INTERNATIONAL DAM SAFETY CONFERENCE

Indian National Committee on Large Dams (INCOLD)

Dam Rehabilitation & Improvement Project

Central Water Commission

Seismic Analysis of 3D Model of Morrow Point Arch Dam

by

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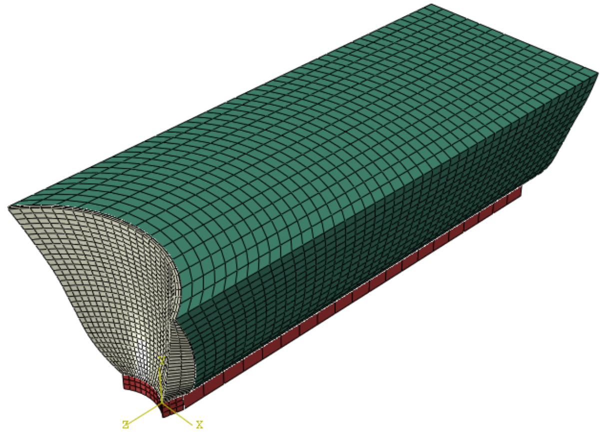

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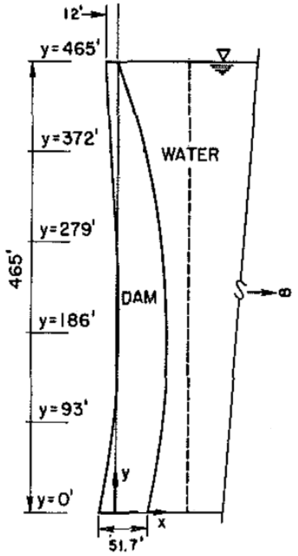
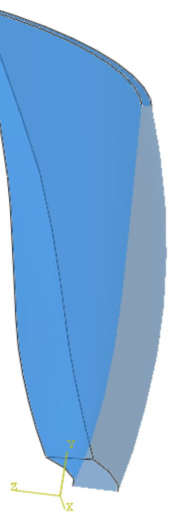
Introduction

- Morrow point arch dam is a typical arch dam representing many realistic arch dams constructed in different regions. A dynamic analysis of the 3D model of the morrow point arch dam with and without water is presented for the Kern county earthquake (1952).
- The analysis is performed in ABAQUS, in which a complete hydrodynamic effect is included in the arch dam with water.
- The responses of the dam with and without hydrodynamic effect are compared to highlight the effect of the hydrodynamic pressure on the responses due to the earthquake. Further, the features of the dam's different mode shapes participating in the responses are investigated.
- The early work on the seismic analysis of dams was done by the United States Department of the Interior Bureau of Reclamation (1977), Clough, Porter, Chopra, Hall, Fok, Tan, Camara, and others.
- Morrow Point arch dam is located on Gunnison River, Colorado, U.S.A. The total height of the dam is 465 feet. This dam is double curvature thin arch dam.

Morrow point arch dam section from reference no. 8 and the section from the 3D model at the crown cantilever is shown below





Theory

- The Coupled-Acoustic approach of finite element modeling is adopted in ABAQUS for solving the Dam-water interaction problem. Acoustics deals with the generation, absorption, propagation, and reflection of the sound pressure waves in the fluid medium. The acoustic wave equation (Helmholtz equation) in terms of pressure *p* (independent variable) is given as

$$\frac{\partial^2 p}{\partial t^2} + c^2 \nabla^2 p = 0$$

- The interaction between the dam's upstream surface-water, water-foundation rock, and dam base-foundation rock is defined by surface-based tie constraint. This type of interaction allows both interacting surfaces to remain in contact throughout the simulation process. Tie constraint applies the same pressure and motion at each node of the acoustic element's fluid surface.

