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Modal and Response Spectrum Analysis of Hoover Dam Using ANSYS

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Abstract. Hoover Dam plays an important role in regional irrigation, water supply, and energy production. In recent years, the continuous decline in the water level of Lake Mead has weakened the stabilizing effect of the reservoir, potentially affecting the seismic response of the dam. To investigate this issue, a two-dimensional nonlinear finite element model of Hoover Dam was developed using ANSYS (2025 R2 Student Version). Several quadrilateral-dominated mesh schemes were compared, and a grid with a global element size of 4 m and local refinement to 1 m near the curved dam surface was selected to balance accuracy and computational efficiency. The results show that displacement and stress responses are mainly concentrated about 100 m below the upstream crest and 50 m below the downstream crest. When reservoir effects are included, crest displacement decreases, while maximum stress below the upstream crest increases. The maximum elastic strain occurs on the downstream face approximately 100 m below the crest. Overall, stress and deformation levels remain within accepted design limits, indicating stable structural performance. The results highlight the importance of reservoir mass and suggest that more detailed hydrodynamic modeling is needed for comprehensive dam–reservoir seismic assessment.

Keywords: Modal Analysis, Response Spectrum Analysis, Hoover Dam.

1. Introduction

Hoover Dam, located on the Colorado River at the Arizona-Nevada border, is a major twentieth-century hydraulic project that supports flood control, irrigation, municipal water supply, and hydropower generation, serving over 2 million acres of farmland and approximately 20 million people [1-3].

Before Hoover Dam was built, the Colorado River Basin experienced frequent snowmelt-driven floods and recurring summer droughts that constrained agricultural production [4]; to address these

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issues, the dam adopted an arch-gravity design that transfers hydrostatic loads to the canyon walls through self-weight and arch action, while any structural failure would pose severe downstream risks [5].

Lake Mead, the upstream reservoir of Hoover Dam, regulates runoff and supports water supply and hydropower, but recent water-level declines due to increased evaporation and demand have weakened its stabilizing effect on the dam, potentially increasing seismic displacement and cracking risk [6]; although the dam is not located on a major fault, nearby seismic sources may still produce significant ground motion [7].

Previous studies have primarily employed three-dimensional linear and nonlinear numerical models to investigate the seismic response of Hoover Dam under maximum credible earthquake scenarios, with consideration of dam-foundation-reservoir interaction. These studies generally indicate that the dam would remain globally stable during an earthquake with a magnitude of approximately 6.72, experiencing only limited structural damage [8,9].

Building on this background, the present study develops a simplified two-dimensional finite element model of Hoover Dam using ANSYS to compare its vibration response under conditions with and without the influence of the Lake Mead reservoir. By applying real seismic response spectra, the study focuses on the effects of reservoir water on stress distribution and displacement response, providing reference for seismic safety evaluation under declining reservoir levels.

2. Model establishment

According to Nuss [8], the geometric data of Hoover Dam are as follows:

Table 1. Geometric data of Hoover Dam

Parameter	Value	Imperial Unit
Dam Height	221 m	727 ft
Crest Length	380 m	1244 ft
Crest Thickness	14 m	45 ft
Maximum Base Width	201m	660 ft
Hydraulic Height (Normal Operating Depth)	176 m	576 ft

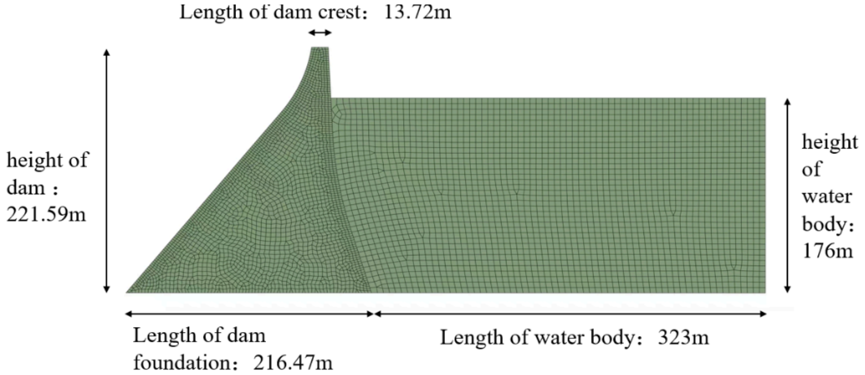

Figure 1. Model of Hoover Dam

The geometry of the reservoir water body is selected based on the topographic range described in Figure 1. Combining these data with the dam’s cross-sectional profile, a simplified model that

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adequately represents the dam's fundamental geometric features is constructed for modal analysis.

