Safety Evaluation of Idukki Arch Dam

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Abstract— **Idukki Dam is considered as Asia's first and largest arch dam, constructed across Periyar River in a narrow gorge. It uses the theory of arch action to resist the large amount of pressure exerted by the reservoir water spread over 36 miles on a height of 2300 ft. above MSL. This is a double curvature arch dam which has curvature in both vertical and horizontal directions. Even though there had never been any doubt regarding the strength and stability of Idukki dam, the present situations like Mullaperiyar issue and frequent earthquakes in the dam vicinity has called for a proper analysis and study of the dam. This has become a necessity to ensure the safety of people in Kerala as the damages caused by the failure of Idukki dam can be catastrophic.**

In this study, the dam coordinates are obtained with the help of a PYTHON program and is modeled in AutoCAD, and Finite Element Analysis (FEA) is done on the dam model for various load combinations. FEA is a method in which complex models or structures are analysed by dividing them into relative finite elements and giving the suitable boundary conditions. Among many FEM packages that are available, ANSYS is a package that makes analysis of complex structures possible with least errors, which made ANSYS appropriate for this analysis.

The results of analysis of model do not disclose any areas of overstress. The values of displacements and stresses obtained from the various load combinations considered in the present study are found to be less than the permissible limits of displacements and stresses.

Keywords— Idukki arch dam; ANSYS; arch dam modeling

I. INTRODUCTION

A dam is a barrier that impounds water or underground streams. Dams generally serve the primary purpose of retaining water, while other structures such as floodgates or levees (also known as dikes) are used to manage or prevent water flow into specific land regions. Hydropower and pumped-storage hydroelectricity are often used in conjunction with dams to generate electricity.

There had never been any doubt regarding the strength and stability of Idukki dam. But the present situations like Mullaperiyar issue and frequent earthquakes in the dam vicinity, has called for a proper analysis and study of the dam. This has become a necessity to ensure the safety of people in Kerala as the damages caused by the failure of Idukki dam can be catastrophic.

Idukki Dam is Asia's first and largest arch dam of 169.16m (555 ft.) height standing between the two mountains – 'Kuravanmala' (839m) and 'Kurathimala' (925m). This prestigious project is situated in Idukki District and its underground Power House is located at Moolamattom which is about 43 kms away from Idukki. Figures 1 and 2 show the upstream and downstream sides of the dam.

When the Idukki Dam was commissioned in 1976, a new landmark was created in Indian construction. In many ways the project is unique and is regarded as a hallmark of construction quality. The dam was constructed for Kerala State Electricity Board (KSEB).

Fig. 1. Idukki Arch Dam – Upstream side

Fig. 2. Idukki Arch Dam – Downstream side

The shape and quality of rock at the deep gorge where this dam was built was immensely suitable for the arch shape. The double curvature arch shape has resulted in a saving in concrete volume by 60% as compared to a gravity dam of this height. The arch has a unique geometrical shape evolved by Canadian Consultants Surveyor Nenniger & Chenevert.

Idukki dam consists of three major dams. It has been constructed across the Periyar river in a narrow gorge between two granite hills. It is 169.164m in height and 19.81m thick at the base. The water impounded by these three dams has formed a single reservoir spread over 36 miles on a height of 2300ft. MSL. A long power tunnel from the Kulamavu basin water flows to the pressure shafts in the underground power house beneath Nadukani hills at Moolamattom. In the power house, there are huge generators of a total capacity of 780 MW. The Idukki project was completed with the economic and technological assistance of Canada in accordance with the Plan of Commonwealth Countries.

A. Objective

The objective of this project is to develop a model of the Idukki dam, using the method of Finite Element Analysis (FEA) and validate the model with the actual dam for different load cases, so that it can be used to analyse the stresses and deflections that would occur in the actual dam for other load cases.

Stresses at critical locations are used to evaluate the dam performance corresponding to each loading combination. The evaluation starts with comparison of the computed stresses with strength of the concrete considering a factor of safety. This will also involve determination of location, magnitude, extent and direction of high stresses that can induce cracks in the structure.

B. Literature Review

Existing concrete arch dams should be evaluated by conducting a review and analysis of all existing data, a field inspection, and any analysis necessary to determine the safety of the dam for continued normal operation and resistance against the unusual and extreme loading conditions.

Anil K. Chopra (1994) [1] identified the limitations of the traditional design procedures, and discussed the factors that should be considered in the dynamic analysis and procedures for earthquake response history analysis. The application of these linear analysis procedures to safety evaluation of dams is also discussed.

