A multidisciplinary approach for the understanding of unusual behavior of Bhakra dam – a case study

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ABSTRACT

India has more than 5500 large dams with an average age of 40 years. Assessment of dam health is the primary step towards the sound management of these existing national assets. With an innumerable number of uncertain factors involved, a multi-disciplinary approach is essential to assess the health of dams with a reasonable level of accuracy. Such an approach is adopted to understand the unusual deflection of 55 years old Bhakra dam, under ongoing Dam Rehabilitation and Improvement Program (DRIP) of Government of India. The Bhakra Dam is a 225.55 m high straight concrete gravity dam with a massive reservoir capacity of 9.86 Billion Cubic Meter (BCM).

The safety evaluation is carried out with a collaborative approach that included testing of existing dam material, scrutiny of available instrumentation data and developing a 3D numerical dam-foundation-reservoir model to execute a sequential thermal, static and linear dynamic analysis on various plausible load scenarios. Observed and analyzed results of the numerical model showed a similar displacement trend, however, deviation in terms of absolute values necessitates detailed non-linear modeling in the future, for which the current study will act as a base. This comprehensive study helped dam owners make an informed decision about its operation and up-gradation of instrumentation. The paper attempts to touch upon the technical aspects and necessary trade-offs involved in undertaking such a holistic study on large dams such as the Bhakra dam.

Key Words: Numerical model, linear dynamic analysis, material test, concrete gravity dam, dam instrumentation

1.0 INTRODUCTION

Management of water as a resource is best implemented through storage dams. As per World register of Large dams globally there are more than 58000 large dams (ICOLD, 2019). India stands third globally with 5264 large dams and 437 large dams under construction (CWC, 2018). The average age of these assets are above 30 years and besides we are moving into the era where new natural and economical dam sites are seldom found. Hence rehabilitation and protection of existing dams assume importance. In line with this thought, the Government of India has taken up the procedure for identifying dams of national importance and rehabilitating them for sustainable future use. Dam Rehabilitation and Improvement Program (DRIP) in association with the World Bank is one such initiative of Indian Government. Under this project, the study of unusual behavior of the Bhakra dam was taken up and concluded recently. Similar studies for Idukki dam (Kerala) and Konar dam (Jharkhand) were completed successfully in the recent past under the ongoing project which supported in informed decision making and to carryout rehabilitation measures in a more rational manner.

This paper presents the case study of Bhakra Dam, which is a 225.55m (740 ft.) high straight concrete gravity dam situated in Himachal Pradesh with storage of capacity 9.3 BCM and built across river Sutlej in a deep and narrow gorge of the Lower Siwalik Hills. The length and width of the dam at the top is 518.16 m (1700 ft.) and 9.14 m (30 ft.), respectively, with the width of dam at base being kept as 190.5 m (625 ft.) and the width including apron and heel claystone plug as 402.33 m (1320 ft.). The second tallest and third largest dam in the country, Bhakra dam is comparable to other large concrete gravity dams in the world such as Grand Dixence Dam in Switzerland (285 m). Completed in 1963 and operating since then, this dam is a typical example of a concrete gravity dam that qualifies for having experienced all plausible dam loads during its lifetime. Moreover, Bhakra is one of the few old Indian dams instrumented with equipment to measure stress, strain, temperature, deflection, and uplift. In the current situation, no major distress was observed in the dam and field investigation was carried out. The data as obtained from the field and laboratory studies were used as an input while developing Finite Element Model of dam for determining reason behind unusual deflection of dam.

Figure 1: Frontal and aerial view of Bhakra Dam

2.0 BACKGROUND TO THE PROBLEM AT HAND

Bhakra dam was designed by the United States Bureau of Reclamation (USBR), Colorado, the USA by Trial Load Analysis in 1952. On completion, re-analysis of stability and structural adequacy by Trial and Load Analysis in accordance with assumed foundation excavation profiles, elastic properties of the foundation rock and concrete and construction program was carried out in 1964. The computed value of maximum deflections, as per latter studies done in 1964, are 1.53 inches (38.86mm) for seismic condition and 1.03 inches (26.16mm) for non-seismic conditions.

Table 1 : Ready referrer of information related to geometry of Bhakra dam utilized in numerical model

1.	Bhakra dam has 30 blocks (numbered 5-35) with 5 Overflow Blocks, numbered 18-22, centrally placed. Block height varies from 50 ft to 739 ft as we move from abutment to centre of dam. Top of dam is at El.1700 ft and deepest foundation level goes as deep as El.1080 ft.
2.	Plumblines are installed in Block 15, 20 and 23. Block 20 and 23 are considered as a representative Overflow (OF) and Non-Overflow (NOF) block for safety evaluation
3.	FRL (Full Reservoir Level), MDDL (Minimum Draw Down Level), Min TWL (Minimum Tail Water Level) and Max TWL (Maximum Tail Water Level) are El. 1685ft, El. 1462ft, El.1166ft and El.1215ft respectively. Maximum silt/sediment load is applied till El.1300ft, this being invert of lowest river outlet

Deflection, in general, is not a governing factor for assessing safety aspects of a concrete gravity dam. However, due to maximum permissible deflections estimated by trial load analysis setting a benchmark, deflection in dam blocks is considered as a safety monitoring parameter for Bhakra dam, particularly after installation of plumb lines in dam block. Scrutiny of maximum deflection observed from 1964 using plumb line installed in Block 20 (refer Table 1) indicates that maximum and minimum deflection exhibited increasing trend. Further, during the years of 1995, 1998, 2008, 2010, 2011 and 2013, maximum deflection was more than 1.03 inches. The maximum value of plumb line deflection perpendicular to the dam axis observed so far is 1.1122 inch (28.25 mm) on dated 01.12.2010 at Reservoir Water Level 1670.34 ft (509.12 m). It is to note that no visible signs of distress, seepage or problems in operation of spillway gates are reported so far with the dam. In this scenario wherein deflection in deepest block continues to show an increasing trend and has crossed the maximum design permissible limits for Bhakra dam, safety of the structure is a question that needed to be addressed considering the huge risk associated with this massive structure.