2.1. Material parameters

The numerical model included two main material types: concrete for the dam body and water for the reservoir. The default material properties provided in ANSYS were not used. Instead, the concrete properties were specified separately to better reflect the engineering background of the problem, with reference to the EM 1110-2-6053 manual issued by the U.S. Army Corps of Engineers for seismic analysis of concrete hydraulic structures.

For the concrete material, the static compressive strength was taken as 50 MPa and the dynamic compressive strength as 55 MPa. The static and dynamic splitting tensile strengths were assumed to be 4 MPa and 7 MPa, respectively. The elastic modulus was set to 45.436 MPa under static conditions and reduced to 29.854 MPa for dynamic analysis. In both loading cases, an apparent cohesion of 0.63 MPa and a friction angle of 48° were adopted.

These values fall within the range commonly used in reservoir and dam engineering studies and were considered sufficient for capturing the seismic response of the dam in the present analysis.

Table 2. Material parameters used in the model

Material	Density (kgm^-3)	Elastic Modulus(Pa)	Shear Modulus(Pa)	Poisson's Ratio	Remarks
Concrete	2300	4.5e7	1.9e7	0.18	Based on USACE standards
Water	998.2	3e-3	1.0e-3	0.499	Treated as incompressible fluid

2.2. Mesh generation and boundary conditions

Grid generation is a core preliminary step in finite element analysis, and its quality directly determines the accuracy, reliability, and efficiency of subsequent calculation results. In this study, the massive scale of the dam body and water body implies a significant correlation between the rationality of grid generation and the analysis results. To explore the appropriate grid size, this research adopts a quadrilateral-dominated grid generation method, designing four different grid sizes (8m, 6m, 4m, and 2m) for dividing the dam body. It then compares the number of nodes, number of grids, grid quality, and first-order natural frequency reports of these grids to comprehensively consider the calculation effect and cost. To ensure that the grid size of the model does not change abruptly at the boundaries, the boundary grids are processed to be dense.

Table 3. Cell size, node, and first natural frequency of the model grid

Mesh Size(m)	8.0	6.0	4.0	2.0
Nodes	10665	10615	11830	22862
Elements	3478	3458	3855	7527
first natural frequency	2.8779	2.8779	2.8779	2.8779

From a comprehensive comparison, to ensure high model accuracy while appropriately shortening the calculation time, a grid size of 4m is adopted for the dam body analysis. Due to the high difficulty in generating grids on the irregular curved surface of the dam body, the boundary grid size is fixed at 1m.

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The generated dam mesh is shown in Figure 2. The dam foundation bottom is modeled as fixed boundaries.

3. Dynamic analysis of dam body

3.1. Modal analysis results

Modal analysis can identify the natural frequencies of a structure in advance. By designing to avoid the coincidence between external excitation and the natural frequencies of the structure, resonance can be prevented. The mode shapes obtained from modal analysis can reveal the "vibration weak parts" of the structure at specific frequencies.

