Seismic Analysis of Concrete Gravity Dam considering Massless Foundation

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Abstract. This paper presents the seismic analysis of an 88.90 m high Roller Compacted Concrete (RCC) gravity dam non-overflow block considering a massless foundation model in accordance with EM 1110-2-6051 provisions. A three-dimensional finite element analysis of the dam monolith has been developed to study the behavior of the structure under earthquake loading. In this study, the reservoir is not modelled explicitly, instead, its effect during seismic events was incorporated using hydrodynamic pressure formulation, which accounts for the inertia of reservoir water acting on the upstream face of the dam. The analysis is carried out for various loading conditions including normal reservoir level, flood condition, and seismic loading corresponding to design basis earthquake (DBE) and maximum credible earthquake (MCE). Material properties of RCC concrete and foundation rock are adopted based on laboratory test results and previously established engineering parameters. The dynamic behavior of the dam is estimated using time-history seismic analysis, which provides information on crest displacement, acceleration response, and stress distribution in the dam.

The seismic response of dam monolith is evaluated by examining the stress distribution within the structure under various static and seismic loading conditions. Higher stress concentrations are observed particularly near the heel and toe regions, which are generally critical locations in gravity dams. The analysis demonstrates that the massless foundation modelling approach, combined with hydrodynamic pressure formulation, provides a practical method for assessing the seismic behavior of concrete gravity dams.

Keywords: Gravity Dam, Seismic Analysis, Massless Foundation.

1 Introduction

Gravity dams are large hydraulic structures that resist external forces under their own weight. These dams play an important role in water resource management, supporting activities such as hydropower generation, irrigation supply, flood control, and water storage. Because many gravity dams are constructed in regions that experience seismic

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activity, it is essential to evaluate their behavior under earthquake loading during the design and safety assessment stages.

During seismic events, the behavior of a dam is influenced by the interaction between several components of the system. The dynamic response depends on the combined behavior of:

- Dam body – the concrete structure that resists external forces
- Reservoir water – which exerts hydrodynamic pressure during earthquakes
- Foundation rock – which provides support and stiffness to the dam

This combined behavior is commonly referred to as dam–reservoir–foundation interaction, and it plays a significant role in determining the seismic response of gravity dams. In seismic analysis, different modelling approaches are used to represent the foundation behavior. One commonly used simplification is the massless foundation model, where the foundation contributes stiffness but does not add inertia to the system. This assumption allows the earthquake ground motion to be applied directly at the base of the dam and simplifies numerical modelling. Research studies have shown that this approach can produce reliable results when the mass of the foundation has a relatively small influence compared with the mass of the dam structure.

The performance of gravity dams is generally evaluated based on stability and stress criteria under operating conditions, including:

- Normal operating reservoir level
- Flood loading conditions
- Seismic loading conditions

To simplify the analysis, certain modelling assumptions are commonly adopted:

- Reservoir interaction is often represented using added hydrodynamic masses
- Foundation flexibility is approximated using a massless foundation model.

However, for dams located in highly seismic regions, the dynamic interaction between adjacent monoliths may influence the seismic response. In such cases, more detailed analysis may be required to capture the overall behavior of the dam system under earthquake loading.

2 Literature Review

Numerical modelling enables more accurate evaluation of stress distribution, displacement response, and hydrodynamic effects under seismic loading conditions. However, detailed modelling of the reservoir and foundation can significantly increase computational complexity. One such simplification in model is the massless foundation, where the foundation is assumed to provide stiffness but does not contribute to inertia forces.

This assumption allows earthquake ground motion to be applied directly at the base of the dam, making the analysis more efficient while still providing reasonable accuracy for gravity dam assessment. Similarly, the effect of reservoir water during earthquakes is often incorporated using added mass formulation, which approximates hydrodynamic pressure acting on the upstream face of the dam.

Studies have further explored the seismic performance of RCC gravity dams using finite element techniques, highlighting the importance of realistic boundary conditions, hydrodynamic effects, and foundation flexibility as compiled in **Table 1**.

Table 1. Literature Review

Author(s)	Modelling Approach	Key Contribution
Chopra (1970)	Analytical DRF interaction / Time history	Developed fundamental equations describing dynamic response of gravity dams considering hydrodynamic pressure.
Fenves & Chopra (1984)	Finite element modelling of DRF system	Introduced numerical modelling techniques for seismic analysis of concrete gravity dams.
Hall (1988)	Dam–reservoir–foundation interaction	Investigated the influence of foundation flexibility on seismic response of gravity dams.
Altunisik & Sesli (2015)	Numerical dynamic analysis	Studied dynamic behavior of concrete gravity dams with different reservoir modelling approaches.
Hariri-Ardebili & Saouma (2016)	Nonlinear seismic analysis	Investigated damage behavior and structural response of concrete dams during strong earthquakes.

