Calculation and Analysis of Seismic Response Dynamics of Gravity Dam

Ping Wei¹*, Liuchuang Wei²

¹Faculty of Architectural Engineering, Kunming University, Yunnan Kunming 650214, China
²Faculty of Mechanical and Electrical Engineering, Kunming University, Yunnan Kunming 650214, China

*Corresponding author’s e-mail: weiping1123@126.com

Abstract. The gravity dam has the characteristics of clear structure, simple design method, safety and reliability, and strong adaptability to topography and geology. The static and dynamic modal analysis of the dam is carried out by the finite element method, and the vibration modes of each step are obtained. The dynamic response characteristics of the dam under seismic loading are analyzed, and the measures to effectively improve the seismic performance are proposed.

1. Introduction
Gravity dam is a large-scale hydraulic structure, mainly built with materials such as concrete or earth and stone. Under the action of water pressure and other loads, the gravity dam mainly relies on the anti-sliding force generated by the dam's own weight to meet the stability requirements. At the same time, it relies on the compressive stress generated by the dam's own weight to offset the tensile stress caused by the water pressure to meet the strength requirements. [1]. In China, many gravity dams are built in earthquake-prone areas, coupled with long-term load of gravity, water pressure and other loads. Once the dam is damaged, the economic losses caused by it are difficult to estimate. Research and analysis of dams Seismic performance and effective evaluation of the seismic safety performance of gravity dams are hot topics in the engineering field.

2. Self-vibration theory of gravity dam
Gravity dam structure is a system with continuous distribution of mass and stiffness. The structure has an infinite degree of freedom. When performing finite element analysis, the structure needs to be discretized into a finite element calculation model with finite degrees of freedom, and due to the damping characteristics of the structure. The effect is small, and the effects of damping are usually ignored in the calculation [3]. In the calculation, it can be assumed that the gravity dam structure has N degrees of freedom, and the kinetic equilibrium equation of structural vibration is analyzed by finite element analysis.

\[
[M]\ddot{U} + [C]\dot{U} + [K]U = \{P(t)\}
\]

(1)

When the external force is not applied, the resistance is not neglected, and the undamped free vibration equation of the model with N degrees of freedom of the above structural system can be obtained.
\[
\begin{bmatrix} M \end{bmatrix} \ddot{\mathbf{U}} + \begin{bmatrix} K \end{bmatrix} \mathbf{U} = 0
\]

Solve the differential equation and get:
\[
\left( \begin{bmatrix} K \end{bmatrix} - \omega^2 \begin{bmatrix} M \end{bmatrix} \right) \Phi = 0
\]

By substituting the natural frequency into equation (3), the vibration mode of the corresponding structure \( \Phi_i (i = 1, 2, \cdots, N) \) can be obtained.

3. Finite element analysis of gravity dam under seismic loading

Through the finite element method, using ANSYS software and APDL language, select the appropriate unit, carry out spatial solid modeling of the actual engineering gravity dam, divide the grid, consider the dam's own weight, and put the water pressure and sediment on the dam. The load applied at the base of the dam is simultaneously applied to the load on the dam to extract the equivalent stress after stress calculation.

![Figure 1](image1.jpg)

Figure 1. X, Y direction displacement and displacement

It can be seen from Fig. 1 that the top of the dam is easy to crack, and the concrete is not cracked when it is cracked due to the characteristics of the material. Therefore, if the concrete is cracked, it is necessarily at the maximum displacement. The first crack is produced. The static stress cloud map is shown in the figure, with a maximum displacement of 1.79 cm and a maximum stress of 4.67 MPa.

![Figure 2](image2.jpg)

Figure 2. X, Y direction stress and combined stress diagram

It can be seen from Fig. 2 that the stress map of the dam is available, and the force of the dam at the dam is concentrated, which is the maximum force point, and the force is gradually reduced from the upstream of the dam toe dam and the dam crest. In the horizontal direction, the stress is mainly concentrated at the dam and the top of the dam. The maximum stress at the top of the dam depends on the downstream side of the dam. The horizontal stress in the dam body gradually increases from the middle to the outside. The displacement generated by the upward pressure in the vertical direction is distributed downward from the upstream surface of the dam body to the downstream surface from the water surface to the downstream surface, and is also at the dam at the force.
When the gravity dam is subjected to the first principal stress (Fig. 3), the stress is at the dam at the maximum stress, and the force is more concentrated than other places. The joint between the dam and the bedrock is most obvious, which is easy to produce. Slip. The second principal stress diagram shows that the stress is mainly concentrated near the dam and at the top of the dam. The stress on the dam is getting smaller from the edge to the inside. The third principal stress diagram shows that the stress is concentrated at the top of the dam and the stress near the upstream dam is large. Since the first, second and third principal stresses are mainly dominated by the stress of the first principal stress, the stress is greatest at the dam dam and the area around the dam is easily unstable.

4. Dynamic analysis of dam seismic response

4.1. Seismic response analysis of dam
The seismic response analysis of the dam involves the analysis of various aspects of the dam. Firstly, the response spectrum is set and analyzed from the results of the modal analysis, and the reaction results are modally expanded to obtain the seismic response spectrum of the dam. The result of the data is modal merge, that is, the results of static and dynamics are equivalently fused to obtain the deformation and displacement of each modal under the final seismic response of the dam.

