ICOLD Symposium on Sustainable Development of dams and River Basins
04-10th April 2020, Delhi, India

3D stress analysis of ageing dam by finite element method towards strengthening -a case study

Rizwan Ali, Hanumanthappa M S, Chetan S Khadane, Shyamli Paswan,
Dr. M.R. Bhajantri
Central Water and Power Research Station, Pune, India

Abstract

Dams built immediately after the independence have been designed based on simple design assumptions and experience without considering any earthquake forces. Over the years these dams have started showing distress in the form of leaching, dislodging of concrete, seepage and cracks etc raising apprehensions about structural integrity. These dams need to be strengthened after assessing their structural integrity to meet the present design criteria as per BIS guidelines and improve their future sustainability. For assessing structural stability, detailed stress analysis by Finite Element Method using in-situ material properties is carried out. This paper discusses a case study of 3D stress analysis by FEM of Hirakud Dam, Sambalpur, Odisha. An account of the three dimensional (3D) static and pseudo dynamic stress analysis by FEM of one spillway block using in-situ material properties has been presented. The analysis has been carried out by discretizing the dam into different zones based in-situ material properties obtained through laboratory testing of extracted cores from two distressed spillway blocks of the dam. The geometry of spillway blocks consisting of sluices and various galleries have been simulated using LUSAS software. Foundation rock mass details have also been reproduced in the model. Analysis has been carried out by applying loads conforming to IS:6512-1984 and seismic loading to IS:1893-1984, 2016. 3D stress analysis has indicated tensile stresses around sluices at bell mouth entry location. This study would be very useful in finalizing remedial measures towards improving structural safety of the dam.

1.0 Introduction

Dams have played a key role in the development of nation building. Most of the dams have been constructed in India just after Independence. During those days modern tools of analysis were not available, hence these dams have been designed using conventional analysis or photoelastic techniques without much consideration of earthquake forces. Due to ageing effect, adverse effect of reservoir water on account of high acidity and seismic activities these dams are showing distresses in the dam in the form of cracking, large displacement, heavy leakage, dislodging of concrete etc. These distresses are raising apprehensions about the structural safety of theses dams. This paper brings out the details about Hirakud Dam, which is experiencing heavy alkali aggregate reaction and dislodging of concrete on upstream face and bell mouth entry of under sluices.

In order to review the structural safety of Hirakud Dam, 3D Stress Analysis by FEM under static and earthquake load combinations of one spillway block has been carried out using in-situ material properties.

2.0 Salient Features

Following are the salient features of the dam:

River	Mahanadi
Type	Composite Gravity consisting of Earthen dykes, Non Overflow Masonry and Concrete
Location	Sambalpur, Odisha
Year of Construction	1957-1958
Purpose	Irrigation, Flood control and Hydropower
Maximum Height of Dam	60.96 m (200 ft.)
Length of Dam	25.460 km

(Main dam 4800 m (Non-overflow portion - 3,652 m + Spillway portion - 1,148 m long earthen dykes on both ends with a total length of about 20.660 km)