Previous studies highlight the importance of dam–reservoir–foundation interaction in seismic analysis of gravity dams. However, detailed modelling of the reservoir and foundation increases computational demand. Therefore, many engineering analyses adopt massless foundation modelling together with hydrodynamic pressure representation. The present study applies this simplified but effective approach to evaluate the seismic response of an 88.90 m high RCC gravity dam non-overflow block using finite element analysis.

3 Methodology

This study employs finite element analysis (FEA) to evaluate the seismic behaviour of a roller compacted concrete (RCC) gravity dam non-overflow block considering a massless foundation model. The numerical modelling and dynamic analysis are carried out to investigate the response of the dam under seismic loading conditions. Hydrodynamic effects of the reservoir during earthquake loading are incorporated using added mass formulation, while the reservoir itself is not modelled explicitly.

3.1 Project Data

The project data given in **Table 2** has been utilized for the studies.

Table 2. Dam Data

Particular	Key Contribution
Elevation of Dam Top	88.90 m
Maximum Water Level (MWL)	86.90 m
Full Reservoir Level (FRL)	86.90 m
Deepest Foundation Level	46.90 m
Top Width of Dam	10 m
Upstream Face Slope	0.2 (H): 1 (V)
Downstream Face Slope	0.7 (H): 1 (V)
Upstream Slope Start Elevation	78.90 m
Maximum Height of NOF above Foundation	88.90 m
Drainage Gallery Location from Heel	7.0 m
Maximum Tail Water Level	10.50 m

3.2 Modelling

A three-dimensional model was developed to represent the non-overflow (NOF) block corresponding to the tallest monolith of the dam, having a height of 88.9 m above the foundation. The modelling approach focuses on capturing the geometry of the monolith and interaction with the supporting foundation.

To capture the structural behavior accurately, an appropriate mesh density was adopted:

- Element Size for Dam Body: Approximately 1–2 m.
- Element Size for Foundation Rock: Approximately 1–6 m.

Time history analysis generally requires large computational effort and memory compared to static analysis. Therefore, the mesh density was optimized to ensure reliable stress distribution without excessive computational demand. The foundation rock was modelled to sufficiently large dimensions in order to reduce boundary effects:

- Depth of Foundation Model: 150 m below the dam foundation level
- Upstream Extension of Foundation: 150 m
- Downstream Extension of Foundation: 150 m

All elements representing the foundation were assumed to be massless. This assumption helps to avoid unrealistic dynamic response caused by reflection of seismic waves from the model boundaries.

The analysis was carried out using the linear elastic material model available in MIDAS software. Both static and dynamic load cases were analyzed, assuming linear behavior of the materials. This approach allows consistent comparison between different loading conditions.

Although more realistic results can be obtained by considering foundation mass and damping, accurate determination of these parameters is often complicated. Therefore, a massless and undamped foundation model was adopted in the present study. This assumption generally results in slightly higher stresses and reaction forces during seismic loading, which provides a conservative estimate of the structural response.

The developed finite element model and mesh configuration of the NOF block are illustrated in **Fig. 1**.

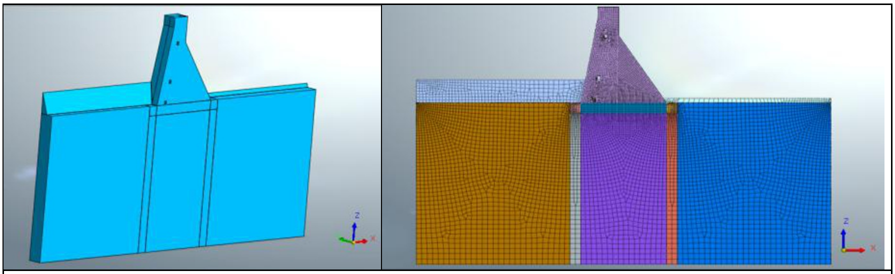

Fig. 1. NOF Block in MIDAS (Solid and Meshed)

3.3 Engineering Properties

The analysis has been carried out as per the engineering properties of concrete material model and foundation rock properties primarily consisting of gneiss with schist bands as mentioned in **Table 3**.

Table 3. Literature Review

Particulars	**Unit**	**Value**
Concrete Properties		
Unit weight of Concrete	kN/m^3	24
Compressive strength (365 days), fck	N/mm^2	15
Modulus of Elasticity, E_{static}*	GPa	18.75
Modulus of Elasticity, $E_{dynamic} = 1.15 \times E_{static}$	GPa	21.56
Foundation Properties		
Cohesion at Concrete-Rock Interface	kN/m^2	210
Angle of Internal Friction	Degrees	43
Modulus of Deformation for Rock	GPa	9.784
Poisson's Ratio	-	0.2

3.4 Massless Foundation Concept

In seismic analysis of concrete gravity dams, modelling of the dam–foundation interaction plays an important role in predicting the dynamic response. Detailed representation of foundation mass and damping requires extensive geotechnical data and large computational domains. Therefore, simplified approaches are often adopted in engineering practice. One such approach is the massless foundation assumption, as discussed in USACE EM 1110-2-6053 [17].