3.0 COMPREHENSIVE CUM ADAPTIVE APPROACH

In order to understand the very reason of above highlighted issue and suggest a befitting remedial solution, a comprehensive safety evaluation of the Bhakra dam was carried out in a collaborative manner. The aforementioned multi-disciplinary study involved expert team from Central Water Commission (CWC), Central Soil and Materials Research Station (CSMRS), National Centre for Concrete for Building Material (NCCBM), dam owners, Bhakra Beas Management Board (BBMB) and M/s Dassault system.

Each team involved in the study had an explicitly defined role. The encompassing activities of the study commenced with a joint site inspection, by officials from team of experts as mentioned above. Subsequently, investigation for existing material properties (mechanical, thermal and dynamic properties) was carried out by (NCCBM) and (CSMRS) for the dam body, abutment/rock and foundation. Based, on the findings of investigation on material properties a separate paper is being presented in ICOLD 2020. Project authority (BBMB) supplied the basic information regarding dam geometry, its construction process, design principles adopted during construction, and the instrumentation data (plumb line, thermometer readings, strain-stress gauge readings, and uplift measurements). CWC officials along with engineer from Dassault system developed a detailed 3D numerical simulation of the Bhakra dam under various plausible loads and their combinations. M/s Dassault system provided support related Abaqus software.

4.0 SOLUTION FORMULATION

University of Roorkee, in the year 1981 and 1998 carried out 2D numerical analysis of block 20 for static (non-seismic) loading condition. The results indicated that the theoretical and measured deflections compare favourably well in the lower half portion of the dam, but there is considerable deviation in the upper portion, which was mainly attributed to the effect of the temperature variation in the body of dam which had been neglected in the 2-D analysis., besides the normal stresses were found fully comprehensive and within the safe limits. In continuation to the above cited study, a 3-D analysis of the Bhakra Dam was carried out for static and seismic condition using pseudo static method. The 3-D analysis showed that the theoretical deflections are in close agreement with the measured values, and stress values are mostly within permissible limits, with isolated regions of stress exceedance. Recently, in the year 2016, the seismic safety evaluation of the dam was carried out by IIT Roorkee then University of Roorkee keeping in view of the recent development in the domain understanding. Now, a 3D thermo-elastic dynamic analysis of Bhakra dam was executed by the design team of Central Water Commission of which details and findings are discussed in this paper.

On studying the available inline literatures, it is understood that numerical simulation of such massive structures along with all plausible load combinations including long term loading effect (such as creep, thermal cycles) are seldom taken up due to associated complexity in the model generation and also since it is computationally-intensive. Hence, a comprehensive cum adaptive approach formulated with certain intentional trade-offs, as discussed in below paragraph, is thought to be well-off to proceed with the analysis.

In concrete gravity dams, 2D numerical analysis of a concrete block is normally adequate. However, in Bhakra dam, presence of transverse grouting (up to Elevation.1640 ft) between blocks, generates beam action resulting in transfer of the loads partially to the abutments. The same necessitated a 3D numerical model for analysis. Intricate geometry simulation of small size galleries, penstocks/outlets passing through dam body, spillway girders etc. is ignored. Minor variation in material properties across the dam body (like thin layer of concrete with higher strengths along the upstream and downstream faces, abutment faces and gallery periphery) is also ignored. The dam is well instrumented, with huge database of monitored data related to temperature, stress and strain which were available, however the same was found to be either incredible or not validated. It is understood that instruments so old (>55years of operation) and especially installed before 1975s, though being the best of its time, may mostly be malfunctioning or erroneous at present. Hence, only basic observations such as deflection, reservoir water levels (RWL) and uplift pressures are utilized. The numerical simulation had to model physical processes related to thermal and mechanical process. Abaqus software has the option to carry out a thermo-mechanical analysis in fully coupled or in a sequential manner. This study utilizes sequential heat transfer simulation wherein the results of thermal analysis due to thermal expansion are imported into the mechanical model to simulate the mechanical processes in this sequence. It has the advantage of higher computational efficiency against fully coupled thermo-mechanical analysis, without much loss in accuracy. Though various studies have accomplished that creep is a major factor in deflection in massive concrete structure as dams, deficiency of accurate data about the same, crippled the team in proceeding with full non-linear analysis. Hence, analysis linear with material but non-linear in geometry and interface interactions was decided upon.

5.0 NUMERICAL MODEL

The geometry of 3D dam body (refer Table 1), including intricate details of spillway, training walls and dam foundation interfaces, is developed using construction drawings. Foundation as a whole is envisaged to have depth of 2 times height of deepest block and along other two directions, it is modeled to have dimension of 1.5 times the height of deepest block. Reservoir is not modeled to its accurate bathymetry. Figure 1 shows the 3D numerical model so developed. For heat transfer analysis only the dam body is considered with foundation ignored. For standard heat transfers hexahedral element DC3D8 (Diffusive Continuum 3D 8 Noded Brick Element) is used. It has a single degree of freedom which is nodal temperature. For structural analysis both the dam body and foundation are considered. The advanced structural hexahedral mesh C3D8I (Structural Continuum 3D 8 Noded Incompatible Brick Element), which is an accurate element for bending and limits shear-locking and hour-glassing, is used. Figure 2 shows the meshed section of an Overflow block. The unit system followed for the analysis was kg-inch-second-Celsius.