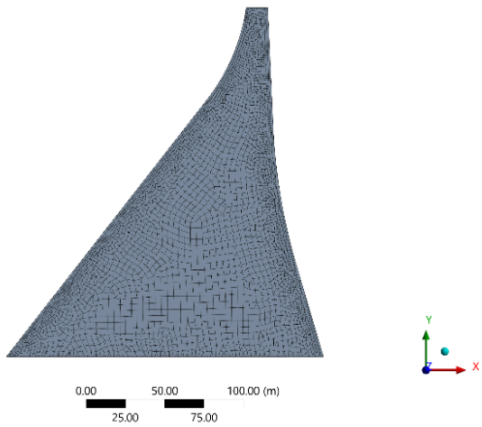

Figure 2. Dam body grid

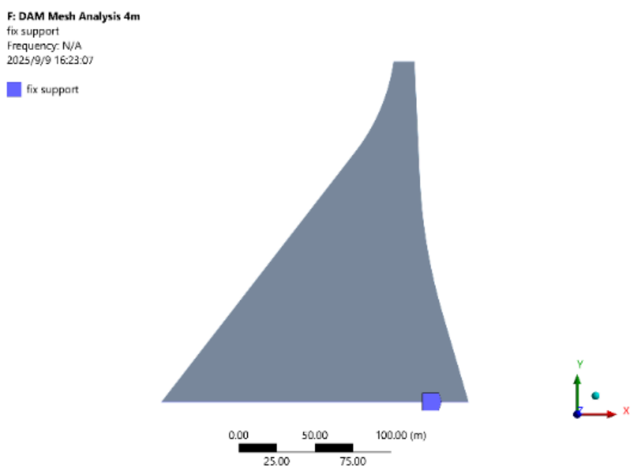

Figure 3. Fixed boundary

Since response spectrum analysis uses the modal superposition method for dynamic analysis, the ratio of the effective mass from modal analysis to the total mass directly affects the solution accuracy. Generally, this coefficient is required to reach 0.9, so the first 30 orders of modes are solved.

The first four natural frequencies are shown in Table 4.

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Table 4. First four natural frequencies

Mode	1	2	3	4
Natural Frequency (Hz)	2.8779	5.7975	7.2842	9.7857

The first four modes of vibration are shown in Figures 4-7.

Among these modes, in the x-direction, the effective mass ratio of the first-order mode reaches 0.32, and that of the second-order mode reaches 0.29, with a cumulative effective mass ratio of 0.93; in the y-direction, the effective mass ratio of the fourth-order mode reaches 0.58, and the cumulative effective mass ratio is 0.91. This indicates that the first order and second-order modes are the dominant modes of vibration in the x-direction, and the fourth-order mode is the dominant mode of vibration in the y-direction. Observing the vibration modes corresponding to these three orders of modes, it can be found that the maximum displacement occurs at the dam crest, which indicates that the dam crest is the key position that requires the most attention under vibration conditions.

3.2. Response spectrum analysis

Response spectrum analysis first needs to obtain the "natural characteristics" of the structure, such as natural frequencies and mode shapes, through modal analysis. Then, combined with the "response spectrum" (which describes the "equivalent maximum excitation intensity" of the excitation at different frequencies), it calculates the contribution of each mode to the total response of the structure. Finally, these modal contributions are combined through specific rules (such as SRSS, CQC methods) to obtain the overall maximum response of the structure.