In this method, the foundation rock is assumed to provide elastic stiffness to the dam structure, while its inertial contribution is neglected. As a result, the earthquake acceleration record is applied directly at the dam–foundation interface. The dynamic response is then governed primarily by the mass of the dam body and the associated hydrodynamic effects. The massless foundation model is considered a conservative representation because the absence of foundation inertia generally leads to slightly higher stresses and accelerations in the dam. For this reason, it is widely used in finite element time-history analysis of gravity dam monoliths during seismic safety evaluation.

3.5 Support Conditions

As recommended in USACE EM 1110-2-6053, when a massless foundation model is adopted, the foundation domain does not need to extend far beyond the structural dimensions of the dam. In the present analysis, the foundation rock was therefore modelled to an extent approximately equal to the height of the dam in all directions, which is sufficient to represent the stiffness of the supporting rock mass [17].

The bottom surface of the foundation was restrained against all translational and rotational degrees of freedom to simulate a stable base. The lateral faces were constrained to prevent out-of-plane displacements. The dam was assumed to be rigidly bonded to the foundation, and cross-valley movement of the monolith was considered negligible.

3.6 Loading Conditions

Static Loads.
The finite element analysis considers the main static loads acting on the dam, applied separately and later combined through load combinations.

- Dead Load: Self-weight of RCC dam and piers calculated using a unit weight of 24 kN/m^3.
- Hydrostatic Load: Water pressure acting on upstream and downstream faces, varying linearly with depth. Maximum upstream pressure corresponds to FRL/MWL (El. 1029 m).
- Uplift Pressure: Assumed to varying linearly upstream to downstream along the dam–foundation interface, with reduction at the drainage gallery under normal conditions.

- Silt Load: Considered on the upstream side below El. 42.90 m, applied as hydrostatic pressure based on the equivalent silt–water density as per IS 6512.

Dynamic Loads.

The dynamic analysis of the dam considers earthquake-induced inertial forces and hydrodynamic effects of the reservoir. These loads are applied through time history analysis using site-specific ground motion records.

- Earthquake Load: Seismic forces are applied as inertia forces varying with ground acceleration time histories. The normalized acceleration records are scaled by 0.27g (horizontal) and 0.18g (vertical) for the Design Basis Earthquake (DBE), and 0.54g (horizontal) and 0.36g (vertical) for the Maximum Credible Earthquake (MCE). The horizontal motion is applied in the upstream–downstream direction.

  Ground Motion Input: The project site lies in Seismic Zone IV as per IS 1893 (Part 1). Site-specific seismic studies carried out by IIT Roorkee and approved by NCSDP were used to generate the horizontal and vertical time-history records for DBE and MCE conditions. The time histories for horizontal and vertical ground motion corresponding to the DBE and MCE are shown below in **Fig. 2** to **Fig. 5**.