A view of the dam and spillway is shown in Figs.1-2

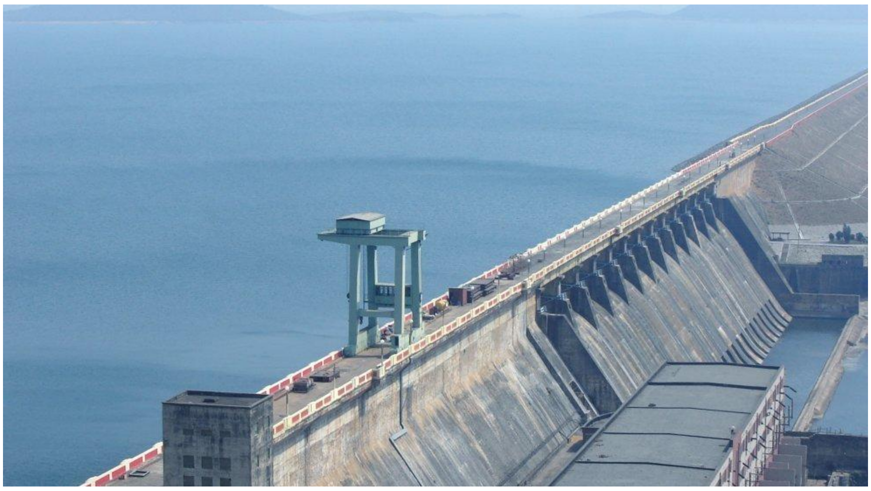


Fig.1: A view of Hirakud Composite Dam

Fig.2: View of LHS Spillway along with Under Sluices

3.0 Stress Analysis

3D stress analysis by FEM of spillway block (Fig.2) has been carried out under various load combinations as per BIS criteria using Pseudodynamic approach. All the openings such as under sluices, operation and foundation galleries alongwith foundation rock mass has been produced in the model. In-situ mass density and elastic parameters based on results of extracted cores, have been considered in the analysis. Figs.3-4 show the details of cross section of spillway and under sluices.