4.2. Process of seismic analysis of gravity dam
The analysis process can be expressed as: create model → meshing → modal analysis → spectral analysis → modal expansion analysis → modal merge analysis → post-processing. According to the specification, in the dynamic calculation, the elastic modulus of the material is obtained by increasing the static modulus by 30%, while the dynamic Poisson's ratio is still the same as the static Poisson's ratio. The material properties of the dam body and the dam foundation in the dynamic calculation are shown in Table 1 for the dam body and foundation material parameters.

| material         | Elastic Modulus (GPa) | Poisson's ratio (µ) | density (kg/m³) | f (MPa) | C (MPa) |
|------------------|-----------------------|---------------------|-----------------|---------|---------|
| Dam concrete     | 33.15                 | 0.167               | 2450            |         |         |
| C20 normal concrete backfill | 33.15     | 0.167               | 2450            |         |         |
| Seismic rock mass | Bedrock              | 11.7                | 0.27            | 1.15    | 1.25    |
|                  | Bedrock consolidation grouting | 19.5          | 0.27            | 1.15    | 1.25    |

Input the synthesized seismic wave and corresponding frequency design, and analyze the response spectrum of the dam. The results of the dam mode diagrams of the first, second, third, fourth, eleventh, twelfth, thirteenth, and fourteenth modes are analyzed.
It is obtained from Fig. 4; the deformation of the dam is the slowest at the first-order frequency, and the deformation of the dam becomes larger as the frequency increases. The increase of the frequency also causes the deformation of the dam to gradually be influenced by the dam crest. The deformation extends to the tensile stress deformation at the upstream and downstream, and finally the deformation becomes more and more severe.

The modal expansion calculations are combined to obtain the final seismic performance deformation map of the dam.

The final deformation results of the final modal combination of the dams in Figures 5 and 6 are shown in the vibration analysis results of the typical modes of Table 2.

|          | Maximum displacement in the X direction (mm) | Maximum displacement in the Y direction (mm) | Overall maximum displacement (mm) | Frequency  |
|----------|---------------------------------------------|---------------------------------------------|----------------------------------|------------|
| 1st mode | 1.237E-03                                   | 2.89E-04                                   | 1.269E-03                        | 3.2217     |
| 4th mode | 1.154E-03                                   | 5.00E-04                                   | 1.254E-03                        | 13.650     |
| 14th mode | 4.14E-04                                   | 7.91E-04                                   | 8.43E-04                         | 51.148     |

4.3. Dynamic displacement analysis of gravity dam

The displacement of the top of the gravity dam is the largest, and the maximum displacement occurs on the upstream side of the dam crest. The displacement is 1.269mm. On the same level, the displacement of the dam from the upstream direction to the downstream direction is gradually reduced. The dynamic displacement of the downstream side is higher than that of the upstream side. The
Dynamic displacement is slightly smaller, and the contour of the dynamic displacement is slightly inclined upstream. The horizontal displacement increases with the increase of the elevation. Under the same elevation, the displacement of each node inside the dam in the same horizontal section is the same in the horizontal direction, especially in the horizontal direction. All appear in a straight line style. The maximum displacement of the dam crest shown in the analysis results is 1.237 mm. In the Y direction, the displacement after the response shows a decreasing trend from upstream to downstream. Under the influence of the earthquake, the displacement in the Y direction near the upstream surface is larger than that in the downstream direction, and the maximum displacement in the Y direction is at the top of the dam, and its value is 0.835 mm. The dynamic displacement in the Y direction near the downstream side is 0.958 mm.

4.4. Dynamic strain analysis of gravity dam

The distribution of stress in the Y direction of the dam under earthquake action is as follows: the dynamic stress near the surface of the dam is large, and the stress generated inside the dam is small; the dynamic stress in the Y direction near the upstream dam is larger than that in the vicinity of the game; The stress concentration phenomenon occurred in the dam dam and the downstream slope, and the dam was at 0.83. The maximum dynamic stress in the Y direction was concentrated in the upstream, and its value was 4.39 MPa. The branching stress in the X direction of the dam is also gradually increased from the upstream side to the downstream side. It is the largest at the toe of the dam. Consider the first principal stress condition of the dam subjected to earthquakes. The first principal stress change of the entire dam is mainly concentrated at the dam.

5. Conclusion

The dynamic calculation model of typical gravity dam is established by finite element method. The dam analysis, response spectrum method and seismic response analysis are used to analyze the seismic response of the dam. Finally, the seismic response law of the dam is obtained:

(1) Under the conditions of empty storage, the principal compressive stress at the dam is very large. The extreme value of the main tensile stress of the gravity dam appears at the downstream slope, which is easy to produce cracks in the dam head, which is a weak part of the structure. Under normal water storage and full-load conditions, there is a main tensile stress at the upstream dam, and the principal compressive stress appears on the downstream dam surface and gradually increases toward the dam toe.

(2) The horizontal displacement of the gravity dam is gradually increased along the dam height, and the displacement of the dam crest is the largest. The dam crest structure should be appropriately reduced or the strength of the dam crest building should be improved. The extreme value of the vertical displacement occurs at the upstream and downstream dams of the dam, and the extreme value of the principal compressive stress is mainly concentrated near the dam toe. The concrete grade at the bottom of the gravity dam should be properly increased to improve the seismic performance of the dam. There is horizontal stress concentration at the dam slope, and vertical stress concentration exists at the dam, dam toe and downstream slope. The structure of the dam slope can be changed appropriately, and the angle of the slope is changed into an arc to reduce the area. Stress concentration, or increase the concrete grade of the part to improve seismic performance.

(3) At the bottom of the dam, the earthquake exerts a large tensile stress on the dam portion of each dam section. From the perspective of seismic safety, it is necessary to provide a layer of normal concrete at the bottom of the gravity dam body to ensure the seismic safety of the dam.

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