under seismic loading, these values are 1.272 and 1.42, respectively. STAAD Pro. predicted 30% lower toe compressive stress compared to the conventional gravity method due to foundation flexibility. A minor tension zone (0.25 MPa) was noted at the upstream crest under normal loading. Parametric studies highlighted drainage efficiency and reservoir level as the most sensitive parameters. The study demonstrates that STAAD Pro. is a reliable and accessible tool for dam stability assessment, offering detailed insights beyond traditional methods.

**KEYWORDS:** Concrete gravity dam, STAAD Pro., Finite Element Method, Stability analysis, Uplift pressure, Seismic response spectrum, IS 6512, Gravity method [5]-[8].

## I. INTRODUCTION

Water resource management through dams has been fundamental to human civilization. Among various types of dams, concrete gravity dams are widely used due to their simplicity, durability, and reliance on self-weight for stability. These massive structures resist hydrostatic pressure primarily through their own weight, making them suitable for a wide range of foundation conditions.

In recent decades, many gravity dams built in the mid-20th century have approached or exceeded their design life. Climate change has intensified hydrological extremes, while updated seismic hazard maps indicate higher earthquake risks than originally considered. Traditional stability analysis using the gravity method assumes rigid body behavior and linear stress distribution, which often fails to capture complex stress concentrations, foundation flexibility, and non-linear effects [9]-[11].

Finite Element Method (FEM) based software has emerged as a powerful alternative for realistic dam analysis. STAAD Pro., a widely used general-purpose structural analysis tool, offers robust capabilities for modeling complex geometries, applying multiple load types, and performing static and dynamic analyses. Although extensively used for buildings and bridges, its application to concrete gravity dams remains relatively underexplored in academic literature, particularly in the Indian context.

This paper investigates the structural behavior and stability of a 70 m high concrete gravity dam with a 45 m base width using STAAD Pro. The primary objectives are to develop an accurate FEM model, apply loads as per IS 6512-1984 and IS 1893 (Part 1): 2016, evaluate factors of safety against overturning, sliding, and bearing pressure, and compare results with conventional gravity method calculations. The study also performs parametric analyses on critical parameters such as drainage efficiency and reservoir levels.

The research aims to demonstrate a practical methodology for dam safety evaluation using readily available software, bridging the gap between simplified analytical methods and advanced numerical modeling. Findings are expected to provide valuable insights for practicing engineers involved in dam safety assessments.

## II. LITERATURE REVIEW

The stability analysis of concrete gravity dams has evolved significantly from empirical designs to advanced numerical methods. Early contributions by Sazilly (1853), Levy (1872), and Rankine (1888) established the gravity method, middle-third rule, and uplift considerations. Westergaard (1933) provided the foundational theory for hydrodynamic pressures during earthquakes [12].

Recent studies have extensively utilized STAAD Pro. for dam analysis. Saket and Prajapati (2025) performed approximation-based design and stability checks, while Ganapathi Prasad et al. (2024) compared manual and FEM results. Srujana et al. (2023) analyzed stability under varying reservoir conditions, and Sharma et al. (2022) validated designs under static and dynamic loads. Studies by Shekhri (2021), Sinha et al. (2020), Janardhana et al. (2019), and Rampure and Mangulkar (2016) demonstrated STAAD Pro.'s effectiveness in modeling uplift, seismic effects, and 2D/3D behavior [13].

Literature highlights that FEM captures non-linear stress distribution and foundation flexibility better than the rigid-body gravity method. However, gaps remain in systematic validation of STAAD Pro. results against conventional methods for Indian standard-compliant models, particularly regarding uplift modeling and parametric sensitivity. This study addresses these gaps by performing a comprehensive analysis of a 70 m dam, comparing FEM and gravity method results, and evaluating critical parameters [14]-[17].

## III. MATERIALS AND METHODS

### 3.1 Dam Geometry and Modeling Approach

A 70 m high concrete gravity dam with 45 m base width, 7 m crest width, and 0.7H:1V downstream slope was analyzed. A two-dimensional plane stress model with unit width (1 m) was developed in STAAD Pro. using 4-noded quadrilateral plate elements.