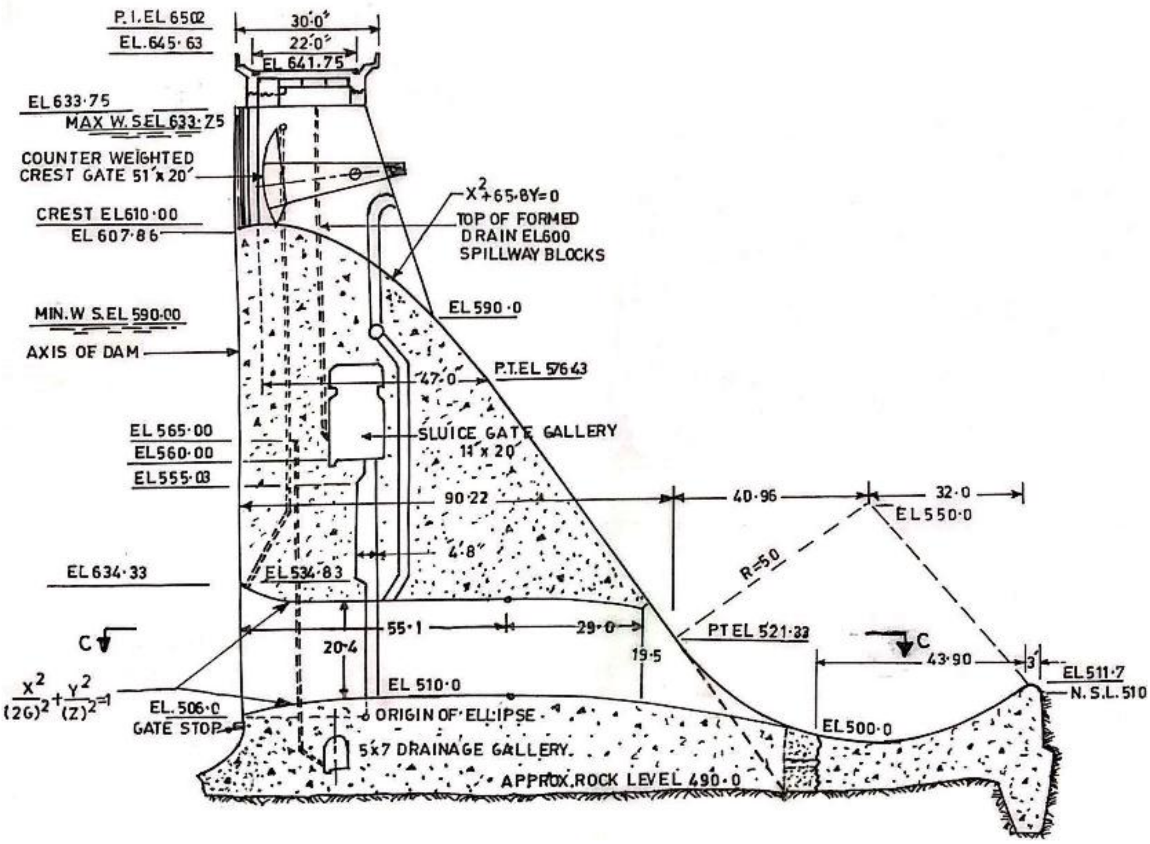


Fig.3: Maximum Spillway Section of Hirakud Dam

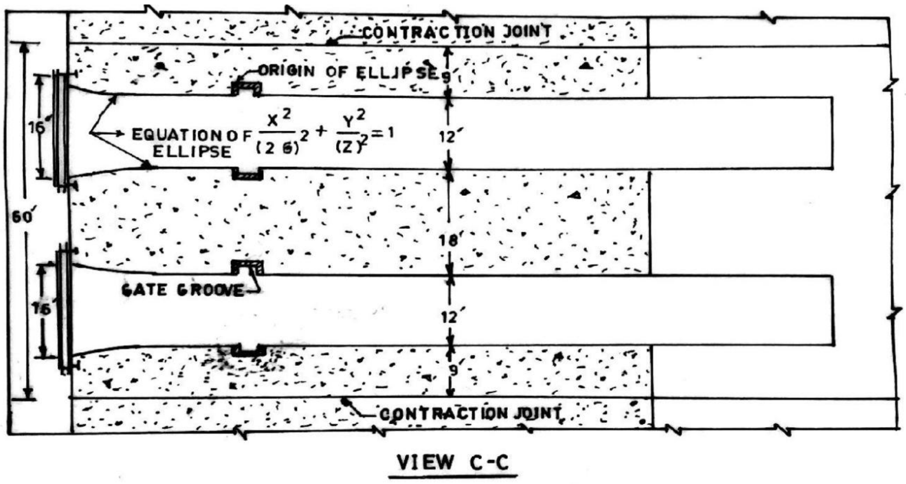
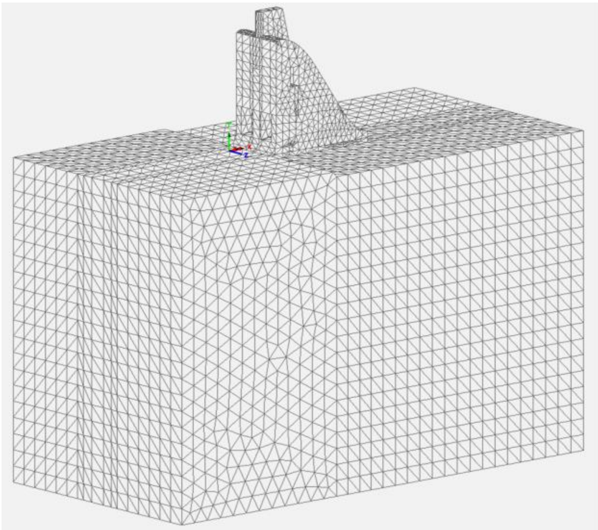


Fig.4: Sectional Plan at C-C through under sluices

3.1 Finite Element Model

The 3D Finite Element studies have been carried out of deepest Spillway Block as per the drawings shown in Figs.3-4. The volume of one Spillway block has been discretized into 80,709 four noded linear tetrahedral solid elements using 17,050 nodes by including all the details of openings such as two under sluices, operation gallery, foundation gallery, gate opening slots and foundation rockmass using LUSAS general purpose Finite Element software version 14.3. 3D Mathematical Model of spillway block is shown in Figs.5-6 with foundation rock mass and without foundation rock mass respectively.