Anil K. Chopra (2008) [2] identified the factors that influence significantly the three-dimensional analysis of arch dams: the semi-unbounded size of the reservoir and foundation rock domains, dam-water interaction, wave absorption at the reservoir boundary, water compressibility, dam-foundation rock interaction, and spatial variations in ground motion at the dam-rock interface.

Feng and Wei (2011) [4] made a comparative study on the performance and ultimate bearing capacity of dams. A set of safety factors was presented in this paper with regard to dam heel cracks and the ultimate bearing capacity of a high arch dam. Finite element modeling of arch dams is also presented in this paper.

Masterarbeit (2012) [5] developed a software based calculation of the 3D coordinates of double curved arch dams and the additional processing of these coordinates using Finite Element software. To calculate these 3D coordinates, a program based on Visual Basic for Applications, which is a Microsoft Excel tool, was developed. By varying the input parameters and using different calculation methods, it is possible to determine the geometry of double curved arch dams and modify it for optimization purposes.

Engineering guidelines for the evaluation of hydropower projects by **Federal Energy Regulatory Commission (FERC)** [3] deals with the static and dynamic analysis of dams. Further it includes few case histories of different dam failures.

II. SCOPE OF PRESENT STUDY

The actual structure of Idukki Arch dam has a thrust block i.e., a slightly enlarged portion towards the end of the left bank. This portion was later added to the design of the dam considering the observation of rock strata during excavation. This thrust block is not considered in this analysis as fixed boundary conditions are assumed in modeling.

The actual structure also consists of horizontal inspection galleries and vertical shafts connecting them. These are also not considered in modeling of the dam. The dam section actually consists of steel reinforcements to support the inspection galleries and shafts which are neglected since in this project, inspection galleries and shafts are not considered.

III. MODELING

A. Material Properties

The material properties of the dam were adopted from the data obtained from KSEB and are as follows:

1. Compressive strength (f_c) = 26.5 MPa
2. Modulus of Elasticity (E) = 21000 MPa
3. Density = 2400 kg/m^3
4. Coefficient of Thermal Expansion = 1.2x10^{-5}/ºC
5. Poisson's ratio (υ) = 0.17

It is assumed that the foundations are homogeneous, isotropic and elastic. Since, the two ends and the bottom of the dam comprises completely of rigid rocks, fixed boundary conditions are assumed.

B. Loads

1. Dead load (concrete) = 2400 kg/m^3
2. Maximum water level = 734.11m
3. Maximum silt level = 72.9m
4. Silt load (equivalent hydrostatic pressure) = 11.86 N/mm^3
5. Minimum temperature = 21 ºC
6. Maximum temperature = 32 ºC

A program was developed in PYTHON with the help of analytical definitions of the dam. On inputting the size of the mesh, the coordinates of the dam were obtained in AutoCAD and Excel files, which were joined using lines and areas, and these areas were converted into solids, which are shown in the following figures (Figures 3, 4, 5 and 6). The mesh size chosen was 7.62m, and hence the model consisted of 22 horizontal levels.