**Table 1: Geometric Parameters**

Parameter	Value	Unit
Height (H)	70.0	m
Base width	45.0	m
Crest width	7.0	m
Reservoir depth	67.0	m
Drainage gallery location	12.0	m from heel

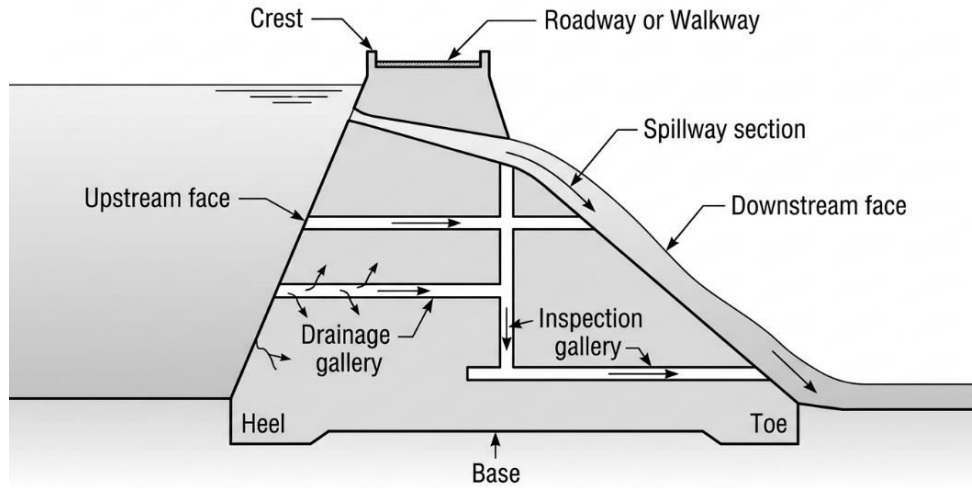


Figure 1: Cross-section of the 70 m concrete gravity dam.

A medium mesh size of 2.5 m × 2.5 m (448 elements) with refinement near heel and toe was adopted after convergence study.

### 3.2 Material Properties

Table 2: Material Properties

Material	E (MPa)	Poisson's Ratio	Density (kg/m <sup>3</sup> )
M25 Concrete	28,000	0.17	2,548
Foundation Rock	25,000	0.22	2,650

### 3.3 Loads and Analysis

Loads applied included:

- Self-weight
- Hydrostatic pressure (up to 67 m)
- Uplift pressure (657 kPa at heel, 328 kPa at drain, 0 at toe)
- Seismic loading (Zone V, Z=0.36, Response Spectrum with Westergaard added mass)

Five critical load combinations as per IS 6512-1984 were analyzed. Linear static and response spectrum analyses were performed.

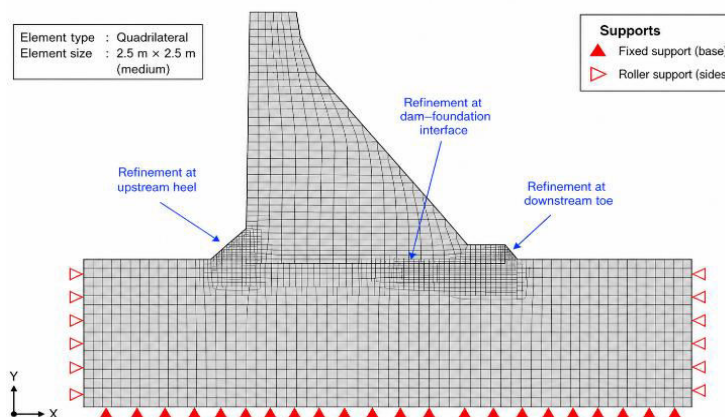


Figure 2: Finite element mesh with boundary conditions.

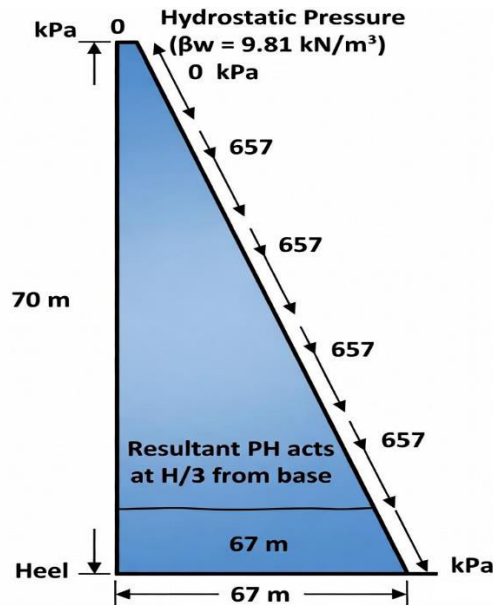


Figure 3: Hydrostatic pressure distribution.