- The water is modeled using an eight-node 3D acoustic continuum element with reduced integration (AC3D8R).
- Dam and foundation are modeled using eight-node 3D stress continuum elements with reduced integration (C3D8R).
- The analysis is performed in ABAQUS software.
- The dynamic explicit time integration scheme is adopted.
- The analyses are performed using the central difference integration method.
- Reflection of pressure waves is characterized by the material of the foundation, and this is defined by wave reflection factor α. This factor α can be written as

$$\alpha = \frac{1-R}{1+R}$$

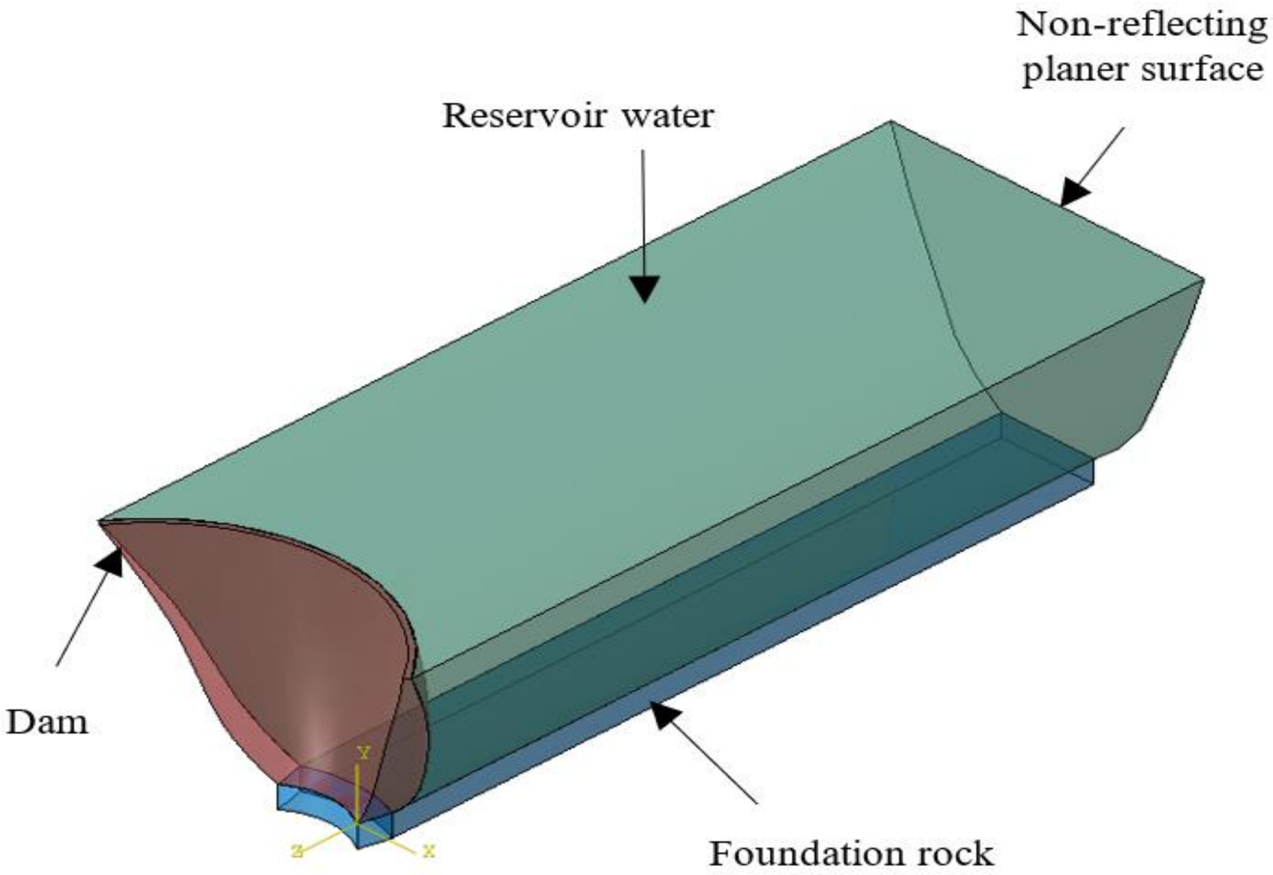
$$R = \frac{\rho_w C_w}{\rho_f C_f} = \frac{\sqrt{\rho_w k_w}}{\sqrt{\rho_f E_f}}$$

Where,

ρ_w is Density of water;
ρ_f is Density of Foundation material;
C_w is Wave propagation speed of water;
C_f is Wave propagation speed of foundation material.