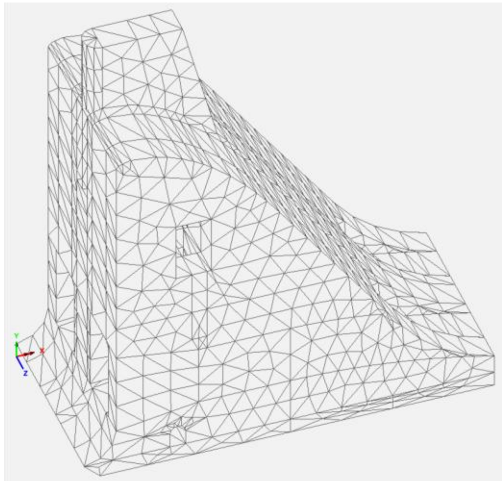


Fig.5: 3D Mathematical Model of Dam with Foundation Fig.6: 3D Mathematical Model of Dam

3.2 Material Properties

The input data in terms of the properties of the dam material, foundation rock mass, water, silt and seismic coefficients (computed *as per IS-1893:2002,2016) for seismic zone-III* considered in the present analysis, are shown in Table-1. The strength parameters have been considered as per test results of extracted cores from spillway blocks.

Table 1: Input Parameters

S.N.	Property	Value	Remark
1.	Dam Body A) Young's Modulus of Elasticity 'E' i) Dam(Top) material (Concrete) ii) Dam(middle) material (Concrete iii) Dam(bottom) material (Concrete) B) Poisson's Ratio 'ν' i) Dam(Top) material (Concrete) ii) Dam(middle) material (Concrete) iii) Dam(bottom) material (Concrete) C) Mass Density 'ρ' i) Dam(Top) ii) Dam(middle) iii) Dam(bottom)	 3.2×10^9 Kg/m^2 3.1×10^9 Kg/m^2 3.2×10^9 Kg/m^2 0.18 0.18 0.18 2324.82 Kg/m^3 2298.80 Kg/m^3 2322.06 Kg/m^3	Based on load test results on concrete cores taken from the dam body and tested in Concrete Technology division of CWPRS. ---Do--- ---Do---
2.	Dam Foundation i) Young's Modulus of Elasticity 'E' ii) Poisson's Ratio 'ν'	 3.3×10^9 Kg/m^2 0.22	

3.	Water Mass Density of water ‘ρ_w’	1000 Kg/m^3	As per literature
4.	Silt Water i) Mass Density of in horizontal direction ‘ρ_{sh}’ ii) Mass Density of silt and water in vertical direction ‘ρ_{sv}’	1360 Kg/m^3 1925 Kg/m^3	As per IS:6512-1984
5.	Seismic coefficient i) Horizontal α_h ii) Vertical coefficient α_v iii)Longitudinal coefficient	0.24 0.12 0.12	Based on IS 1893 (Part 1):2016 Pg 12. (α_v & α_l 50% of α_h As per IS-1893:1984)

3.3 Boundary Conditions

For dam body, deflections are allowed along three directions. The deflections and rotations in all three directions are assumed to be zero at base of the foundation block whereas vertical settlement along all four faces of foundation block has been allowed.

3.4 Load Combinations

The analysis has been carried out by applying various loads such as self weight of dam, hydrostatic pressure, uplift pressure, silt pressure under two static load combinations and two earthquake load combinations alongwith static loads based on IS: 6512 - 1984 as mentioned below:

1. **Load Combination A:** (Construction Condition): Dam completed but no water in reservoir and no tail water
2. **Load Combination B:** (Normal Operating Condition): Full reservoir elevation, Gates Closed, Normal uplift, tail water, silt load
3. **Load Combination C:** (Flood Discharge Condition):- Reservoir at maximum flood pool elevation at MWL all gates open, tail water and silt load
4. **Load Combination F:** Combination C, but with extreme uplift (drains inoperative)
5. **Load Combination D:** Combination A, but with earthquake loads
6. **Load Combination E:** Combination B but with earthquake loads
7. **Load Combination G:** Combination E, but with extreme uplift (drains inoperative)