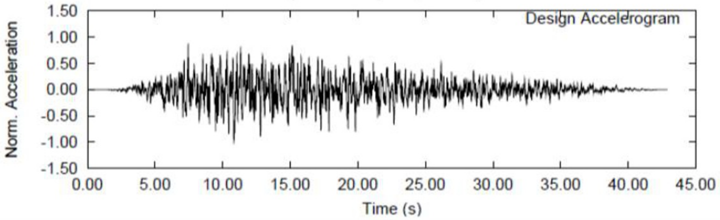

Fig. 2. Time History of MCE Horizontal Ground Motion

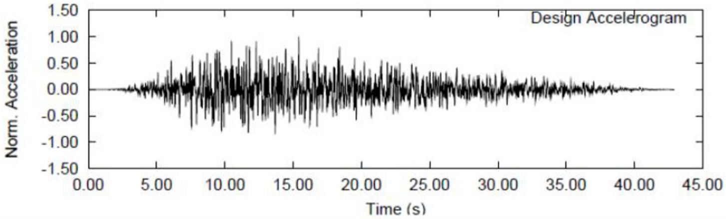

Fig. 3. Time History of MCE Vertical Ground Motion

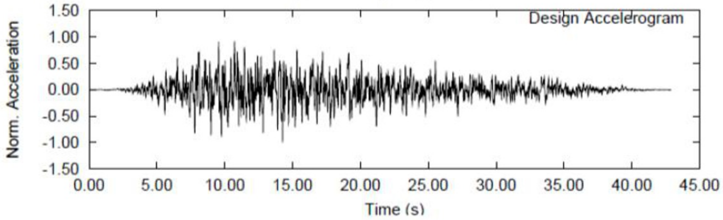

Fig. 4. Time History of DBE Horizontal Ground Motion

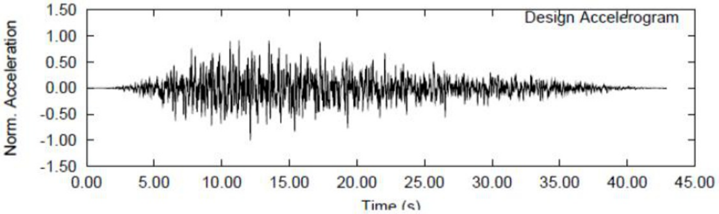

Fig. 5. Time History of DBE Vertical Ground Motion

- Hydrodynamic Pressure: During earthquake shaking, additional water pressure develops on the upstream face of the dam due to reservoir inertia. This hydrodynamic pressure is evaluated in accordance with IS 1893 (1984) and is modelled as added mass along the upstream face of the dam. The force acts opposing the direction of seismic acceleration and depends on the reservoir depth, seismic coefficient, and unit weight of water.

  The hydrodynamic pressure acting on the structure due to earthquake would be calculated as per clause 7.2 of IS 1893: 1984 [21]. Considering water is incompressible, incremental pressure due to earthquake at any depth 'y' below the reservoir level shall be calculated as:

$$p = C_s \times \alpha_h \times \gamma_w \times h$$

Where,
p = Hydrodynamic Pressure at Depth 'y' (kN/m^2)
C_s = Coefficient varying with shape/ depth

$$= \frac{C_m}{2} \times \left[\left\{ \left(\frac{y}{h}\right) \times \left(2 - \frac{y}{h}\right) \right\} + \sqrt{\left\{ \left(\frac{y}{h}\right) \times \left(2 - \frac{y}{h}\right) \right\}} \right]$$

C_m = Maximum Value of Cs Obtained
y = Depth Below Water Surface (m)
h = Depth of Reservoir (m)
α_h = Design Horizontal Seismic Coefficient
γ_w = Unit weight (Water) (kN/m^3)
H = Reservoir depth (m)

3.7 Loading Combinations

Dams in general are designed and evaluated for three basic loading combinations: Usual, Unusual and Extreme discussed below in **Table 4**.

Table 4. Load Combination (LC) [19]

Load Combination	Description	Category

Load Combination A (Construction Condition)	End of construction of dam however no reservoir water or tail water	Unusual
Load Combination B (Normal Operating Condition)	Reservoir at FRL, Normal Tail Water, Normal Uplift, Ice and Silt (If Applicable)	Usual
Load Combination C (Flood Discharge Condition)	Reservoir at maximum flood level, all gates (Open), flood tailwater level, Normal Uplift, and Silt (as applicable)	Unusual
Load Combination D	LC A with Earthquake (DBE)	Unusual
Load Combination E	LC B with Earthquake (DBE)	Unusual
Load Combination F	LC C, but with maximum uplift (considering drains inoperative)	Extreme
Load Combination G	LC E, but with maximum uplift (Drains Inoperative)	Unusual
Load Combination H	LC B with Earthquake (MCE)	Extreme

3.8 Permissible stress criteria

Evaluation of dam and foundation stresses shall be done based on the allowable stress method. Stresses obtained from unfactored loads and forces by the FEA, shall be smaller than the relevant allowable stresses.

The allowable stresses are obtained applying appropriate safety factors to the RCC compressive and tensile strengths. Static and dynamic stress criteria shall be generally according to Indian Standards; however, U.S. documents will be used where IS code is not available/ambiguous.

Allowable stresses apply for following stress components:

- Tension and compression within the dam body (RCC)
- Vertical pressure on the foundation interface

However, cracking along the dam-foundation interface is allowed during static load cases if the resultant stays within the required portion of the foundation joint length, according to USACE stability requirement (1/2 for unusual, and within joint length for extreme LC).

Regarding cracking the following requirements apply:

- Usual loading condition: No cracking is allowed in concrete and along foundation joint.
- Unusual loading conditions: Cracking along the foundation joint is allowed if the stability requirements are met.
- Extreme loading conditions: Cracking along the foundation joints is allowed. In addition, during extreme seismic loading conditions (MCE) the tensile stresses in concrete may exceed the allowable tensile stress (tensile strength), i.e., concrete may

crack (USACE guidelines). In both cases the stability requirements must be met without uncontrolled release of water from the reservoir.