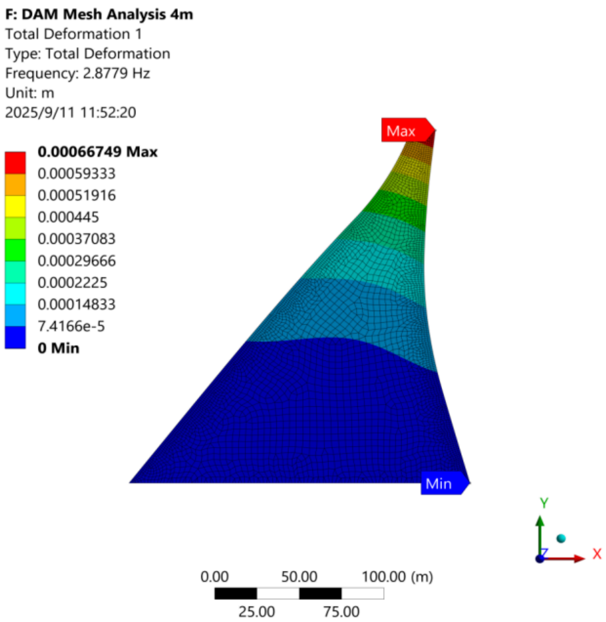

Figure 4. Mode shape 1

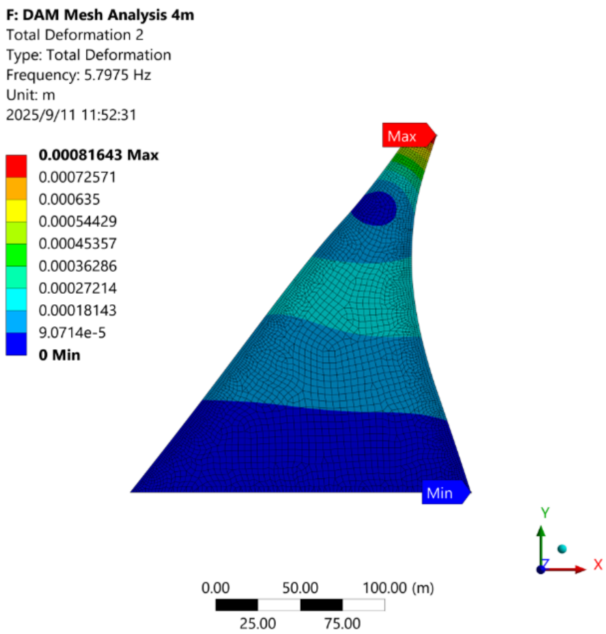

Figure 5. Mode shape 2

DOI: 10.54254/2755-2721/2026.MH31721

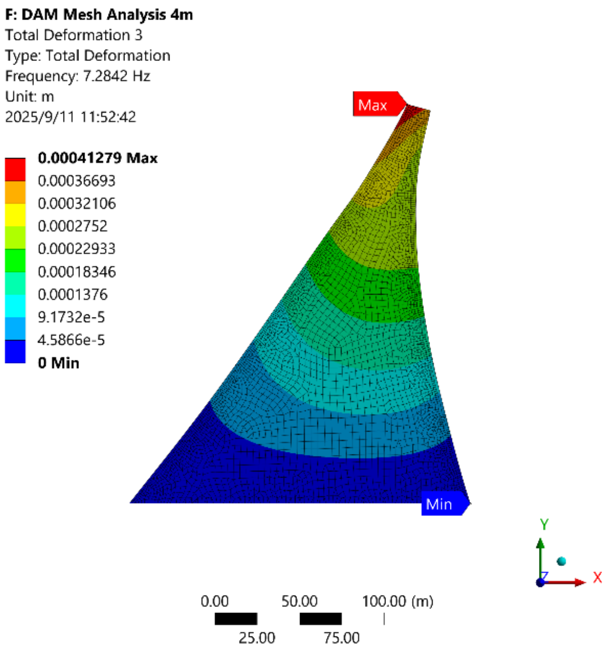

Figure 6. Mode shape 3

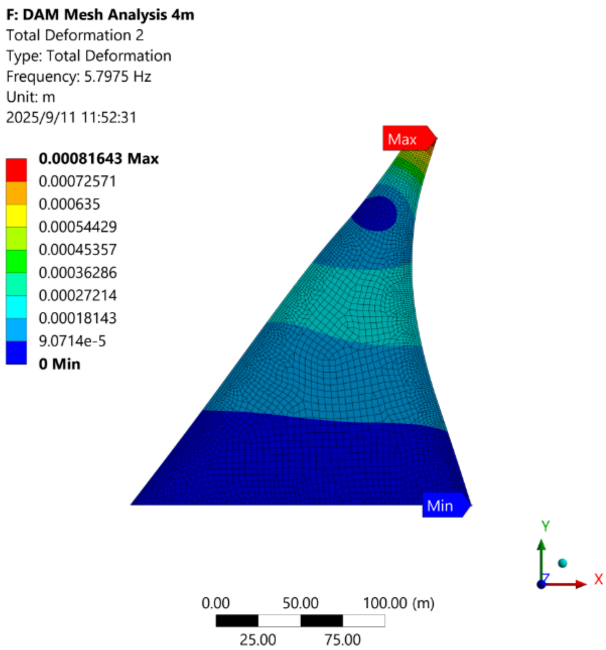

Figure 7. Mode shape 4

This report uses the monitoring data from the Whittier Narrows Dam downstream monitoring station during the 1999 Hector Mine earthquake (California, M 7.1) in the PEER NGA-West2 ground motion database as the response spectrum. The detail response spectrum is shown in Figure 8.

Finally, the external excitation is applied to the dam bottom, in the Y-axis direction. The results after solving are shown in Figure 9-12.

It can be seen that the maximum displacement of the dam is at the top. Cracks are more likely to occur at approximately 100 meters below the dam crest on the upstream face and approximately 50 meters below the dam crest on the downstream face. Meanwhile, the maximum displacement and effective stress of the dam body under external excitation are relatively small, so there may be no obvious cracks that appear, which is consistent with the conclusion in reference [8].