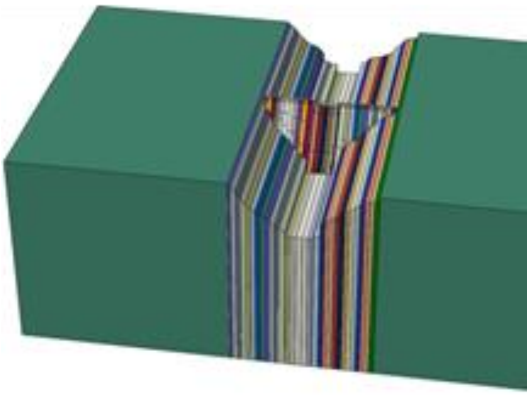


Figure 1: 3D dam-foundation numerical model

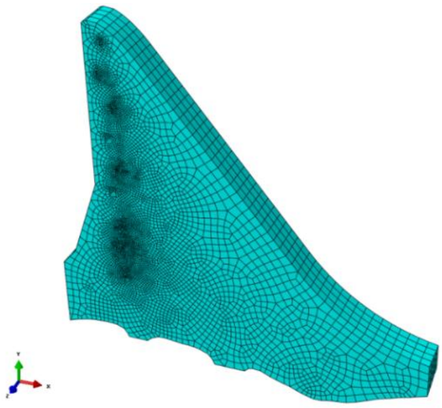


Figure 2: 3D Meshed Overflow section

6.0 MATERIAL PROPERTIES AND INTERACTION

The material properties used in the numerical model were obtained from field investigations done by NCCBM/CWPRS, and the values that are not available were taken from available literatures/guidelines. The same is given in the Table 2. There are two different type of contacts used in the numerical model i.e. Cohesive interaction between dam and foundation, dam-dam blocks; Tie between foundation blocks. The cohesive interaction is applied till elevation 1640 ft which simulates the transverse grouting and keying between dam blocks. Cohesive interaction between dam and foundation is used to apply the uplift pressure.

Table 2: Material properties adopted in numerical analysis

Description/Parameter	Units	Value
Concrete		
Volumetric Weight (dry density) of concrete, γ_c	g/cc	2.35
Compressive strength of intact concrete, f_c'	MPa	27.44/32.9
Tensile Strength of intact concrete, f_{tc} (static/dynamic)	MPa	3.39/4.5
Sustained/Dynamic Modulus of Elasticity of concrete, E_{Static} / E_d	GPa	25.95/35.62
Poisson Ratio of Concrete Material, μ_c		0.2
Coefficient of Thermal Expansion of concrete, α_c	Per °C	11.9×10^{-6}
Thermal Conductivity of concrete, K	W/(m-°K)	2.6 to 2.7
Solar Absorptivity		0.65
Solar Emissivity		0.9
Foundation/Rock mass		
Volumetric Weight, γ_r	g/cc	2.61
Modulus of rock foundation, E_m	GPa	14.944
Poisson Ratio Rock Mass, μ_r		0.186
Convection Coefficient of air with concrete, h_a	$W/m^2.°K$	55.6
Convection Coefficient of water with concrete, h_w	$W/m^2.°K$	556
Cohesive Contact Properties		
Tangential stiffness, K_{tt}	N/mm	1e8
Normal Stiffness, K_{nn}	N/mm	0.001
Shear Stiffness, K_{ss}	N/mm	1e8
Critical damping ratio of concrete, ζ		0.05

7.0 Loading Scenario and Analysis

The loadings such as self-weight, hydrostatic load due to reservoir water level (RWL) and tail water level (TWL), uplift (drain operative and inoperative conditions), sediment/silt load, thermal load (summer/winter) and earthquake loads along with hydrodynamic effect were used in the analysis. The loading scenario used in the analysis as explained in Table 3 is based on combinations of these loads created as per Indian Standard (BIS, 1984) and international guidelines (USBR, 2006). User-defined subroutines, namely DLOAD, UTRACLOAD, DFLUX and FILM, are used in this study. DLOAD is used to apply hydrostatic and uplift forces for varying reservoir water levels (RWL). UTRACLOAD is used for application of silt load as traction force. Application of film coefficients on upstream and downstream face based on varying RWL/TWL and modeling of convection are executed by FILM. DFLUX is used to apply thermal flux on dam surfaces and model radiation to - from dam body (due to its exposure with air and water). Usage of time-dependent thermal, hydrostatic and uplift loads made application of user-defined subroutines mandatory for simulation. The geostatic step is applied as a pre-cursor to all structural analyses to ensure zero deflection on application of dead weight.

Table 3: Scenarios of load combinations analyzed in numerical model

Scenario 1:	3 year simulation wherein observed/real data of reservoir water level, ambient air temperature, sediment load and uplift during 2015-2017 are applied to the 3D model to assess the realistic dam behavior and hence qualify the trend/reasons of observed dam deflection
Scenario 2:	Instantaneous applications of critical combinations of hydrostatic (maximum and minimum RWL/TWL), thermal (extreme summer and winter), uplift (drain operative and inoperative) and sediment loads to assess safety of dam
Scenario 3:	Linear dynamic (time history) analysis of Bhakra dam to assess seismic safety of dam

The thermal loads in case of a dam includes heat of hydration, ambient air temperature, reservoir water temperature and incident solar radiation. Since the dam is more than 50 years old, the effect of heat of hydration is not considered. The thermal analysis, includes conduction within dam body, convection (across dam-air and dam-reservoir interfaces) and radiation/emission from dam body.