- Post-seismic loading condition: Cracking along joints in RCC and foundation is kept from the seismic loading condition. The modified uplift is used, as per USACE (crack<100%) and FERC (crack=100%) definitions. No cohesion along the crack is considered. The stability requirements must be met.

For load combinations A to G, the computed stresses in concrete shall not exceed the allowable values given below in **Table 5**:

Table 5. *Permissible Value of Tensile and Compressive Stresses in Concrete [19]*

Loading Condition	Allowable Tensile Stress
Load Combination A	No tension
Load Combination B	No tension
Load Combination C	0.01 f_{ck} (0.15 MPa)
Load Combination D[1]	0.324 $f_{ck}^{2/3}$ (1.97 MPa)
Load Combination E	0.324 $f_{ck}^{2/3}$(1.97 MPa)
Load Combination F	0.02 f_{ck} (0.30 MPa)
Load Combination G	0.324 $f_{ck}^{2/3}$(1.97 MPa)

Where, fck= Ultimate Compressive Strength of RCC at the point of stress

For load combination H involving the MCE loading, an interpretation and evaluation of results of the linear elastic time history analysis shall be carried out in the terms of Demand Capacity Ratio (DCR) in consideration of possible modes of failure.

As per IS 6512-2019 clause 6.13.2.2 must meet the requirements related to early loading and construction stages. By the age of one year, the compressive strength of the concrete should be at least four times the maximum calculated stress in the dam or 14 N/mm^2, whichever value is greater. In addition, the working stress in any part of the structure shall not also exceed 7 N/mm^2 [19].

3.9 Analysis Procedure

The seismic response of the dam is evaluated through dynamic time history analysis using the developed finite element model. The objective of this analysis is to determine the stresses, deformations, and dynamic behaviour of the dam–foundation–reservoir system under earthquake excitation corresponding to the design basis earthquake (DBE) and the maximum credible earthquake (MCE) conditions.

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[1] The values has been modified based on Raphael values as per EM 1110-2-6051 [18]

Time History Analysis.
The seismic response is computed using time history analysis, where the structural behaviour is simulated over a series of small-time intervals. In this process:

- Horizontal and vertical ground accelerations are applied simultaneously at base of the model.
- The analysis computes displacements, velocities, accelerations, and stresses at each time step.
- The maximum and minimum response values for each element are extracted from the entire duration of the earthquake record.
- A time step of 0.05 seconds is used to capture the dynamic response accurately.

Modelling Assumptions.
The dynamic analysis is based on the following key assumptions:

- Linear elastic behaviour: Stress is proportional to strain following Hooke's law.
- Material properties: RCC and foundation rock are assumed to be elastic, homogeneous, and isotropic.
- Dynamic material properties: The dynamic modulus of elasticity for RCC and foundation rock is taken as 1.15 times the static modulus, in accordance with USACE recommendations.
- Foundation modelling: The foundation is considered massless, and earthquake accelerations are directly applied as input at the base of the model.
- Reservoir interaction: The dynamic effect of reservoir water is represented using added mass concept along the upstream face of the dam.
- Hydrostatic pressure: Represented as pressure acting on the upstream face.

Evaluation of Results.
The finite element model is subjected to both static loads and seismic loads. Static loads are applied as constant loads, while earthquake loads are introduced through time histories of horizontal and vertical ground acceleration for DBE and MCE conditions. The maximum stresses and deformations obtained during the seismic event are identified and combined with the corresponding static load results. During interpretation of results, localized extreme stresses caused by finite element mesh singularities, such as at re-entrant corners or dam–foundation interfaces, are identified separately and not directly used for determining RCC strength requirements.

4 Results and Discussion

The stresses in the gravity dam structure for static and dynamic loads are shown below:

4.1 Static load combinations

The results of static load combinations are presented below in **Fig. 6** to **Fig. 9**.