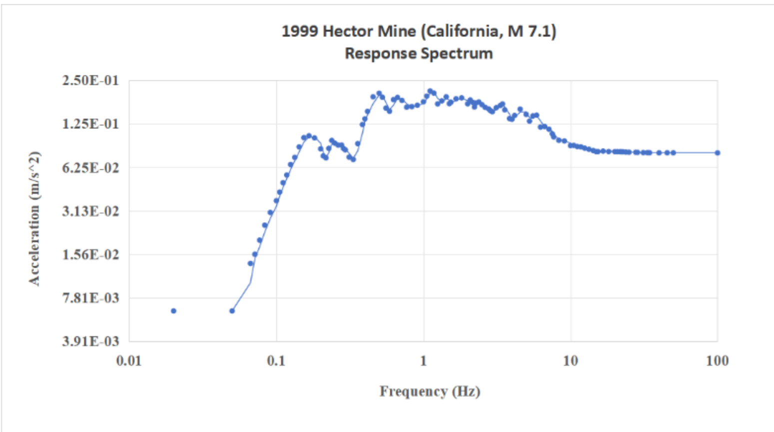

Figure 8. The 1999 Hector Mine earthquake

(California, M 7.1) Response Spectrum

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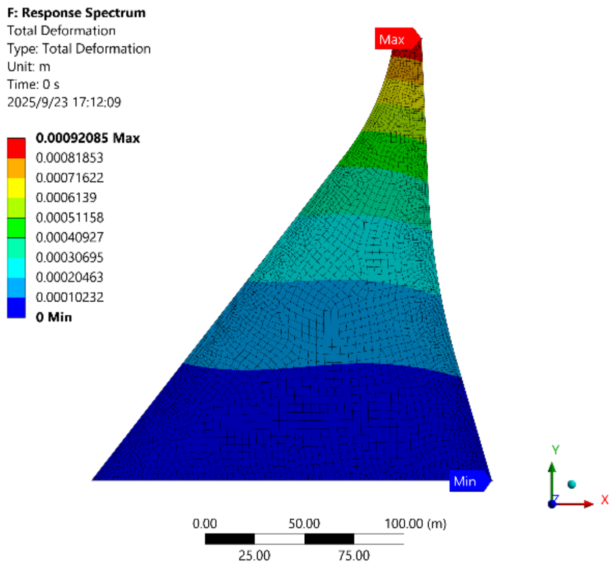