The solar radiation incident at a given geographical site (based on latitude and longitude) varies in time, between day and night and between seasons. Further, it varies in space due to obliquity of solar rays with respect to alignment/inclination of surface chosen. Solar radiation constitutes three components viz. direct radiation, uniform diffused sky radiation and ground reflected radiation. In this study, ground reflected radiation was found negligible. Solar radiation/flux (direct and uniform diffused sky radiation) for upstream and downstream faces of Bhakra dam was estimated at a uniform time interval of 2 hours for a duration of a year (CBRI, 1994). The generated solar flux was applied as thermal load on exposed areas of upstream and downstream faces of dam. The information for depth wise variation of reservoir water temperature was not available, so, as an alternate Zhu-Bofang equation (Mirzabozorg & etal, 2014) was used to estimate reservoir water temperature at various water depths using ambient air temperature as input. Incident solar radiation, reservoir water temperature variation and ambient air temperature are inputs for the estimation of radiation and convection. Film coefficients (refer Table 2) defined along the dam-water and dam-air interfaces assist convection to be modeled. The Figure 3 shows the different components considered in the thermal analysis of the dam body.

Time to attain thermal equilibrium by a concrete dam depends on its size, concrete placement temperature and average ambient air temperature at dam site. Being constructed 55years ago, dam body of Bhakra is expected to have attained thermal equilibrium with the surrounding atmosphere. To mimic this thermal equilibrium state of dam body, model is run (simulating conduction, convection and radiation), with an initial state of 18.3ºC (final stable temperature as per design and construction of Bhakra dam) and observed ambient air temperature for a period of 10 years. The thermal equilibrium state so obtained is applied as the initial thermal boundary.

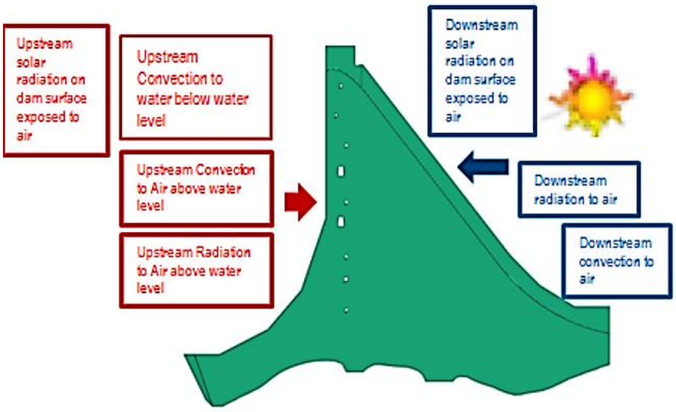
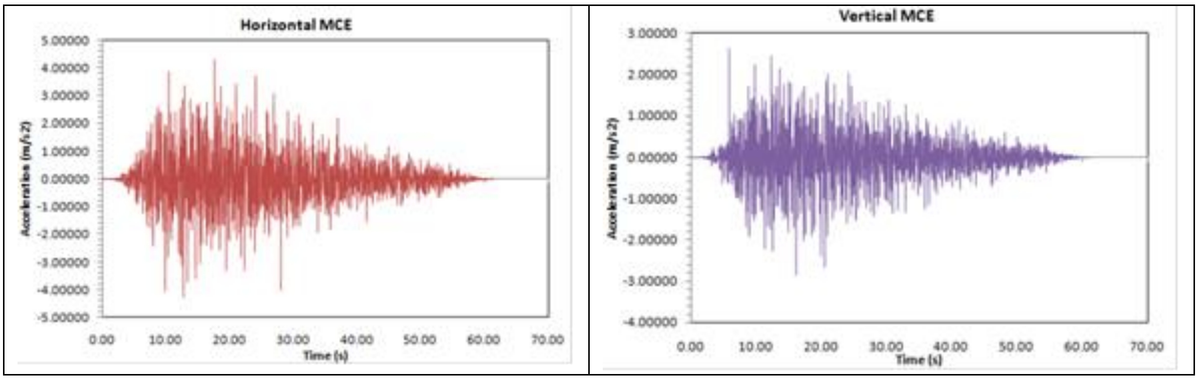


Figure 3: Physical processes of convection, conduction and radiation caused by thermal load (incident solar radiation) that are analyzed in the numerical model

For cases in Scenario 1 and 2, model with massless foundation is chosen. For cases in Scenario 3, site specific seismic parameters had to be applied at base of dam and hence rigid foundation was chosen. In cases in Scenario 3, dam-reservoir interaction during an event of earthquake (hydrodynamic effect) is captured by means of Zangar's added mass (USBR, 2006). Input site specific seismic parameters for Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE) are shown in Figure 4.



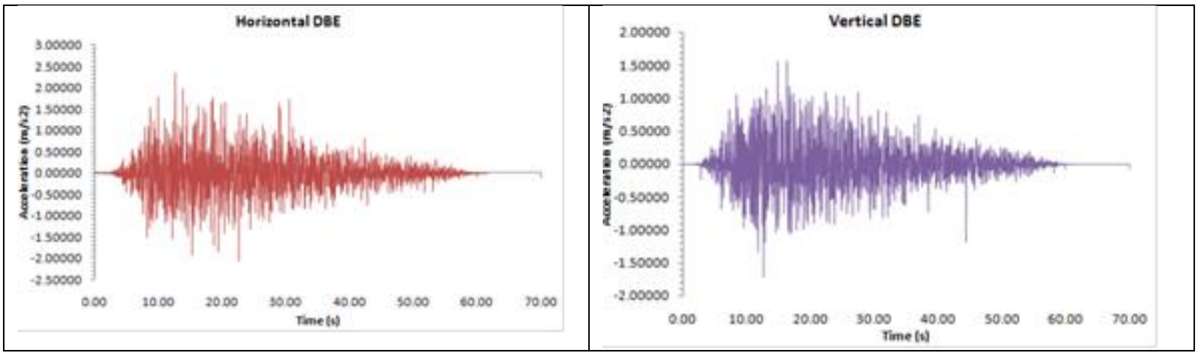


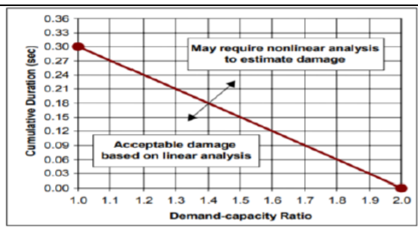
Figure 4 : Site Specific Time History Accelerations (both horizontal and vertical) in MCE (top) and DBE (bottom) input for linear dynamic analysis