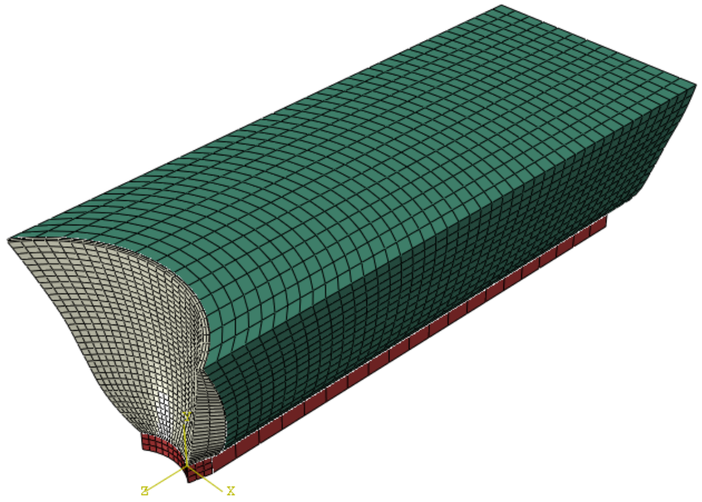
Numerical Study

- The properties of the mass concrete of the dam are elastic modulus, E_d = 4 X 10^6 psi (2.75 X 10^{10} Pa), unit weight w_d= 155 pcf (2483 Kg/m^3), and Poisson's ratio υ = 0.2, the damping ratio for all modes of the vibration of the dam, ξ = 5 %. The water has unit weight *w* = 62.4 pcf (1000 kg/m^3) and Bulk Modulus *K* = 3.19 X 10^5 psi (2.2 X 10^9 Pa). The reflection coefficient α is chosen as 1. Morrow point arch dam and reservoir geometry details are taken from [8].
- Surface-to-surface tie-type interactions are applied between the dam's upstream surface water, dam bottom-foundation rock, and reservoir water bottom-foundation rock. Zero acoustic pressure is applied at the top surface of the reservoir water.
- The properties of the foundation are assumed to be the same as the properties of the Dam concrete except assuming it as massless, i.e., a negligible value of the Density is chosen.