RESULTS:

Results have been obtained in the form of principal stresses and displacements along three directions as discussed below:

4.1 Maximum Principal Stresses (Tensile)

As FRL and MWL are same in Hirakud dam, under static load combinations, maximum principal tensile stress occurs under load combination B due to less tail water. The distribution of maximum principal tensile stress in the dam body is shown in **Fig.7**. The maximum principal tensile stresses of the order of **6.895 x 10^4 Kg/m^2** has been found to develop near the heel portion and bell mouth entry of under sluices of the dam under load combination B. Very large volume of spillway block comes under tension under normal operating condition.

Under earthquake load combinations, the maximum principal tensile stresses of the order of **15.208x10^4 Kg/m^2** has been found to develop near heel portion and bell mouth entry under load combination E The distribution of maximum principal tensile stress in the dam body is shown in **Fig.8**.Very large volume of spillway block comes under tension under earthquake load combinations.

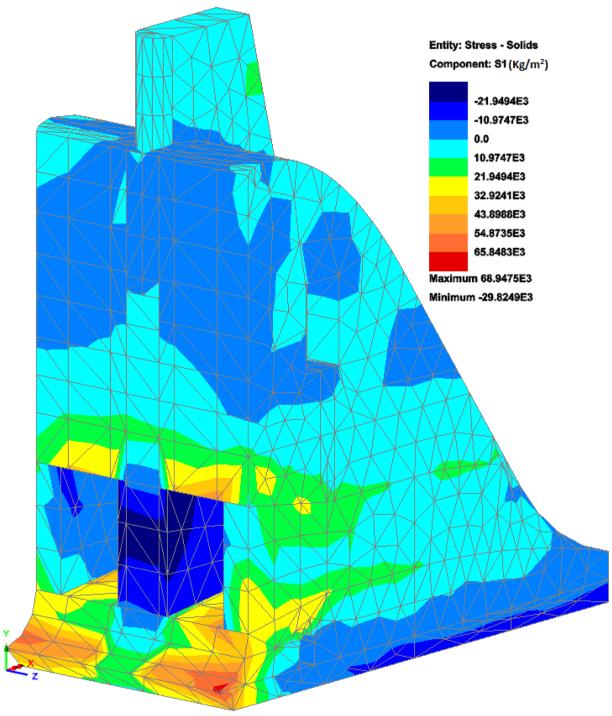


Fig.7: Maximum Principal Stress Distribution under Static Load Combination B

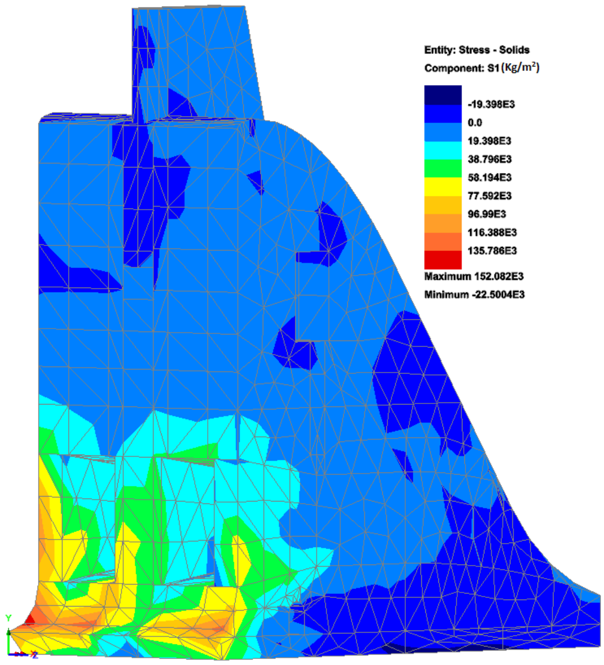


Fig.8: Maximum Principal Stress Distribution under Earthquake Load Combination E

The distribution of peak value of maximum principal stress under all load combinations is shown in the form of bar diagrams in Fig.9**.** It can be seen from the bar diagram that maximum tensile stress under load varies from 3.886x10^4 to 15.208x10^4 kg/m^2. Under earthquake load combinations, high tensile stress covering significant volume of dam block is found to develop. Though the mass concrete inside dam body is having very high strength as indicated by core test results but surface concrete near to bell-mouth entry might have become weak due ageing and acidic water effect resulting dislodging of concrete near to bell-mouth at some places.