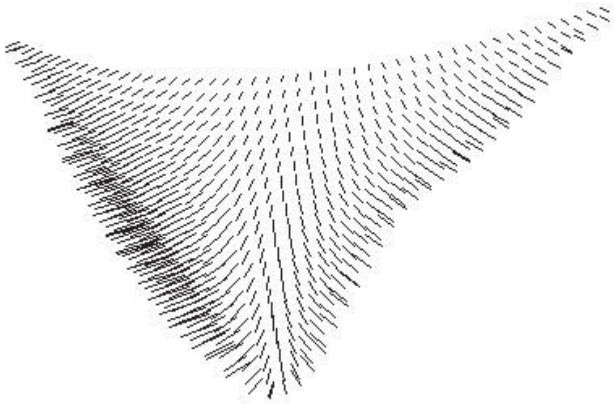

Fig. 3. Coordinates of the Dam in AutoCAD

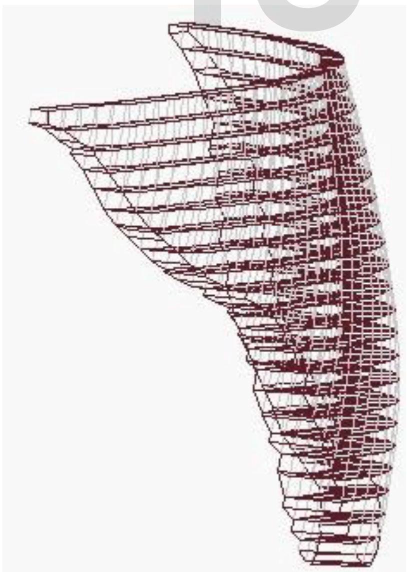

Fig. 4. Lines connecting the Coordinates

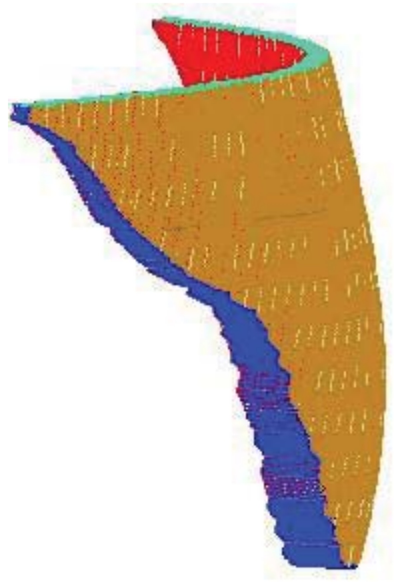

Fig. 5. Lines converted to areas

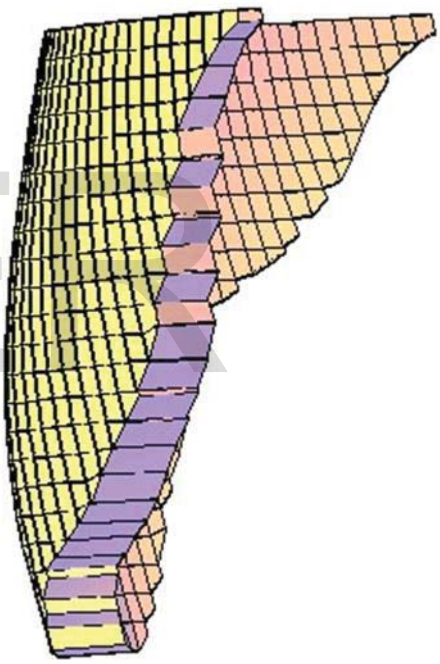

Fig. 6. Idukki Arch dam modeled in AutoCAD

C. *Meshing*

The element used for meshing was Solid Shell 190 (SOLSH190). SOLSH 190 is a brick element, and it makes possible to include the proper bending behavior of the dam material. Using other elements like tetrahedral elements can make the dam stiff and induce more shear forces. SOLSH 190 is an eight noded hexahedral element used for simulating shell structures with a wide range of thickness (from thin to moderately thick). The element possesses the continuum solid element topography and features eight-noded connectivity with three degrees of freedom at each node: translations in the nodal x, y and z directions. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities.

The material properties of the dam were assigned and meshing was done. Figure 7 shows the meshed model in ANSYS.

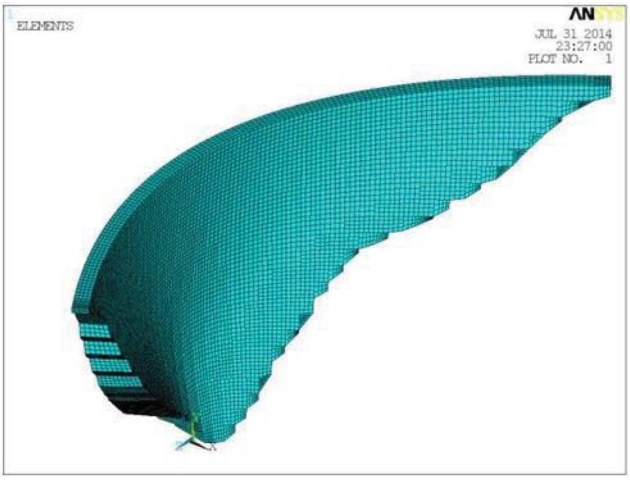

Fig. 7. Meshed model in ANSYS

IV. ANALYSIS

Arch dams are subjected to various loads. Loads can be categorized into two basic types – static and dynamic. Static loads are sustained loads that do not change, or change very slowly compared to the natural periods of vibration of the structure. A dam's response to static loads is governed by its stiffness. Examples of static loads include dead load, hydraulic load from normal or flood conditions, forces from flowing water changing direction, uplift, forces from ice expansion, and internal stresses caused by temperature changes. Dynamic loads are transitory in nature. They are typically seconds or less in duration. Because of the speed at which they act, the inertial and damping characteristics of the dam as well as its stiffness affect the dam's behaviour. Examples of dynamic loads include earthquake induced forces, blast induced forces, fluttering forces, or forces caused by the impact of ice, debris or boats.