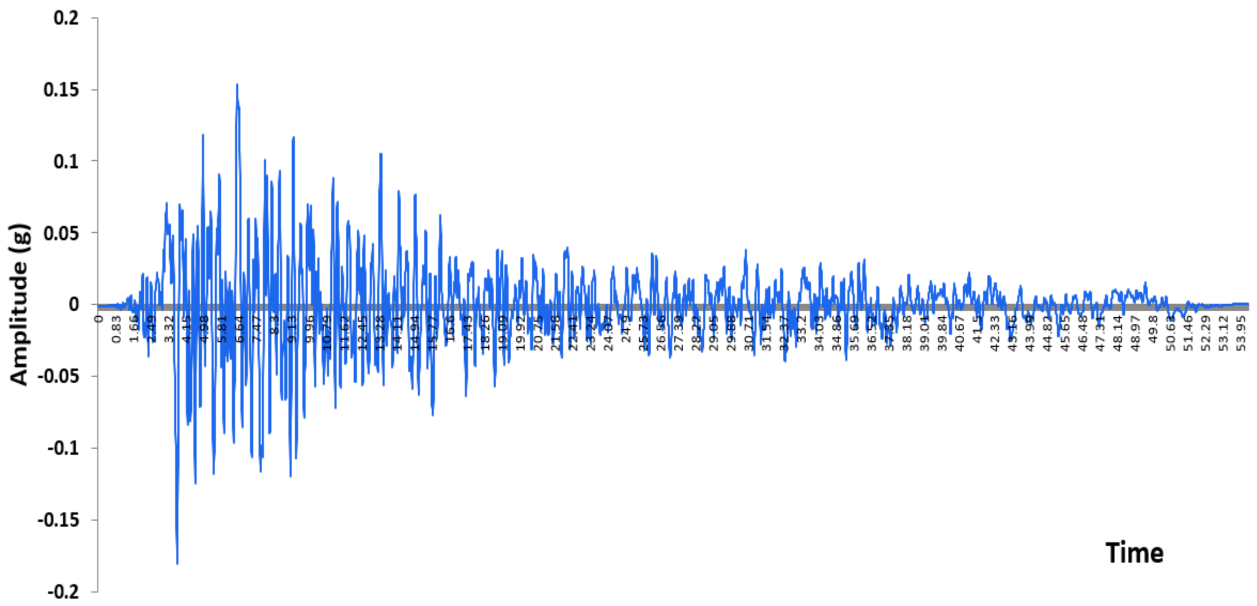

Non-reflecting
planer surface
Reservoir water
Dam
Foundation rock

Mesh properties of the dam model

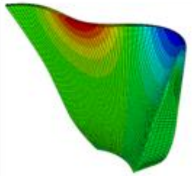
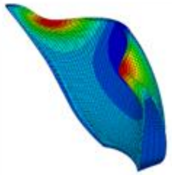
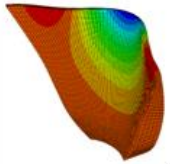
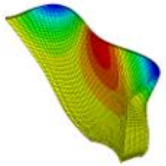
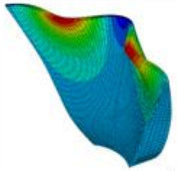
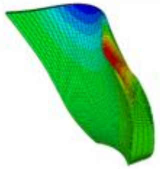
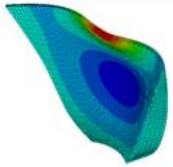
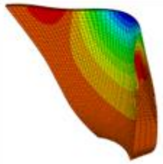
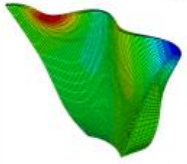
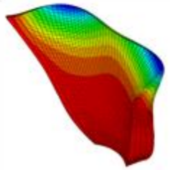
Part of the Model	Element type	Number of elements	Number of nodes
Dam	C3D8R	1782	2856
Reservoir water	AC3D8R	9724	11340
Dam foundation	C3D8R	90	176
Reservoir foundation	C3D8R	60	168



Acceleration time history of the Kern County earthquake (1952), Taft component 111 was applied in the upstream-downstream direction at the dam base (PGA = 0.18g). No time history was applied in vertical and cross-stream directions.

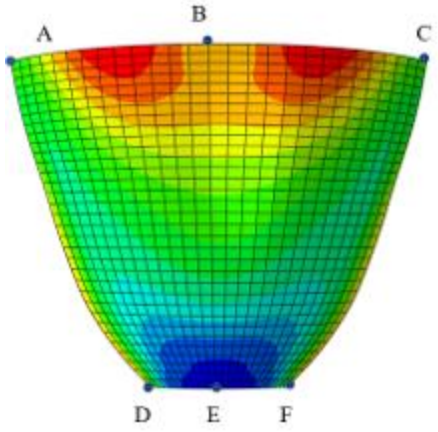


Mode shapes and Frequencies of empty and full reservoir Dam

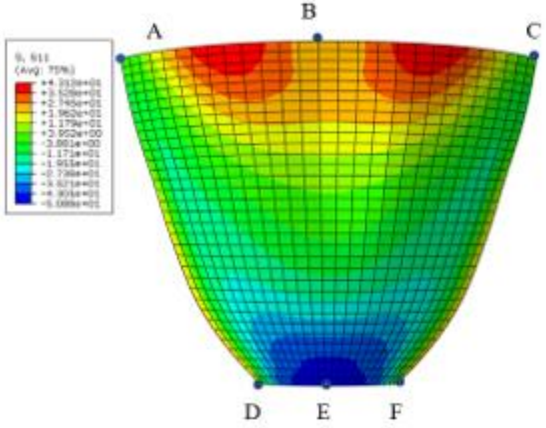
Mode No.	Dam with Empty Reservoir	Dam with full Reservoir (CAS Approach)
1	 3.65 Hz (3.92 Hz from Tan and Chopra 1996)	 3.08 Hz (2.59 Hz from Tan and Chopra 1996)
2	 4.16 Hz	 3.56 Hz
3	 5.93 Hz	 3.59 Hz
4	 6.64 Hz	 4.12 Hz
5	 7.32 Hz	 4.66 Hz