8.0 PERFORMANCE EVALUATION CRITERIA

The interpretation of analysis' results (viz. deflections, principal stresses, temperature gradients, acceleration time history etc.) for evaluating safety of the dam is the next logical step. This study utilized the provisions stipulated in guidelines of US Army Corps of Engineers EM 1110-2-6051 (USACE, 2003) in con-junction with the existing practices for better interpretation of results of both non-seismic and seismic condition. A brief about the aforementioned USACE safety evaluation criteria which is based on concepts of Demand Capacity Ratio (DCR), Cumulative Inelastic Duration (CID), Performance Curve, DCR plots and Performance Levels is given in Table 4.

Table 4: Concepts used in performance evaluation criteria for seismic condition

1. Demand Capacity Ratio (DCR): ratio of computed principal stress/tensile strength of concrete
2. Cumulative inelastic duration (CID): total duration of stress excursions above the tensile strength of the concrete
3. Performance curve: Plot of CID vs DCR. Figure shows limiting performance curve for a concrete gravity dam



4. Performance Levels
   - Serviceability performance: structure is expected to be operational immediately after earthquake
   - Damage control performance: structure is expected to slightly yield at small locations but may be operational on repair
   - Collapse prevention performance: structure is damaged to the extent of being non-repairable, but doesn't collapse

Performance Criteria for Non-Seismic (Static) Condition: This criterion is employed on results obtained from numerical analyses under Scenario 1 and 2.

i). Stress values at critical locations of dam (heel, toe, crest, galleries, points of changing slopes etc) are extracted. Maximum positive normal stresses are checked against static tensile strength of concrete (3.39MPa) and maximum negative normal stresses are checked against static compressive strength of concrete (27.44MPa).

ii). Deflections unlike stresses cannot be checked against any specific value. However, deflections at critical locations (crest, heel and toe) are extracted and compared with the permissible design values. Alarming deflections are taken as indicators of distress which are cross verified with stress values.

iii). Temperature gradients are studied to understand critical conditions.

Performance Criteria for Seismic Condition: This criterion is applicable for checking dynamic safety of Bhakra dam and hence applied for analyses in Scenario 3.

i). Traditional method of dynamic safety (Pseudo Static method as in IS 6512 - 1984), particularly in sliding and overstressing, are employed to check the factor of safety at various horizontal planes of possible instability as a primary check.

ii). Modal frequencies and modal mass participation are obtained for an overflow (block 20) and non-overflow block (block 23) by means of modal analysis. Consequently, prediction regarding critical mode frequencies and non-linearity of dam are achieved.

iii). Linear time history analysis is executed. Time history of responses (displacement, acceleration and principal stress) are obtained for critical locations (heel,toe and crest of dam blocks) for a broad qualification of distress in dam due to seismic event. Plots of minimum principal stresses are checked to see if the dam body is stressed beyond its compressive strength. Plots of maximum principal stresses are used for DCR estimations.

iv). DCR plots for linear time history are developed. Seismic criticality of dam is identified based on DCR≥1, 1.15, 1.53 and 2. On studying the DCR plots, critical locations are identified for which cumulative duration and performance curve are developed, if required (to assess non-linearity in the model). Based on stress plots, DCR values and performance curve, performance level of Bhakra dam and identification of critical/unsafe areas in dam body are estimated as explained below:

- If DCR≤1.15, the dam response to DBE condition is considered to be within the linear elastic range of behaviour with little or no possibility of damage. The dam is understood to be in serviceable level of performance. In such cases, DCR ≥2 for MCE is acceptable, however only a non-linear analysis can fully reinforce whether it comes under damage control or collapse prevention performance level.
- If DCR≤1.53 and cumulative duration of stress excursions beyond the tensile strength of the concrete falls below the performance curve as given in Table 4, the dam will exhibit nonlinear response in the form of cracking of concrete and/or opening of construction joints, however, it is acceptable and deemed to be in damage control performance level.
- If DCR≤2 and limited to 15 percent of the dam cross-section surface area and the cumulative duration of stress excursions beyond the tensile strength of the concrete falls below the performance curve, the level of nonlinear response or cracking is considered acceptable and deemed to fall in damage control performance level.
- Any state other than a, b and c as far DCR values or performance curve are concerned, a non-linear analysis will be required to assess the behaviour of dam.

9.0 OBSERVATIONS

Key observations based on performance evaluation criteria for non-seismic condition with results from Scenario 1 and 2 are:

1. Bhakra dam is assessed to be safe from aspects of both static compressive and tensile strength of concrete.

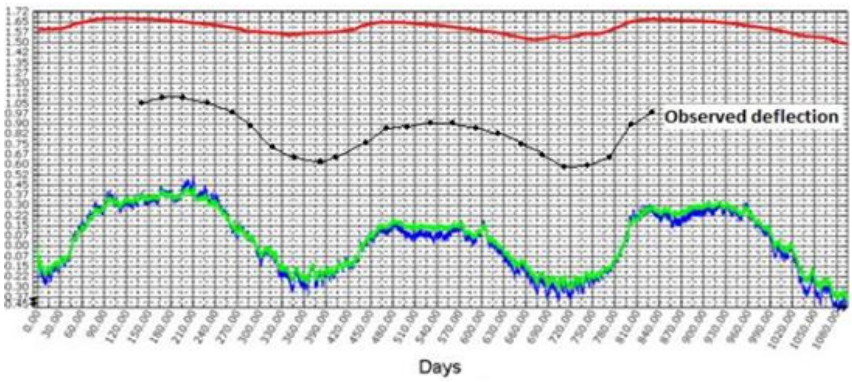


Figure 5: Comparison of deflections in Block 20 for simulation in Scenario 1. Deflection (inches) at the crest and plumb line measurement point of Block 20 are given in blue and green respectively. RWL in 1000ft (red) and observed deflection in inches (black line) are also indicated