A. Validation of the model

Kerala State Electricity Board (KSEB) has conducted a trial load analysis on Idukki arch dam and provided data for a particular load case of dead load, maximum water load, silt and temperature. The same load case was adopted in the present study to validate the model proposed. The maximum stress values of both cases were compared. It is seen that a maximum compressive stress of 5.844 MPa is obtained in the present study against a value of 5.729 MPa obtained for the trial load analysis done by KSEB. On comparing these two values, it is seen that the variation is found to be negligible. Also the maximum displacement for the present model was less than the limiting displacement of 5 cm, and thus the model proposed is validated.

Various load combinations adopted for the analysis are shown in Table I.

TABLE I. DAM LOAD CLASSIFICATION
(SOURCE: KSEB)

A	**Probable Max Flood Level: 734.11m**	EXTREME LOAD	In combination with: Concrete Weight, Full Silt Level, Minimum Concrete Temperature
B	**Max Operation Level: 732.43m**	UNUSUAL LOAD	In combination with: Concrete Weight, Full Silt Level, Minimum Concrete Temperature
C	**Normal Operation Level: 716.28m**	EXTREME LOAD	In combination with: Concrete Weight, Full Silt Level, Minimum Concrete Temperature
D	**Normal Operation Level: 716.28m**	USUAL LOAD	In combination with: Concrete Weight, Min Silt Level, Maximum Concrete Temperature
E	**Normal Operation Level: 701.04m**	USUAL LOAD	In combination with: Concrete Weight, Min Silt Level, Maximum Concrete Temperature
F	**Min Operation Level 694.94m**	USUAL LOAD	In combination with: Concrete Weight, Min Silt Level, Maximum Concrete Temperature

B. Load combination A

The loads considered were Concrete dead weight, Maximum Flood level, Full Silt level and Minimum Concrete temperature. The distribution of load is as shown in Figure 8.

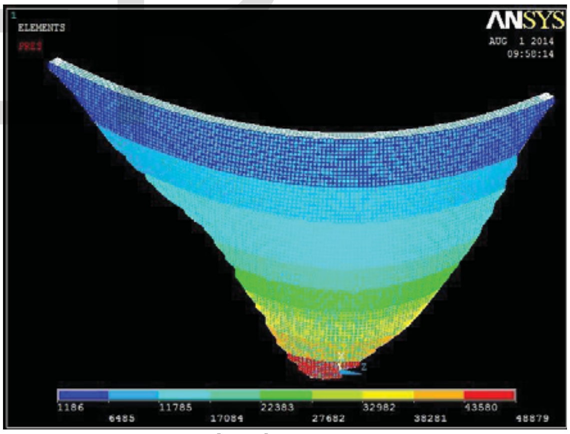

Fig. 8. Load combination A in ANSYS

C. Load combination B

The loads considered were Concrete dead weight, Maximum Operation level, Full Silt level and Minimum Concrete temperature. The distribution of load is as shown in Figure 9.

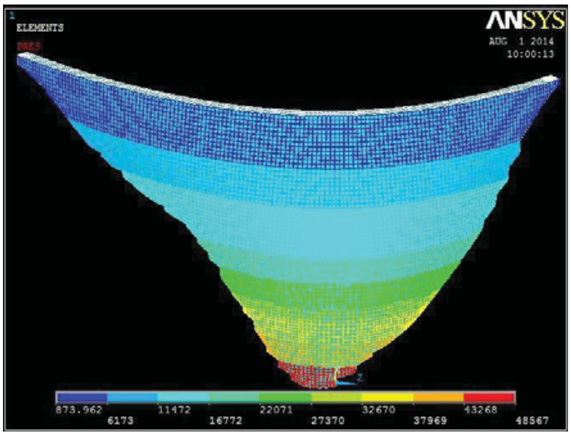

Fig. 9. Load combination B in ANSYS

D. Load combination C

The loads considered were Concrete dead weight, Normal Operation level, Full Silt level and Minimum Concrete temperature. The distribution of load is as shown in Figure 10.

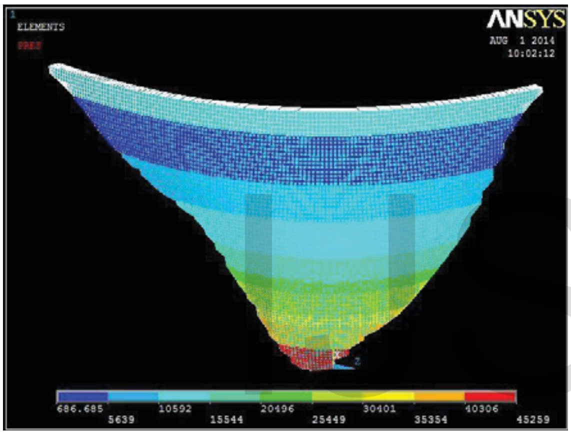

Fig. 10. Load combination C in ANSYS

E. Load combination D

The loads considered were Concrete dead weight, Normal Operation level, Full Silt level and Maximum Concrete temperature. The distribution of load is as shown in Figure 11.