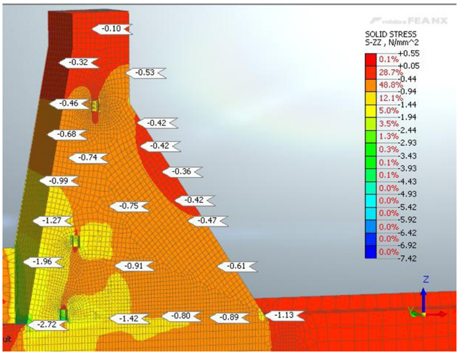

Fig. 6. Normal Stress plot for LC A

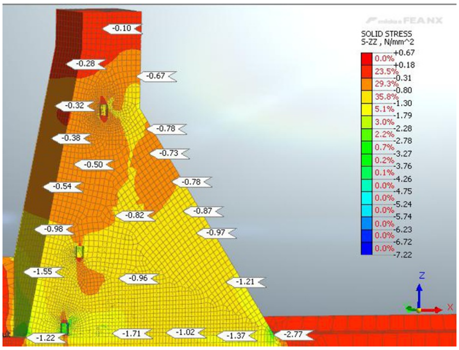

Fig. 7. Plot of Normal Stress for LC B

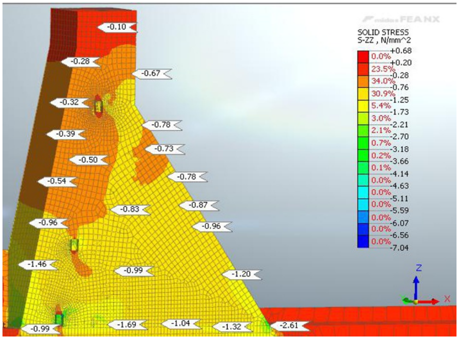

Fig. 8. Normal Stress plot for LC C

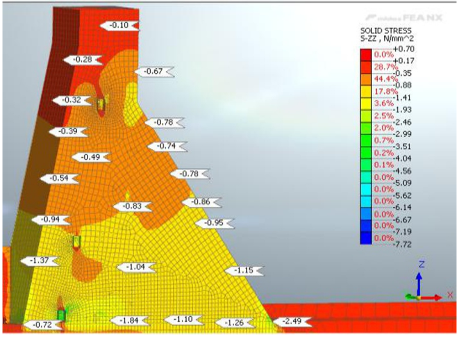

Fig. 9. Plot of Normal Stress for LC F

4.2 Dynamic load combinations

The results of dynamic load combinations are presented below in **Fig. 10** to **Fig. 17**.