2. Deflection at crest of dam block estimated by numerical method (elastic deformation) is seen to follow the trend of observed deflection and is in tandem with the varying reservoir water level. However, observed and estimated deflection in Block 20 is seen to have a difference by a definite margin (by an amount ~4 inch) as shown in Figure 5. This margin is expected to be caused by inelastic deformation

(creep) which Bhakra dam has undergone in past 55 years. Graphs in Figure 6 and Figure 7 further verify this aspect.

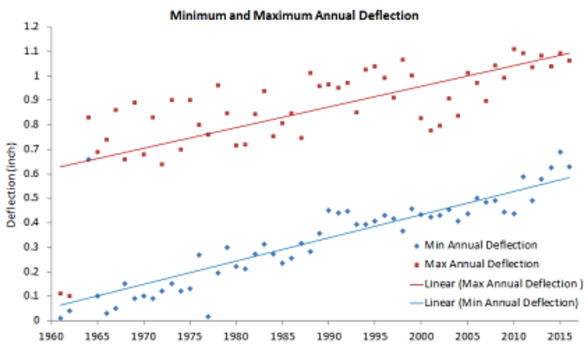


Figure 6: Plot of minimum and maximum annual deflections in observed at plumb line point of Block 20 from 1964. Over the years the values have slowly increased by about 4 inches

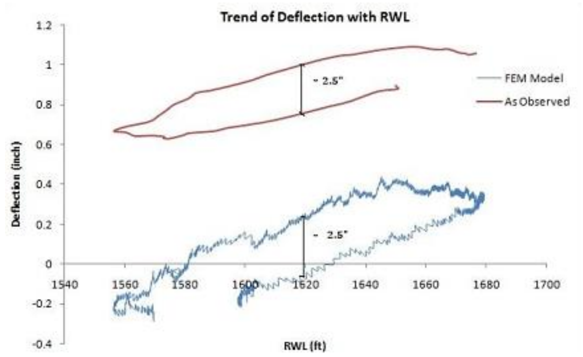


Figure 7: Trend of annual deflection due to RWL is seen to be a hysteresis with similar margin (~2.5inch) for both deflection series as observed in ground and from numerical model. This shows the numerical analysis is successful in capturing the effects of RWL.

3. Temperature of dam body ranges between 0-26^{O}C during winters and 16-40^{O}C during summers; the interior temperature of dam body is seen to have stabilized in the range of 11-18^{O}C (i.e. dam body has attained a thermal equilibrium); only a definite depth of concrete (around 4-5m deep) on the periphery of dam experiences considerable variation in temperature due to seasons in a year as shown in Figure 8.

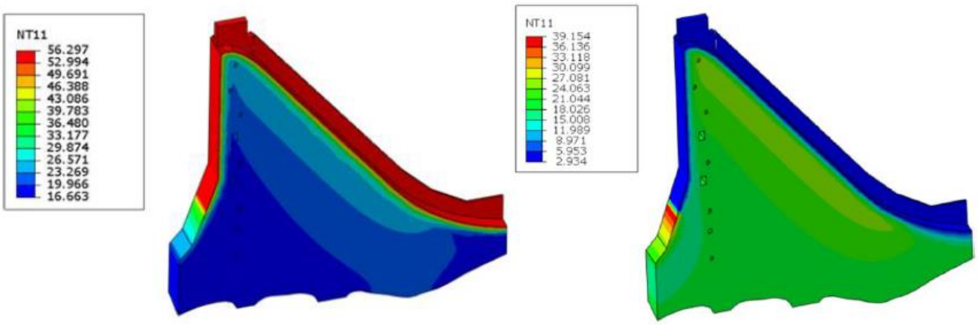


Figure 8: Temperature variation across Block 20 during extreme summer (on left) and extreme winter with lowest reservoir level.

4. In straight concrete gravity dam such as Bhakra dam, thermal stresses due to high air temperatures (summer) adds to stability as it introduces an upstream warping and introduces instability during winter times due to forward deflection; 3 year simulation from Scenario 1 with all static loads including and excluding thermal loads (Figure 9) gave maximum forward deflection of 0.5 inch and 0.78 inch respectively, exhibiting the conservative nature of thermal load in reality; occurrence of critical deflection is shifted from summer to winter in presence of thermal loads; thermal load may be significant to the extent of 25-30% of total deflection of dam body

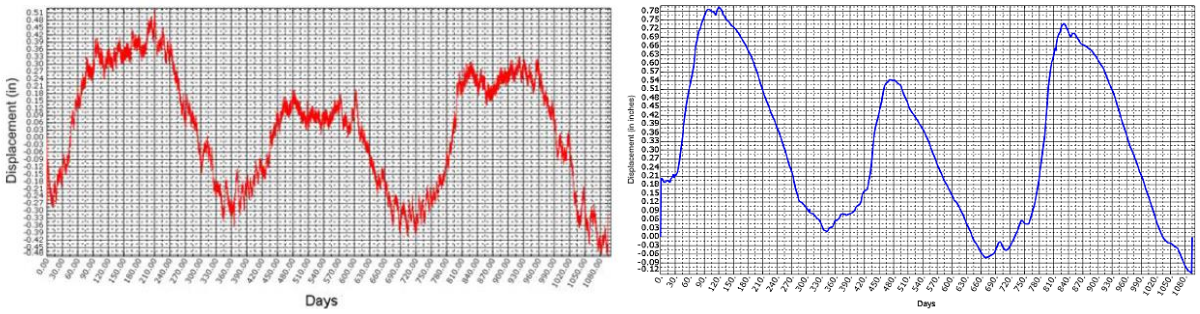


Figure 9: Deflection (inches) at plumb line point in Block 20 for load case in Scenario 1 - with (left) and without (right) thermal loads