Absolute Maximum Arch and Cantilever stresses at points A, B, C, D, E, and F

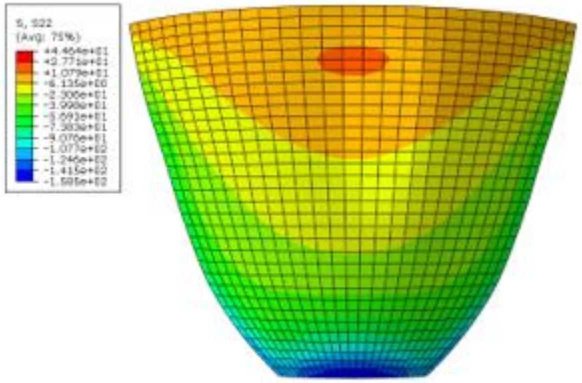
Point	Arch Stress (psi)				Cantilever Stress (psi)			
	Empty Reservoir		Full Reservoir		Empty Reservoir		Full Reservoir	
	Compression	Tension	Compression	Tension	Compression	Tension	Compression	Tension
A	9.2	8.7	8.06	8.8	4.98	4.8	4.36	4.0
B	159	192	160	156	1.4	2.6	1.4	2.6
C	9.2	8.7	8.06	8.8	4.98	4.8	4.36	4.0
D	94.93	90	204	243	671.49	633	1172.05	1011
E	293.59	277.9	267.49	230	847.27	797	626.36	547
F	94.93	90	204	243	671.50	633	1171.99	1011

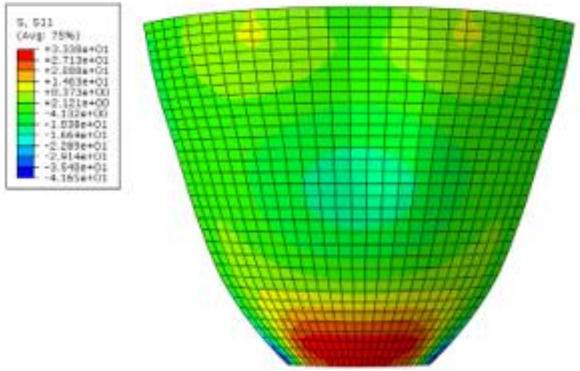


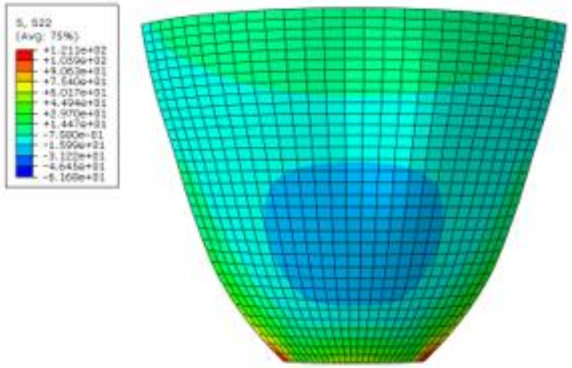
Arch and Cantilever Stresses at time t=10.5 sec



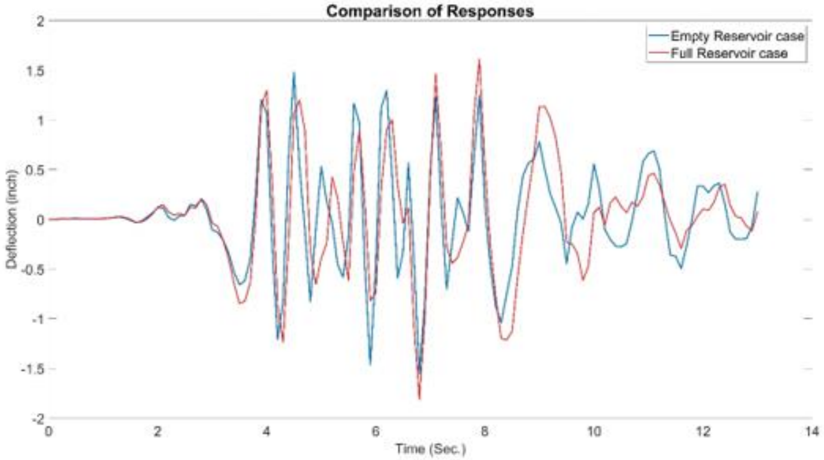
Arch stresses (psi) at the dam's upstream face for the empty reservoir condition at 10.5 sec.


Cantilever stresses (psi) at dam's upstream face for empty reservoir condition at 10.5 sec.