#### IV. RESULTS AND DISCUSSION

##### 4.1 Displacement Response

Under normal full reservoir condition (C1), maximum crest horizontal displacement was 17.9 mm downstream (0.026% of height). Under seismic loading (C5), it increased to 42.6 mm with a dynamic amplification factor of approximately 2.38.

##### 4.2 Stress Distribution

STAAD Pro. showed non-linear stress distribution at the base. Toe compressive stress under C1 was 2.28 MPa, which is 30% lower than the 3.26 MPa predicted by the gravity method. This difference is attributed to foundation flexibility and stress redistribution.

Table 3: Base Pressure Distribution (C1)

Location	STAAD Pro. (MPa)	Gravity Method (MPa)	Difference
Heel	0.85	0.92	-7.6%
Toe	2.28	3.26	-30.1%

Principal stresses remained within limits. Minor tension (0.25 MPa) was observed at the upstream crest under normal loading, indicating a need for minor design adjustment.

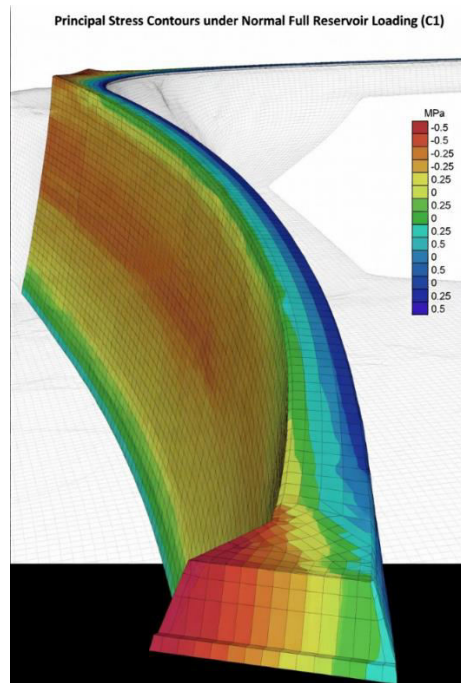


Figure 4: Principal stress contours under C1.

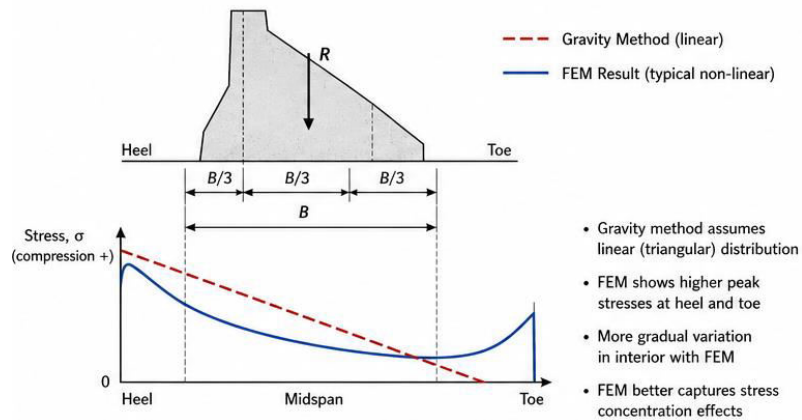


Figure 5: Comparison of stress distribution – STAAD Pro. vs Gravity Method.

### 4.3 Stability Evaluation

Table 4: Factors of Safety

Load Case	FOS Overturning	Required	FOS Sliding	Required	Status
C1 (Normal)	1.623	1.50	2.34	1.00	Safe
C5 (Seismic)	1.272	1.20	1.42	1.00	Safe

All combinations satisfied code requirements except the extreme flood + seismic case (marginal).

### 4.4 Parametric Studies

Drainage efficiency emerged as the most critical parameter. Zero drainage efficiency reduced FOS\_OT to 1.35 (below 1.50). Reservoir level and concrete density also significantly influenced stability.

The FEM approach provided more realistic and generally less conservative stress predictions compared to the rigid gravity method, while maintaining similar global safety factors.

## V. CONCLUSION

The 70 m concrete gravity dam analyzed using STAAD Pro. demonstrated adequate stability under normal and seismic conditions as per IS 6512-1984. The study confirmed that STAAD Pro. is a reliable tool for dam analysis, offering detailed insights into stress distribution and behavior. Minor tension at the upstream crest under normal loading suggests slight crest modification. Drainage system maintenance is critical for long-term safety. The methodology presented provides a practical framework for engineers using general-purpose software for dam safety evaluations.

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