Major observations on executing performance evaluation criteria for seismic condition with results from Scenario 3 are:

i). The modal frequencies for Block 20 and 23 are shown as in Table 5. Further, based on the mass participation, the first 4 and 2 modes are found dominant in case of Block 20 and 23 respectively.

Table 5: First 5 modal frequencies per second obtained for Block 20 (OF) and Block 23 (NOF)

Mode	1	2	3	4	5
Block-20	2.754	4.9071	5.5893	6.5378	9.1297
Block-23	2.958	6.088	7.2548	9.6572	13.909

ii). The deflection in dam is expected to cross the maximum computed limit (1.53 inch for seismic condition) as per design of Bhakra dam in both DBE and MCE conditions. Time histories of deflection obtained are shown in Figure 9. The deflection at crest/plumbline measuring point deviates heavily from its initial value only after 4.2s in DBE condition. On the other hand, the deflections at the aforementioned locations oscillate vehemently after 0.3s in load case for MCE. Also, cycles of heavy deflections are more in number in the MCE condition. Conclusively, MCE condition seems to be in damage/collapse level of performance (though deflections in isolation cannot give any indication regarding safety of dam)

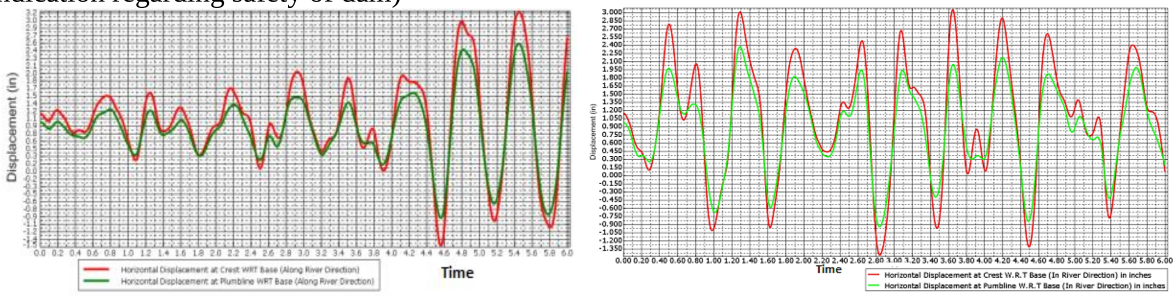
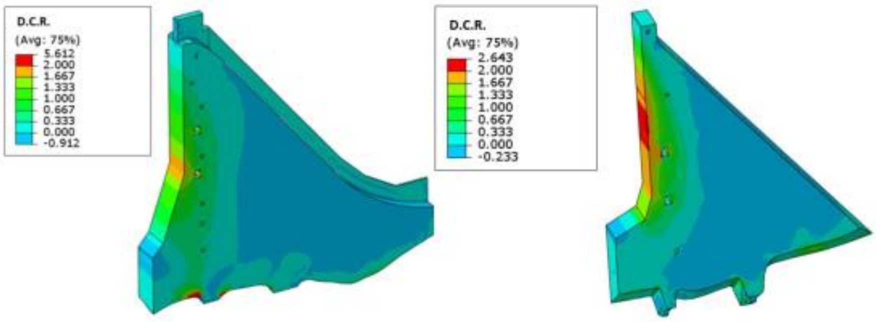


Figure 10: Deflection for time history analysis for DBE (top) and MCE (bottom) condition. Deflection (inches) at crest and plumb line point in Block 20 are given in red and green respectively

iii). Response (acceleration) time histories obtained for Block 20 and 23 show that Block 23 (NOF) has higher probability of damage than Block 20 (OF). Inspite of Block 20 being deeper than Block 23, concentration of more mass at higher elevations in Block 23 is attributed as the reason for this. Maximum acceleration at the crest in DBE condition is 1.16g for Block 20 and 1.47g for Block 23. When it comes to MCE condition, maximum acceleration at crest of Block 20 is 1.55g and at Block 23 is 2.17g.

iv). From animations of minimum principle stresses across dam body, it is seen that the dam blocks are seen to be safe in compression in all seismic load cases.



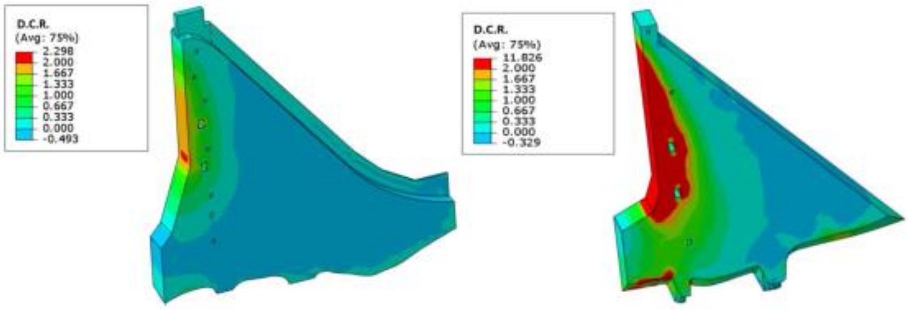


Figure 10: DCR plots of Block 20 and 23 for DBE (top) and MCE (bottom) are given. Plots of Block 20 and 23 are on left and right sides