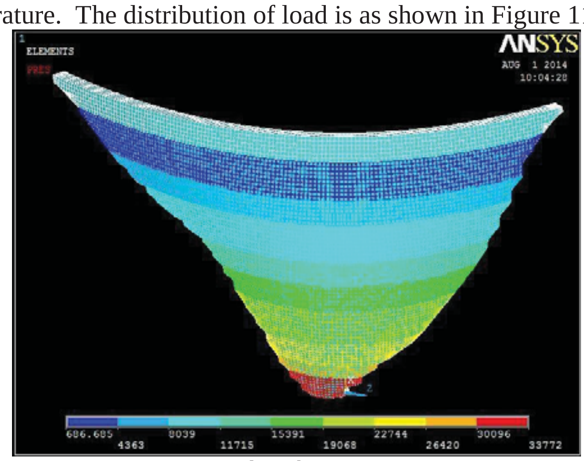

Fig. 11. Load combination D in ANSYS

F. Load combination E

The loads considered were Concrete dead weight, Normal Operation level, Minimum Silt level and Maximum Concrete temperature. The distribution of load is as shown in Figure 12.

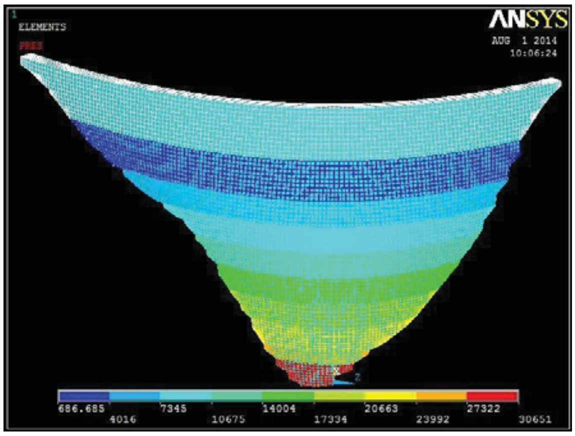

Fig. 12. Load combination E in ANSYS

G. Load combination F

The loads considered were Concrete dead weight, Minimum Operation level, Minimum Silt level and Maximum Concrete temperature. The distribution of load is as shown in Figure 13.

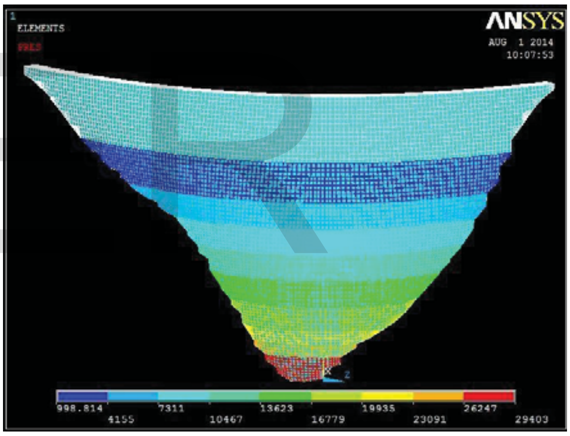

Fig. 13. Load combination F in ANSYS

V. RESULTS AND DISCUSSION

A. Load combination A

The maximum deflection was obtained as 2.689cm at the crown section, and the maximum stress as 6.512 N/mm^2 at the downstream face near the left abutment.