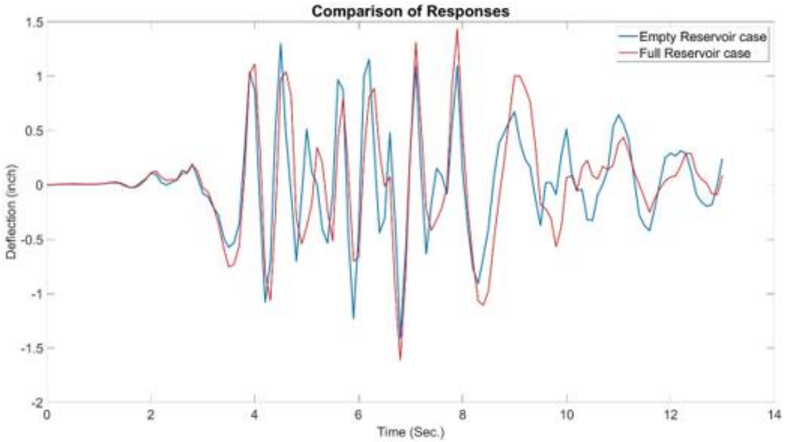

Arch stresses (psi) at dam's upstream face for full reservoir condition at 10.5 sec.


Cantilever stresses (psi) at dam's upstream face for full reservoir condition at 10.5 sec.

Comparison of Deflections at top central and at one third point



Deflection (inch) in the upstream-downstream direction at the top central crest node of the crown cantilever for empty reservoir and full reservoir case



Deflection (inch) in the upstream-downstream direction at the one-third node of the perimeter of the top arch for empty reservoir and full reservoir case

Results and Discussions

- It is seen that the natural frequencies of the empty dam are greater than the corresponding dam with a full reservoir. It is expected because, in a full reservoir condition, added mass contributes to the free vibration of the dam, resulting in the lowering of natural frequencies. Further, it is observed that mode shapes are quite different for the two cases. A significant difference in the mode shapes is observed in the upper half of the dam.
- Frequencies shown within brackets are those obtained by Tan and Chopra 1996 [8]. It is seen that the natural frequencies obtained by the present analysis fairly match those obtained by Tan and Chopra 1996.
- The difference in the natural frequencies between the present analysis and that performed by Tan and Chopra is largely attributed to the size of the foundation, considered in the dam monolith.

- The difference in the maximum value of deflection between an empty reservoir and a full reservoir is of the order of 17 percent with respect to empty dam condition. The full reservoir case gives a higher value. Deflection in the upstream-downstream direction at the one-third point at the perimeter of the top arch is also observed, Similar differences are observed in the time history of deflections at the observed top central crest node of the crown cantilever. The difference in the absolute maximum deflection between the two cases is 14 percent with respect to the empty dam condition. Full reservoir condition provides higher value.
- It is seen that arch and cantilever stresses have lower values at the top (points A, B, and C) compared to values at the bottom (points D, E, and F). Arch and Cantilever stresses are higher at the bottom (points D and F) compared to that at point E for full reservoir condition, while the opposite trend is observed for the empty reservoir condition.

- It is observed that the cantilever tensile stresses are significantly high at the points D and F that is at the bottom two corner points, whereas for the empty reservoir condition the cantilever tensile stress is very high at point E, that is the center of the bottom arch. These observations indicate that the dam might undergo cracking at the bottom level both under the empty and full reservoir conditions
- It may be noted that arch stresses are competitively less compared to cantilever stress at the top and bottom points. Thus, the cracking of the dam at bottom would appear as horizontal cracks.

Conclusion

1. There exists a considerable difference between the first few mode shapes for empty and full reservoir dam conditions; the significant difference between mode shape patterns is observed in the upper half of the dam.

2. The fundamental empty reservoir dam frequency fairly matches with those obtained by other authors [8].

3. The natural frequencies of the full reservoir condition are lower than the empty reservoir condition, as they will be expected.

4. Time histories of the deflections at the selected two points at the crown of the dam do not significantly vary between the two cases; the absolute maximum deflection for the case of a full reservoir dam is approximately 14 to 17 percent more than the empty reservoir dam.

5. The pattern of the stress contours at the upstream face of the dam significantly varies for the two cases captured at time t = 10.5 sec. It is expected that such differences could show up at other time stations also.

6. The comparison of the absolute maximum stresses developed at six strategic points shows that the maximum stress for both the arch and cantilever stress is at the bottom of the dam.

7. For the present study, it is observed that horizontal tensile cracks are likely to develop at the bottom of the arch dam

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Thank You