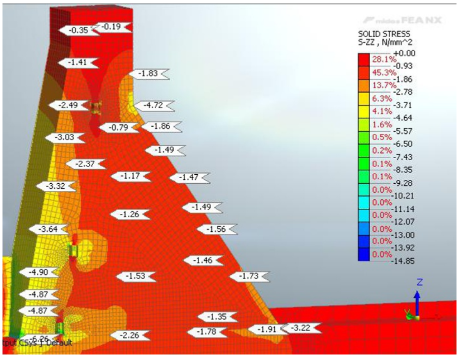

Fig. 10. Compressive Stress plot for LC D

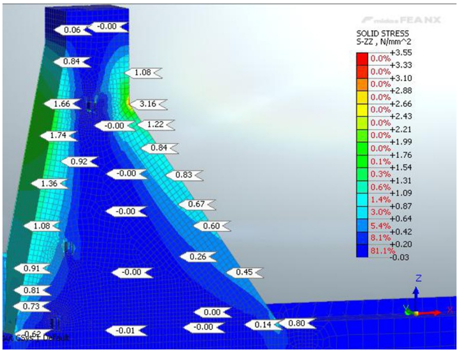

Fig. 11. Tensile Stress plot for LC D

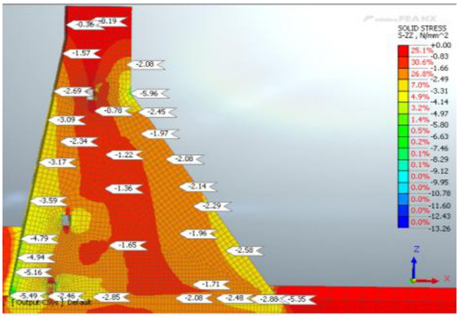

Fig. 12. Compressive Stress plot for LC E

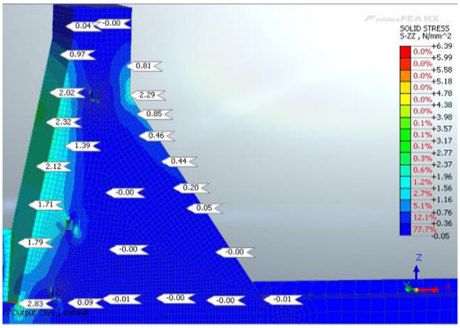

Fig. 13. Tensile Stress plot for LC E

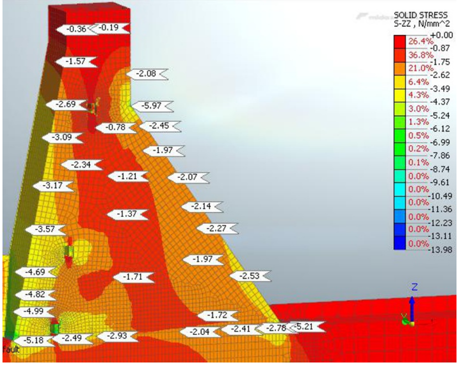

Fig. 14. Compressive Stress plot for LC G

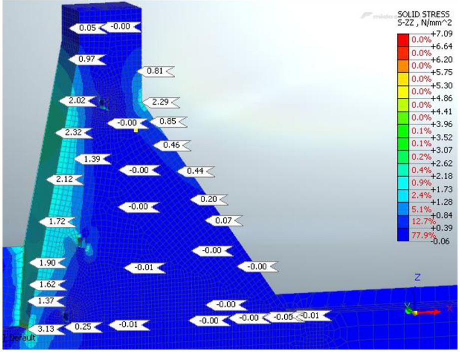

Fig. 15. Tensile Stress plot for LC G

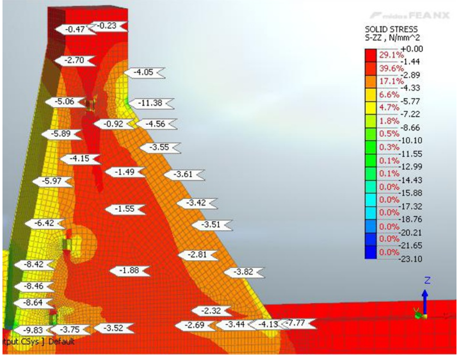

Fig. 16. Compressive Stress plot for LC H

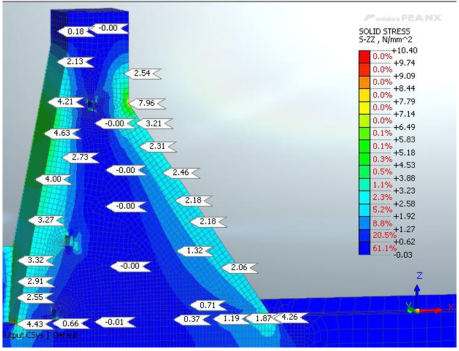

Fig. 17. Tensile Stress plot for LC H

The results of static load combinations are presented below in **Table 6**.

Table 6. Load Combinations

Load Combination	Description	Compressive stress (MPa)	Tensile stress (MPa)
A	End of Construction	~2.93	0.00

B	Norma Operating Condition	~3.9	~0.00
C	Normal Operating Condition	~2.95	<0.15
D	End Of Construction +DBE	<7.0	Limiting value 1.97
E	Normal Operating Condition at FRL + Normal Uplift +DBE	<7.0	
F	Normal Operating Condition at MWL + Max Uplift+ Drain inoperative	~3.2	<0.30
G	Normal Operating Condition at FRL + Normal Uplift +DBE+ Drain at chock	<7.0	Limiting value 1.97
H	Normal Operating Condition at FRL + Normal Uplift +MCE	<10.0	

The performance of the gravity dam being subjected to earthquake ground motions has been checked using demand-capacity ratio (DCR). It is the ratio of stress demands (principal stress) to static tensile strength of the concrete. The allowable maximum DCR for linear analysis of dams is 1 for DBE condition and 2 for MCE condition. In addition, the overstressed region should be restricted to a maximum of 15% of the total cross-sectional area of the dam. The total time during which the stress exceeds the allowable tensile strength of the concrete should also be limited to 0.3 seconds. The DCR plots for load combination G and H has been represented below in **Fig. 18** and **Fig. 19**.