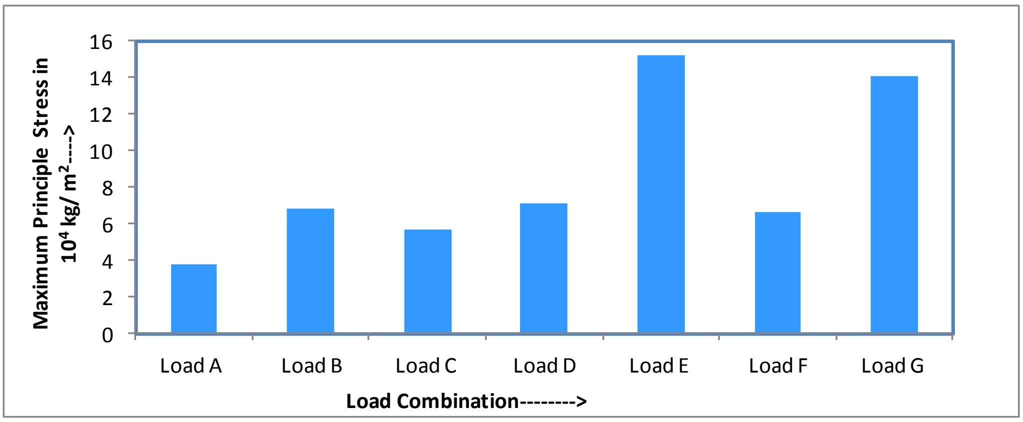


Fig.10: Variation of Maximum Principal Tensile Stress in Dam Body under all Load combinations

4.2 Minimum Principal Stresses (Compressive)

Under static load combinations, the minimum principal compressive stress of the order of **29.292x10^4 kg/m^2 (29.292 Kg/cm^2)** has been found to develop under load combination C in the toe region of the dam as shown in **Fig. 11**. Under earthquake load combinations, the minimum principal compressive stress of the order of **29.005x10^4 kg/ m^2 (29.005 Kg/cm^2)** has been found to develop under load combination G in the toe region of the dam as shown in **Fig. 12**. The distribution of peak value of minimum principal stress under all load combinations is shown in the form of bar diagrams vide **Fig. 13.** The peak value of minimum principal stress under all load combinations in entire dam body, remains within permissible limits.