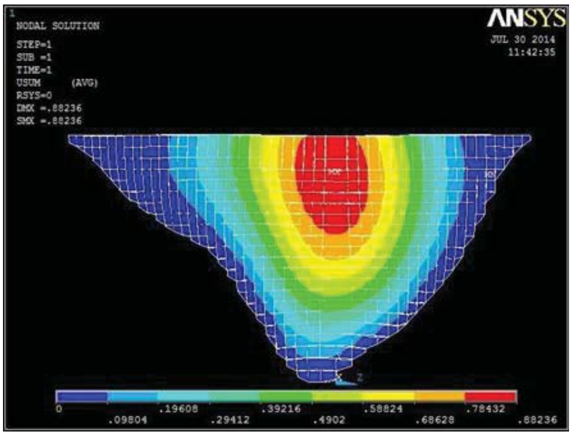

Fig. 14. Deflection due to Load combination A

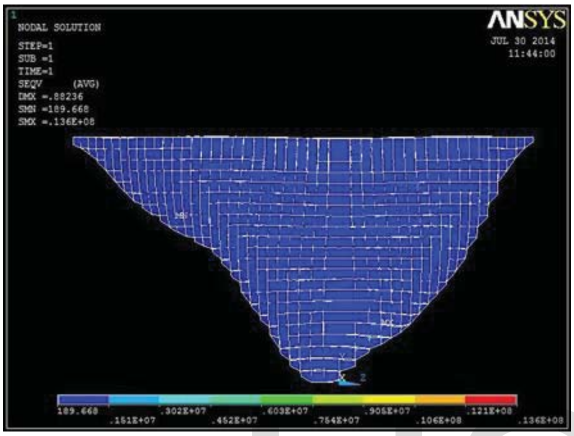

Fig. 15. Stress resultant due to Load combination A

B. Load combination B

The maximum deflection was obtained as 2.54cm at the crown section, and the maximum stress as 6.512 N/mm^2 at the downstream face near the left abutment.

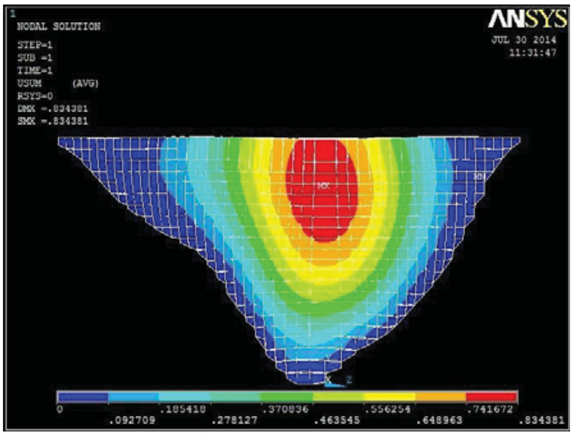

Fig. 16. Deflection due to Load combination B

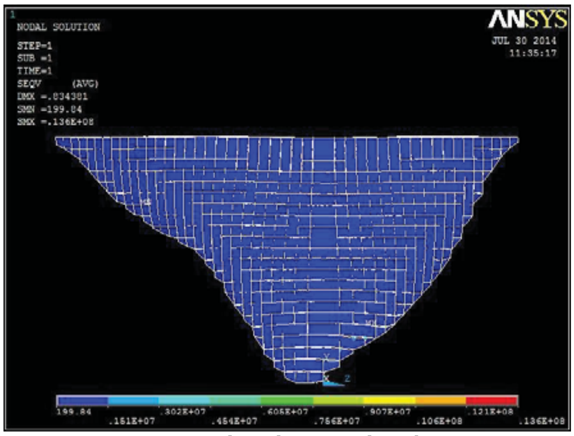

Fig. 17. Stress resultant due to Load combination B

C. Load combination C

The maximum deflection was obtained as 1.457cm at the crown section, and the maximum stress as 5.841 N/mm^2 at the downstream face near the left abutment.

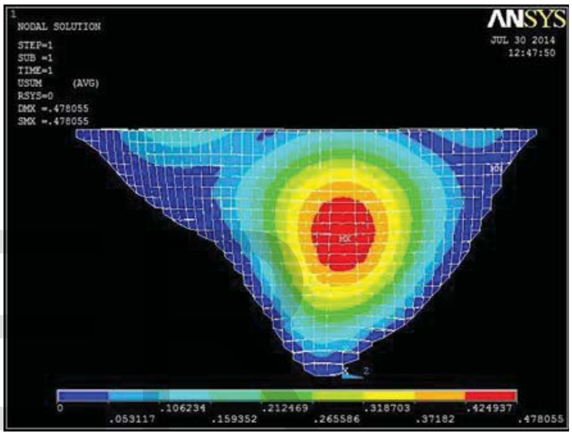

Fig. 18. Deflection due to Load combination C

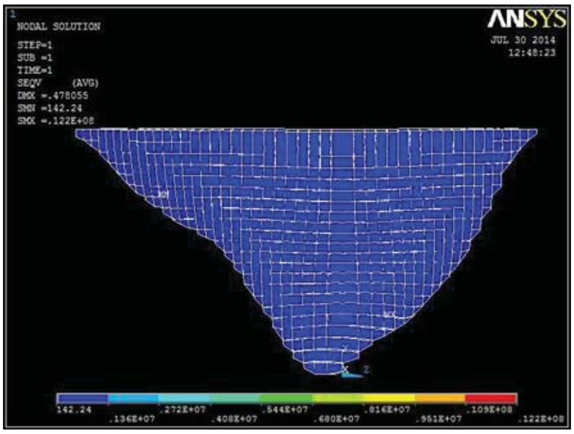

Fig. 19. Stress resultant due to Load combination C

D. Load combination D

The maximum deflection was obtained as 2.086cm at the crown section, and the maximum stress as 5.362 N/mm^2 at the downstream face near the left abutment.