Figure 9. Total deformation

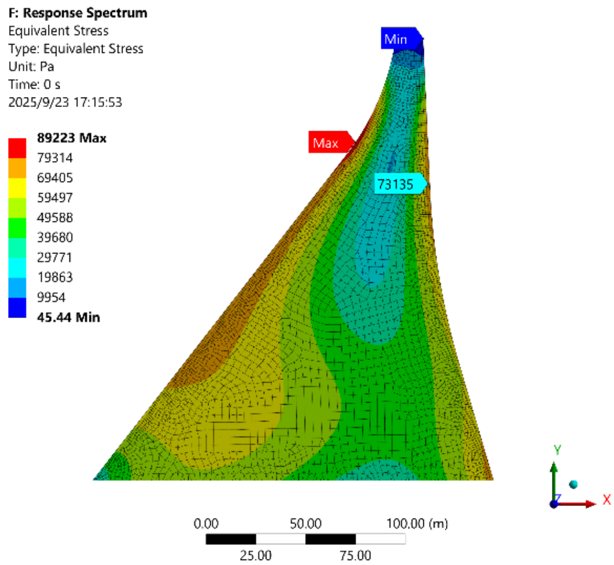

Figure 10. Von-mises stress

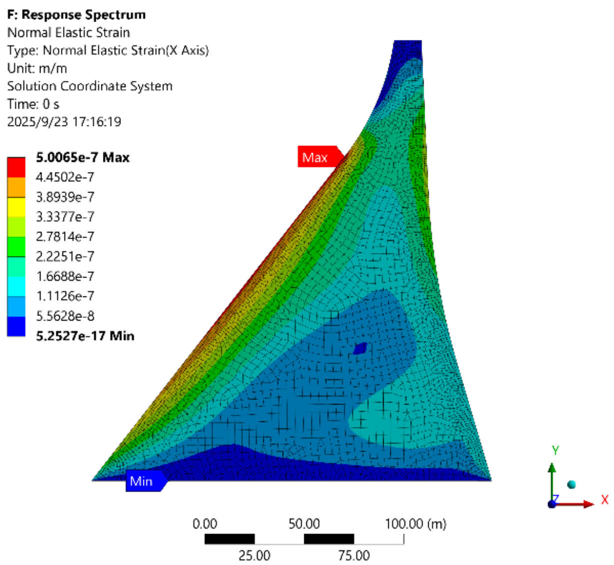

Figure 11. Normal elastic strain

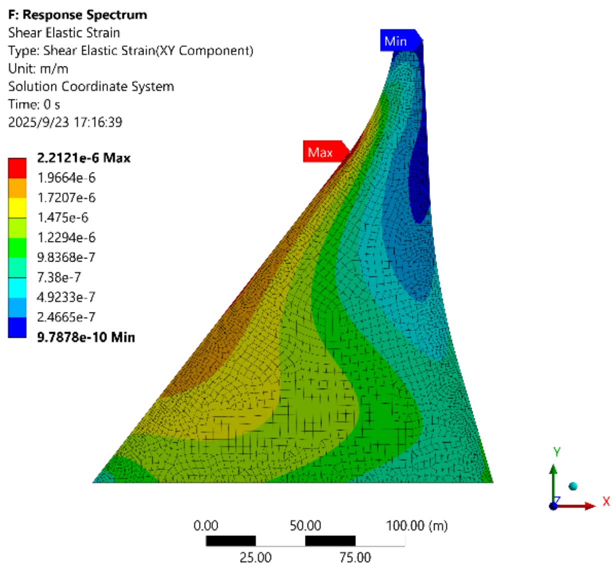

Figure 12. Shear elastic strain

4. The dynamic analysis of the dam considering water

4.1. Modal analysis

Due to the overall model being too large, the effective mass ratio cannot be guaranteed. The solution is to ensure that the effective mass ratio in the vibration direction is as high as possible. It is found that as the number of modal calculation orders increases, the growth rate of the cumulative effective mass ratio gradually increases, and mode 2 plays a dominant role in the Y direction. Therefore, the 9000th order is selected for the modal calculation.

The first six natural frequencies are shown in Table 5.

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Table 5. First four natural frequencies

Mode	1	2	3	4
Natural Frequency (Hz)	3.7647e-002	4.4045e-002	4.5641e-002	5.4027e-002

The first four modes of vibration are shown in Figures 13-16.

Since the first-order mode is dominated by the effective mass ratio in the x-direction, and the second and third-order modes are dominated by the effective mass ratio in the y-direction, the focus is on examining the first three orders of vibration modes. It can be seen that compared with the results of the dam body alone, the water body exacerbates the displacement on the upstream face of the dam body while maintaining a high displacement at the dam crest.