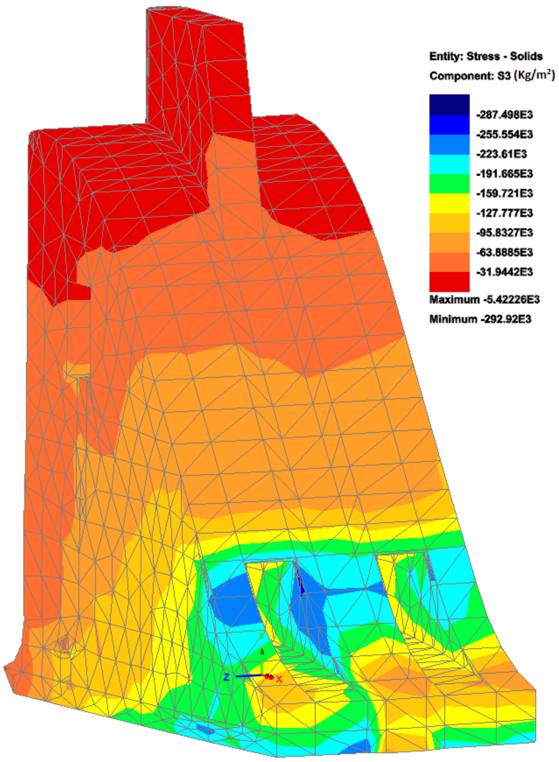


Fig.11: Minimum Principal Stress Distribution under Static Load Combination C

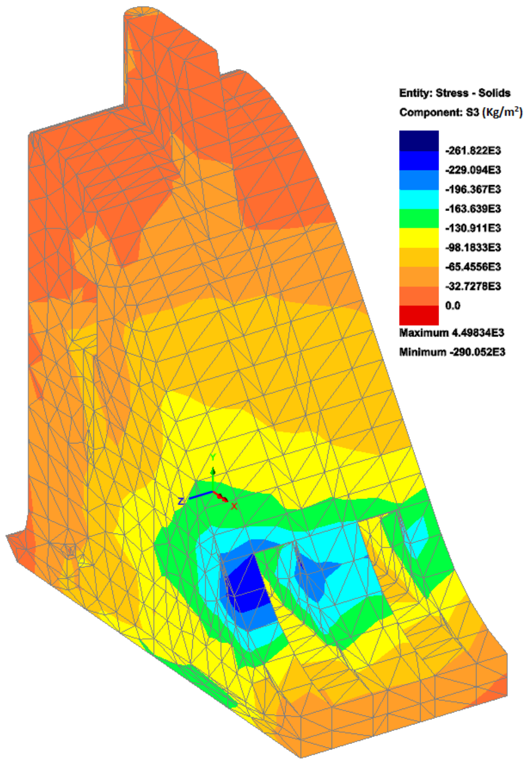


Fig.12: Minimum Principal Stress Distribution under Earthquake Load Combination G

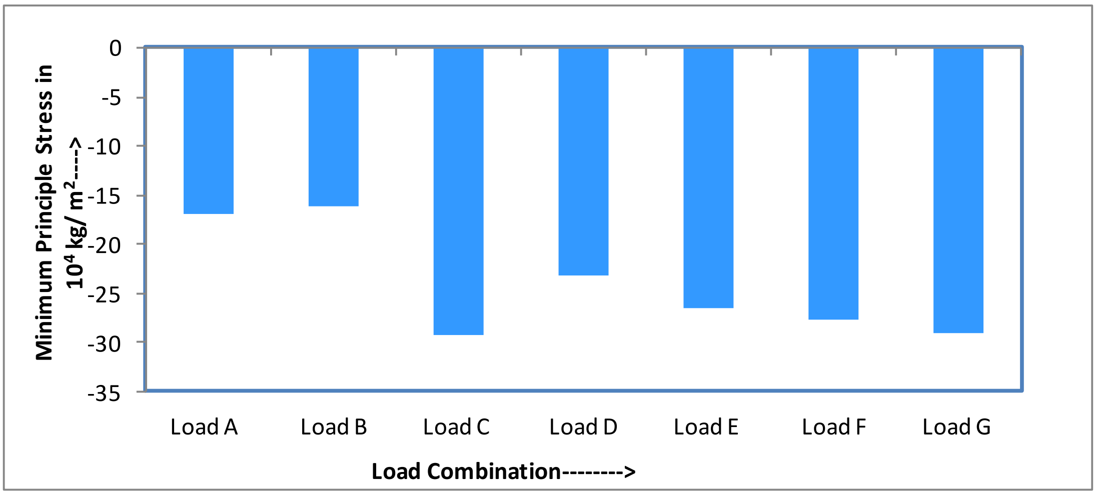


Fig.13: Variation of Minimum Principal Stress in Dam Body under all Load Combinations

4.3 Displacements

The displacements have been computed at nodes along three directions i.e. horizontal (Transverse), Vertical and Longitudinal (Along dam axis). The maximum transverse/horizontal displacement under static load combinations of the order of 2.18 mm towards d/s has been found to develop under load combinations C at top of the dam. Under earthquake load combinations maximum horizontal displacement of the order of 2.81 mm towards d/s has been found to develop under load combinations E.