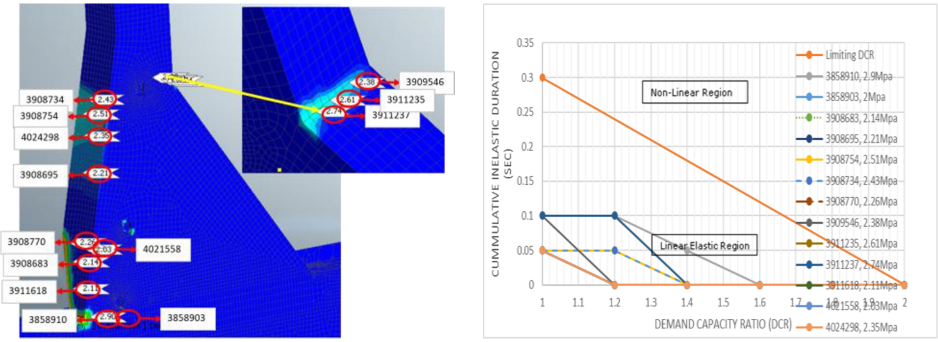

Fig. 18. DCR plot for load case G

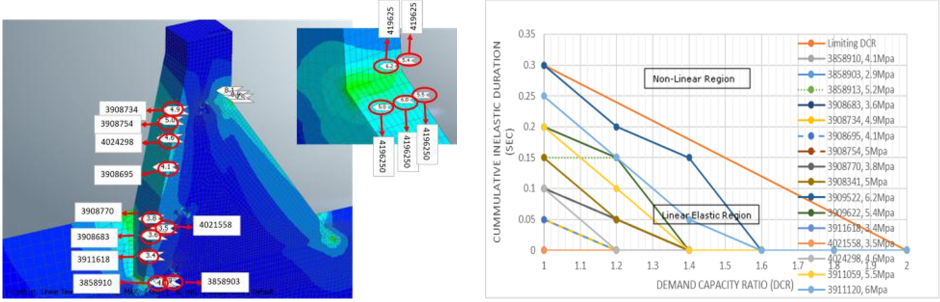

Fig. 19. DCR plot for load case H

5 Conclusions

The studies shows that the dam remains safe against sliding under DBE conditions and maintains a factor of safety of unity under MCE conditions with uplift. Although localized tensile stresses occur near the heel, toe and downstream junction due to stress concentration and geometric discontinuities, the possible crack length is limited compared to the base width, indicating no critical instability.

For DBE cases, the demand-capacity ratio remains below 1, and for MCE cases it is generally below 2, confirming that stresses are within permissible limits. Compressive stresses also remain within allowable values. Overall, the dam section is expected to remain stable and perform satisfactorily under the considered loading conditions.

References

1. Chopra, A.K.: Hydrodynamic pressures on dams during earthquakes. Journal of the Engineering Mechanics Division 96(5), 779–802 (1970)
2. Chakrabarti, P., Chopra, A.K.: Earthquake analysis of gravity dams including reservoir interaction. Earthquake Engineering and Structural Dynamics 2(2), 143–160 (1973)
3. Fenves, G.L., Chopra, A.K.: Earthquake analysis of concrete gravity dams including dam–foundation interaction. Earthquake Engineering and Structural Dynamics 12(3), 379–394 (1984)
4. Hall, J.F.: Coupled dam–foundation response during earthquakes. Journal of Engineering Mechanics 114(9), 1484–1500 (1988)
5. Léger, P., Bhattacharjee, S.S.: Seismic response of concrete gravity dams by finite element modelling. Computers and Structures 45(2), 201–209 (1992)
6. Altunisik, A.C., Sesli, M.: Seismic analysis of concrete gravity dams considering dam–reservoir interaction. Soil Dynamics and Earthquake Engineering 76, 88–98 (2015)
7. Hariri-Ardebili, M.A., Saouma, V.E.: Seismic performance evaluation of concrete dams using nonlinear finite element analysis. Engineering Structures 118, 252–263 (2016)
8. Sotoudeh, M., Ghaemian, M.: Seismic analysis of concrete gravity dams considering reservoir and foundation interaction. Soil Dynamics and Earthquake Engineering 119, 12–24 (2019)
9. Wang, B., Li, H., Zhang, Y.: Dynamic response analysis of gravity dams subjected to earthquake loading using finite element modelling. Engineering Structures 234, 111742 (2021)
10. Xu, J., Chen, Z., Liu, H.: Seismic response analysis of RCC gravity dams using time history finite element method. Soil Dynamics and Earthquake Engineering 167, 107646 (2023)
11. Westergaard, H.M.: Water pressures on dams during earthquakes. Transactions of the American Society of Civil Engineers 98, 418–433 (1933)
12. Chopra, A.K.: Earthquake analysis of arch dams including dam–water–foundation interaction. Earthquake Engineering and Structural Dynamics 6(4), 325–344 (1978)
13. Fenves, G.L., Chopra, A.K.: Simplified earthquake analysis of concrete gravity dams. Journal of Structural Engineering 112(5), 1208–1224 (1986)

14. Leger, P., Boughoufalah, S.: Earthquake response of concrete gravity dams considering dam–foundation interaction. Journal of Structural Engineering 115(6), 1344–1362 (1989)
15. Hariri-Ardebili, M.A.: Seismic safety evaluation of concrete dams: A state-of-the-art review. Engineering Structures 144, 372–395 (2017)
16. Ghaemian, M., Ghobarah, A.: Nonlinear seismic response of concrete gravity dams. Journal of Engineering Mechanics 125(5), 520–528 (1999)
17. USACE: Structural stability of concrete gravity dams. Engineer Manual EM 1110-2-6053, U.S. Army Corps of Engineers, Washington DC (2005)
18. USACE: Time-history dynamic analysis of concrete hydraulic structures. Engineer Manual EM 1110-2-6051, U.S. Army Corps of Engineers, Washington DC (2003)
19. Bureau of Indian Standards: Criteria for design of solid gravity dams. IS 6512, Bureau of Indian Standards, New Delhi (2019)
20. Bureau of Indian Standards: Criteria for earthquake resistant design of structures. IS 1893 (Part 1), Bureau of Indian Standards, New Delhi (2016)
21. Bureau of Indian Standards: IS 1893 (1984): Criteria for earthquake resistant design of structures