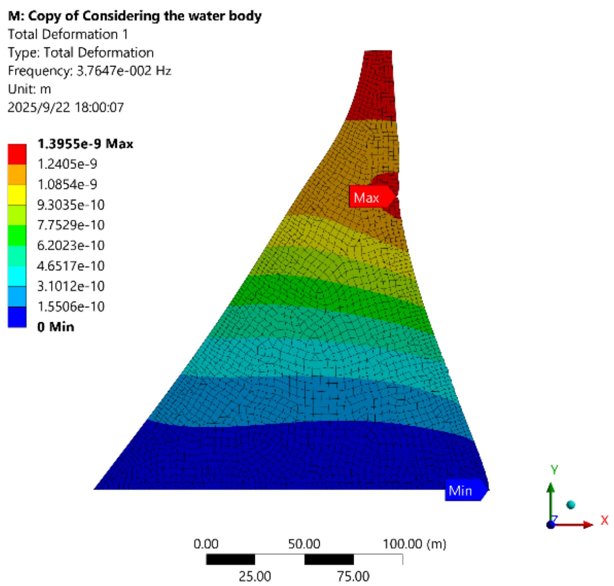

Figure 13. Mode shape 1

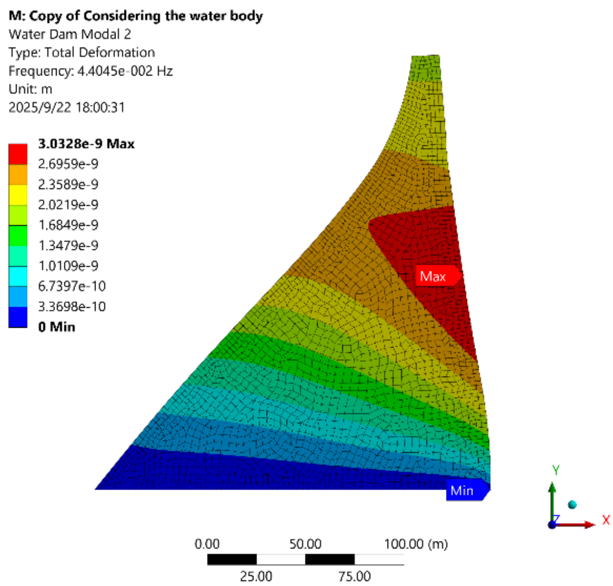

Figure 14. Mode shape 2

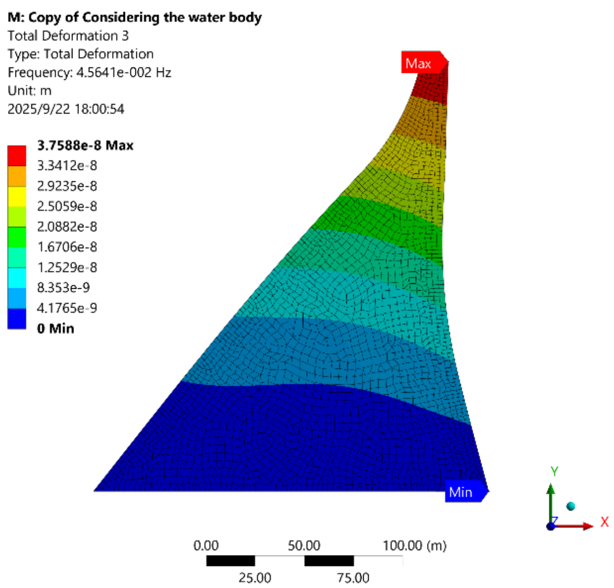

Figure 15. Mode shape 3

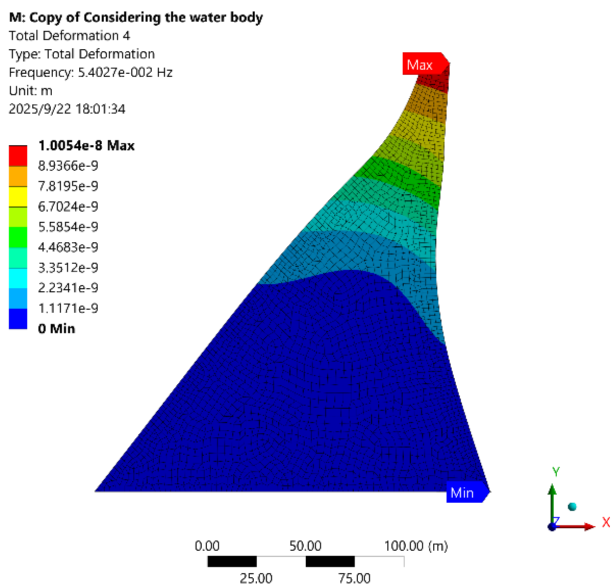

Figure 16. Mode shape 4

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4.2. Response spectrum analysis

Using the same seismic response spectrum as Section 3.2, apply the external excitation to the dam base and the water bottom, with the direction along the XY axis. The solved results are shown in Figures 17-20.

As can be seen from the above figure, the maximum displacement occurs on the upstream face and the dam crest, with the maximum deformation at the dam crest being 7.7310-4m. When water is considered, the displacement at the dam crest decreased by 16% compared to when water is not considered, and the maximum Von Mises stress at a position approximately 100 meters below the dam crest on the upstream face increased 21%. It is also noted that the maximum normal elastic strain and maximum tangential elastic strain appear at a position 100 meters from the dam crest on the downstream face of the dam. This means that once more intense vibrations occur, this location will enter the failure stage relatively quickly.