The maximum vertical displacement under static load combinations of the order of 1.28 mm downwards has been found to develop under load combinations A at top of the dam. As spillway portion of Hirakud dam is never emptied hence displacement under load Combination C is most likely to happen frequently. Vertical displacement of the order of 1.22 mm downward has been observed to occur under load combination C. Under earthquake load combinations maximum vertical displacement of the order of 1.60 mm downward has been found to develop under load combinations D which is a very rare event to happen. Next peak value of vertical displacement of the order 0.81 mm under earthquake load combinations occurs under load combination E.

The maximum longitudinal displacement under static load combinations of the order of 0.35 mm has been found to develop under load combinations C at top of the dam. Under earthquake load combinations maximum horizontal displacement of the order of 1.53 mm has been found to develop under load combinations E.

Peak value of principal stresses and displacements along three directions is shown in table 2.

Table 2: Maximum Stresses and Deflections under various Load Combinations

Load Combinations	Maximum Principal Stress S1 ($x10^4$ Kg/m^2)	Minimum Principal Stress S3 ($x10^4$Kg/m^2)	Transverse/ Horizontal δ_x ($x10^{-3}$ m)	Vertical δ_y ($x10^{-3}$ m)	Longitudinal δ_z ($x10^{-3}$ m)
A	3.8	-16.4	-1.27	-1.28	0.076
B	6.8	-16.1	1.40	-0.57	0.33
C	5.7	-29.2	2.18	-1.22	0.35
D	7.1	-23.1	-2.32	-1.60	0.90
E	15.2	-26.5	2.81	-0.81	1.53
F	6.6	-27.6	2.22	-1.07	0.34
G	14.1	-29.0	2.64	-0.76	1.50

5.0 Conclusions

Following conclusions are drawn from the present study:

- Structural safety of old major dams should be assessed using in-situ material properties and site specific seismic parameters by modern practices such as Finite Element Method.

- For carrying out 3D stress analysis of spillway block of Hirakud dam, in-situ dam materials properties have been used as per laboratory studies conducted at CWPRS on extracted cores from two spillway blocks of Hirakud dam.
- Seismic coefficients have been computed based on the IS 1893-2016 by considering location of the dam in seismic zone III.
- The load combinations have been considered based on IS: 6512 – 1984. The earthquake loading has been applied as per IS-1893 :1984.
- From the analysis, it has been observed that Maximum principal tensile stress varies from 3.886×10^4 to 15.208×10^4 kg/m^2 under different load combinations. Maximum tensile stress occurs near heel portion and bell-mouth entry of the spillway blocks. Very large volume of blocks comes under tension during earthquake load combinations as well as static normal operating conditions.
- Though the mass concrete inside dam body is having very high strength as indicated by core test results but surface concrete near to bell-mouth entry might have become weak due ageing and acidic water effect resulting dislodging of concrete near to bell-mouth at some places.
- Minimum compressive stress of the order of 29.292×10^4 kg/m^2 under normal operating condition has been observed to develop in the toe region of the spillway blocks. Minimum compressive stress remains well within the allowable limits under all load combinations.
- Displacements along three directions are not excessive and indicate elastic behaviour of the dam.

6.0 Suggestions and Remedial Measures

- All loose and weak concrete near to bell-mouth should be chipped out and be repaired using micro concrete/epoxy concrete and mortar after assessing suitability under dry as well as saturated conditions.
- Acid resistant coating should be provided on finished surface in the entire Under sluice barrel of all spillway blocks.

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Acknowledgement

The authors are grateful to Dr.(Mrs.)V.V.Bhosekar, Director, CWPRS for guidance, encouragement and permission to publish this paper. Facilities and cooperation provided by the project authorities are acknowledged with thanks.