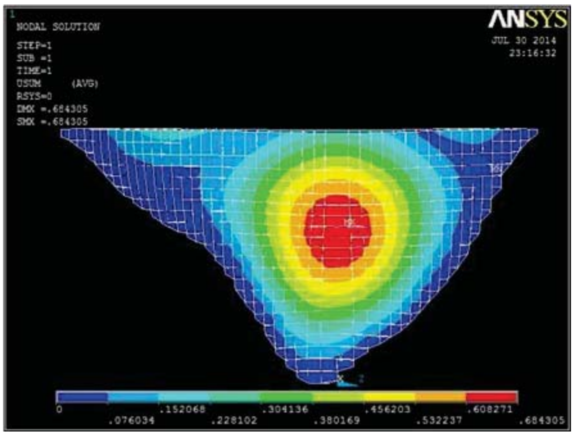

Fig. 20. Deflection due to Load combination D

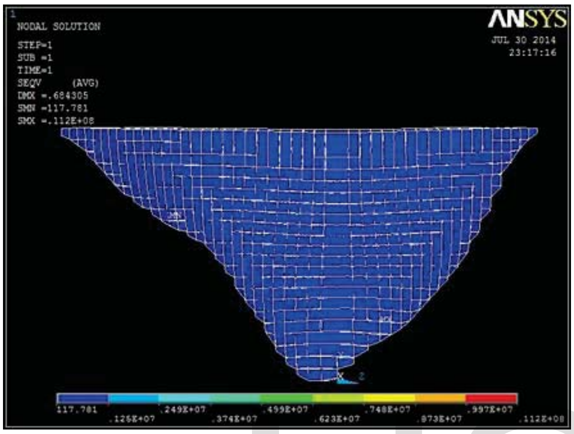

Fig. 21. Stress resultant due to Load combination D

E. Load combination E

The maximum deflection was obtained as 1.387cm at the crown section, and the maximum stress as 4.764 N/mm^2 at the downstream face near the left abutment.

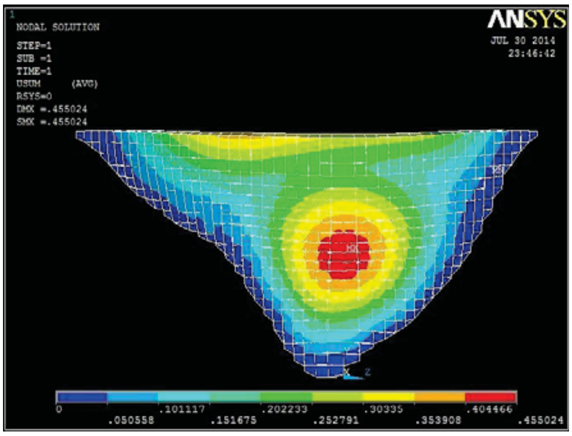

Fig. 22. Deflection due to Load combination E

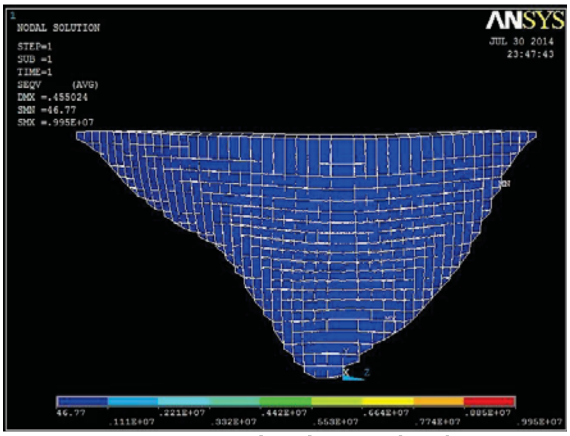

Fig. 23. Stress resultant due to Load combination E

F. Load combination F

The maximum deflection was obtained as 1.366cm at the crown, and the maximum stress as 4.519 N/mm^2 at the downstream face near the left abutment.