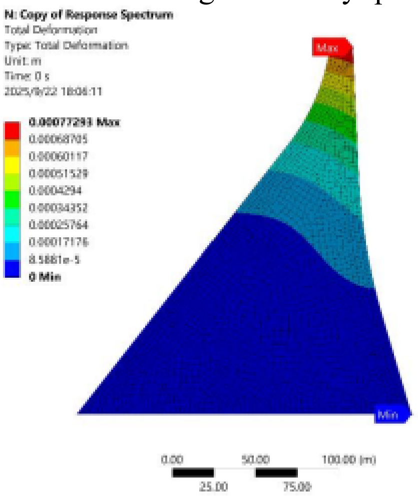

Figure 17. Total deformation

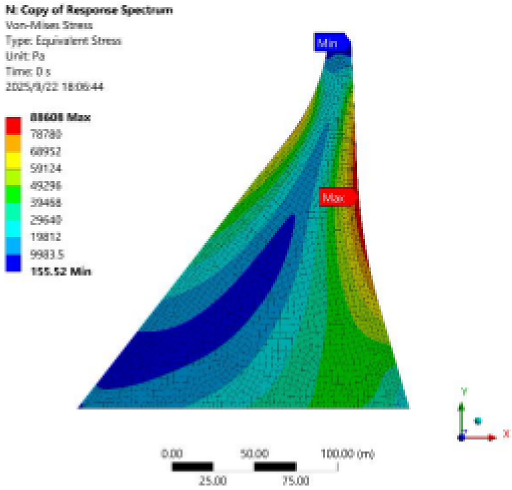

Figure 18. Von-mises stress

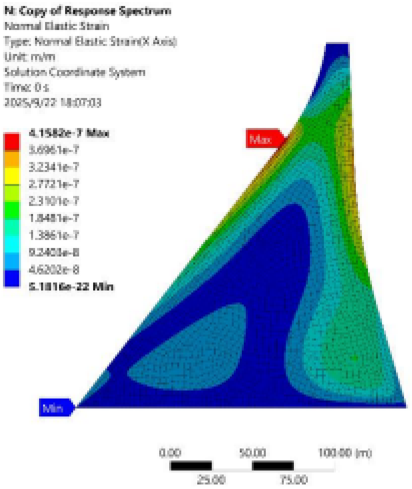

Figure 19. Normal elastic strain

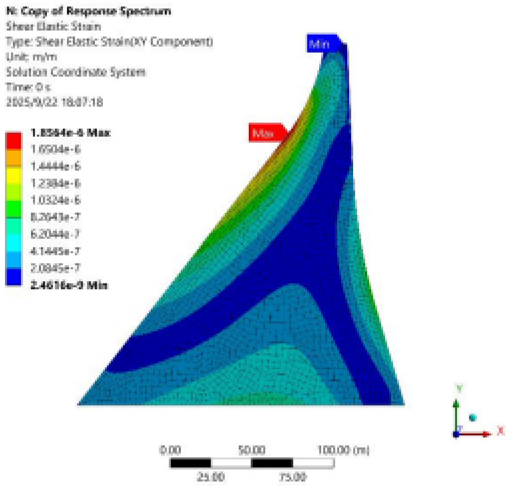

Figure 20. Shear elastic strain

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5. Conclusion

A simplified two-dimensional finite element model of the Hoover Dam was developed in ANSYS to examine its dynamic characteristics and seismic response with and without the Lake Mead reservoir. Modal and response spectrum analyses were performed using a seismic spectrum derived from the 1999 Hector Mine Earthquake.

The results indicate that the maximum seismic displacement occurs at the dam crest, suggesting high sensitivity to dynamic loading. In the sixth vibration mode, stress concentration appears on the upstream face about 100 m below the crest and on the downstream face about 50 m below the crest, while the associated displacements remain small. Under the selected seismic scenario and modeling assumptions, overall stress and strain levels remain within commonly accepted safety limits for concrete gravity dams, indicating stable structural performance without immediate risk of global instability.

Reservoir effects significantly influence the dam’s dynamic response. When the reservoir is included, natural frequencies decrease and mode shapes change. Crest displacement is reduced compared with the dry condition, whereas equivalent stress on the upstream face increases, showing that the reservoir alters both deformation and stress characteristics and should be considered in seismic evaluations.

This study is limited by the use of a simplified two-dimensional model, which cannot fully capture three-dimensional behavior or detailed dam–foundation interaction. Material properties, boundary conditions, and damping were idealized, and complex seismic hazards such as reservoir landslides and hydrodynamic effects were not considered. Future work should incorporate three-dimensional modeling, uncertainty analysis, and coupled dam-reservoir fluid-structure interaction to achieve a more comprehensive seismic safety assessment.

Statement of contribution

Annie Bao: Literature review, historical-geographical context, and introduction drafting.

Zhenglan Qiu: Team coordination, literature support, model development, and numerical analysis.

Junkai Chen: Drawing interpretation, ANSYS modeling, and base model development.

Tengwen Zhang: Model validation, refinement and accuracy improvement, and presentation support.

Yunqing Wu: Literature support, slide preparation, and conclusions synthesis.

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