v). Animations of maximum principal stresses of Block 20 and 23 are analyzed to study tensile stresses generated during dynamic analysis. Tensile stresses exceeding dynamic tensile strength of concrete (4.5MPa) develop at various instants, at galleries and point of change in slope on the upstream and downstream faces in both Block 20 and 23. To evaluate safety, DCR plots are generated as shown in Figure 10. Block 23 shows distress due to tension with DCR>2 implying a non-linear study is required to see whether it falls in damage or collapse control performance level. Block 20 falls in the category DCR≤2 (in DBE condition) with less than 15% area being non-linear and hence could be categorized as damage control level of performance provided a satisfactory performance curve is obtained. Consequently, performance curve for a critical point (point of change in slope in upstream where DCR close to 2 is observed) in Block 20 is developed for DBE condition as given in Figure 11. Graph falling well above the limiting line shows that non-linearity in the model is high to be captured in an inelastic study and hence a non-linear study may be required to model the real behavior of dam.

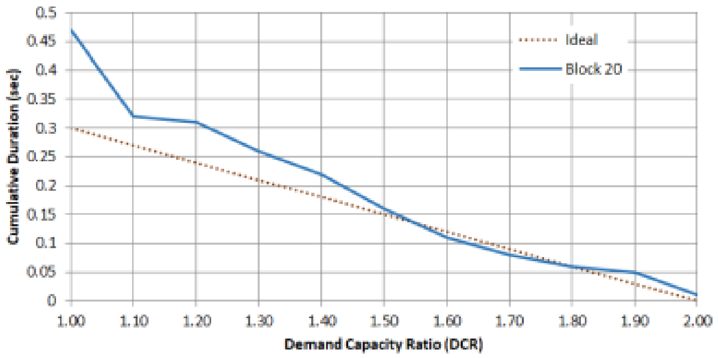


Figure 11 : Performance curve of point of changing slope in upstream face of Block 20 for time history analysis in DBE condition

CONCLUSIONS

Conclusions of the present study are summarized in this section. Safety evaluation is crucial for any hydraulic structure. A periodic evaluation for safety utilizing the contemporary state of the art shall be an integral part of any dam safety program. These studies aid in informed decision making for implementation of befitting remedial measures such as instrumentation, deploying safety protocols for operation and maintenance as well as the planning for evacuation of the downstream population in extreme situations.

A 3D thermo-mechanical seismic analysis of Bhakra dam under various plausible load scenario is executed. The trend of displacement history as obtained from numerical model and observed at the dam site are in good agreement, however difference in numerical values exists. Dam is found to be safe in static condition from perspective of compressive and tensile stresses generated in dam body compared to its strengths. Further, long term (3year) simulation of dam behavior with observed static loads showed that creep (inelastic deformation) has contributed substantially to the unusual deformation of Bhakra dam.

The difference in the numerical value in deflection can be improved by refining the existing 3D model by incorporating the creep behavior, foundation heterogeneity and other factors as applicable. The detailed thermal analysis, which is unique part of this present study, showed that temperature has a considerable impact on the deflection and may contribute to 20-30% of total deflection. Thermal loads are seen to have conservative upward warping during summers and destabilizing effects during winter times. Further, necessity of including thermal analysis as an integral part of any numerical modeling of dam along with other anticipated loads is felt.

Evaluation of safety utilizing the traditional seismic evaluation method, when used in conjunction with the process laid in USACE, 2007 fetched better interpretation of the analysis outcome and helped in planning for a systematic and progressive linear to nonlinear analysis. The DCR plots helped in better visualizing the spatial extent of stress distribution. Additionally, the performance threshold curves show the Cumulative Inelastic Duration (CID) and requirement for nonlinear analysis. Criteria for evaluation of safety of dam in non-seismic and seismic condition are devised and employed on the results of various numerical analyses carried out in this study. Modal analysis is executed to understand critical modal frequencies. Linear time history analysis of Bhakra dam is executed for both DBE and MCE condition. On examination of DCR plots and time history of accelerations obtained in dynamic analysis, non-overflow block is seen to exhibit higher possibility of damage. Further, performance curve and DCR plots showed that non-linear studies may be needed to model the real dam behavior during earthquakes.

References

BIS. (1984). *IS 6512, Criteria for design of solid gravity dams, (Reaffirmed 1998).* Bureau of Indian Standrads.

CBRI. (1994). *Building Research Note 80.* Roorkee, India: Central Building Research Institute.

CWC. (2018). *Nationa Register of large dams.* Delhi: Central Water Commission.

ICOLD. (2019, 12 26). *ICOLD*. Retrieved from International Commission on Large dams: https://www.icold-cigb.org/GB/world_register/database_presentation.asp

Mathematical Modeling and Numerical Analysis of Thermal Distribution in Arch Dams Considering Solar Radiation Effect. (2014).

Mirzabozorg, H., & etal. (2014). Mathematical Modelling and Numerical Analysis of Thermal Distribution in Arch Dams considering Solar Radiation Effect. *Scientific World Journal Volume 2014*. Retrieved from http://dx.doi.org/10.1155/2014/597393

USACE. (2003). *Time History Dynamic Analysis of Concrete Hydraulic Structures EM 1110-2-6051.* US Army Corps of Engineers.

USACE. (2007). *Earthquake Design and Evaluation of Concrete Hydraulic Structures EM 1110-2-6053.* US Army Corps of Engineers.

USBR. (2006). *State-of-Practice for the Nonlinear Analysis of Concrete Dams at the Bureau of Reclamation.* USBR.