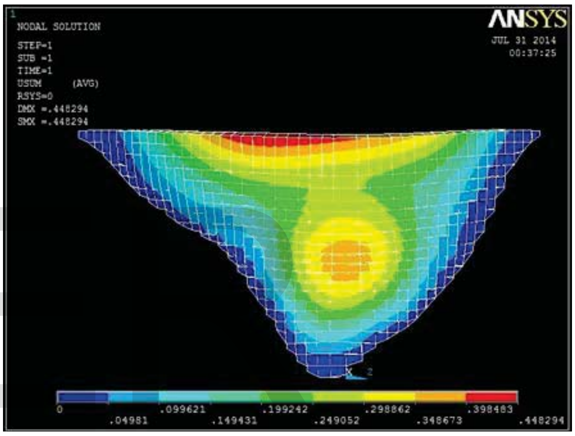

Fig. 24. Deflection due to Load combination

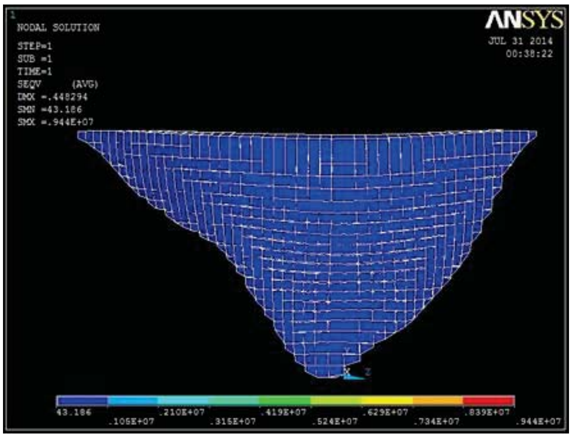

Fig. 25. Stress resultant due to Load combination F

G. Discussions

Table II shows the different values of maximum displacement obtained for various load combinations.

TABLE II. MAXIMUM DISPLACEMENT VALUES FOR VARIOUS LOAD COMBINATIONS

Load combination	Finite Element Model displacement (cm)
A	2.689
B	2.540
C	1.457
D	2.086
E	1.387
F	1.366

The limiting value of displacement as per KSEB norms is 5 cm. It can be observed from Table II that all the displacement values are within the prescribed limit.

Table III shows the different values of maximum compressive stress obtained for various load combinations.

TABLE III. MAXIMUM COMPRESSIVE STRESS VALUES FOR VARIOUS LOAD COMBINATIONS

Load combination	Finite Element Model stress (MPa)
A	6.512
B	6.512
C	5.841
D	5.362
E	4.764
F	4.519

FERC gives the limit for the maximum compressive stress for any existing arch dam. Table IV shows the Factors of Safety that should be adopted for different load combinations. Limiting stress as per 'Engineering guidelines' by FERC is the concrete compressive strength reduced by the prescribed factor of safety.

TABLE IV. FACTORS OF SAFETY FOR EXISTING ARCH DAMS (SOURCE: ENGINEERING GUIDELINES BY FERC)

Loading Combination	Compressive Stresses
Usual	2.0
Unusual	1.5
Extreme	1.1

Hence, for usual load combination, limiting stress was found to be 13.25 MPa, for unusual load combination 17.67 MPa and for extreme load combination, the limiting stress was 24.09 MPa.

It can be observed from Table III that the maximum compressive stress values for the proposed model have not exceeded the limiting values as per FERC.

VI. CONCLUSION

The analytical definitions of Idukki arch dam were obtained with the help of a PYTHON program. The dam was modeled using AutoCAD, and imported to ANSYS, where analysis was done for various load combinations.

The stresses corresponding to each load combination were checked with the permissible limits as per FERC guidelines. The results of analysis of model do not disclose any areas of overstress. The maximum displacements for each load combination were obtained from ANSYS, and were found to be within the limits specified by KSEB. Therefore, it is justified to state that the actual stresses and deflections in the Idukki dam are expected to be within the established criteria, under existing loading conditions.

A model was developed successfully for Idukki Arch dam, which can be used for analysis of the dam under any kind of loading.

A. Scope for Future Work

Further studies can be conducted by incorporating the actual support conditions. Uplift due to piping action can also be considered for analysis at a later stage. Also earthquake forces can be taken into consideration. Horizontal galleries and vertical shafts can also be included in the FEM model.

Acknowledgment

I would like to thank Er. Aloushy Paul C., Assitant Executive Engineer, Kerala State Electricity Board for his support throughout this project.

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