Three-dimensional linear seismic analysis of normal concrete gravity dam

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Abstract. The three-dimensional linear finite element model is established for the bottom outlet dam section of concrete gravity dam. Mode-superposition response spectrum method and the massless foundation time history method are adopted to analyze the static and dynamic comprehensive stress response and displacement response of the dam under the action of the standard response spectrum of the design earthquake or the corresponding artificial wave under the action of design earthquake and check earthquake. The results show that the dam works well in seismic condition. In addition, the influence of radiation damping of infinite foundation on the dynamic response of the dam section under different seismic waves is analysed. By comparing the dynamic and static comprehensive stress changes of the dam, it shows that after considering the radiation damping effect of the infinite foundation, the dynamic response of the dam body is significantly reduced.

1. Introduction

As a simple and practical dam type, gravity dam has been widely used in dam construction at home and abroad because of its rapid construction. Gravity dams are generally built in valleys with a large width-to-height ratio, and the horizontal size is much larger than that along the river. The seismic action can be decomposed into three components along the river, horizontal and vertical. Because the horizontal stiffness of the gravity dam is much greater than that of the horizontal and vertical directions, the deformation and stress of the dam caused by the earthquake in the horizontal direction are much smaller than those caused by the earthquake in the other two directions. Therefore, in the seismic design calculation and safety evaluation of dams, the horizontal seismic effects are often ignored, and only the downstream and vertical seismic effects are included. Ignoring the seismic action in the transverse direction may be difficult to faithfully reflect the dynamic response of the dam under the action of strong earthquakes when encountering an earthquake.

In view of the above problems, the typical dam section is often selected using the simple, practical and safe one-dimensional cantilever method or the two-dimensional finite element method. However, for dam sections with complex structures, in order to accurately reflect the local stress state of the structure near the piers, orifices and pipelines, the "dam section three-dimensional" finite element calculations need to be carried out.

In this paper, the 3D linear FEM is established for the bottom outlet dam section of concrete gravity dam. The massless foundation model is adopted in foundation calculation. The interaction between the foundation and the dam is considered for the bottom outlet dam section, the mode-superposition...
response spectrum method and the massless foundation time history method are adopted to analyze the static and dynamic comprehensive stress response and displacement response of the dam under the action of the standard response spectrum of the design earthquake code or the corresponding artificial wave under the action of design earthquake and check earthquake.

2. Calculation model and basic parameters

The dam of a hydropower project consists of a retaining dam section, an overflow dam section, a powerhouse dam section and bottom outlet dam section. The body shape and structure of the other dam sections are relatively complex except the retaining dam section.

The main structure of the dam section of the bottom outlet dam section is simulated in detail, and the dam body is discrete with three-dimensional solid elements. The range of foundation simulation is as follows: the upper and downstream directions from the dam heel and the dam toe respectively extend 2 times the maximum dam height; the depth direction is 2 times the maximum dam height downward from the lowest foundation. The foundation is also simulated by three-dimensional solid elements.

According to the above modeling principles, the three-dimensional finite element model of the bottom outlet dam section established in this study is shown in Figure 1. The main calculation scheme is shown in Table 1.

![Figure 1. Finite element mesh of the bottom outlet dam section](image)

**Table 1. Calculation scheme**

| Working condition | Basic static load combination | Design earthquake | Check earthquake | Foundation model | Calculation method |
|-------------------|-------------------------------|-------------------|------------------|------------------|------------------|
| 1                 | Steel pipe without water      | √                 |                  |                  | response spectrum method |
| 2                 |                               |                   |                  |                  |                  |
| 3                 | Steel pipe with full water    | √                 |                  |                  |                  |
| 4                 |                               |                   |                  |                  |                  |
| 5                 | Steel pipe without water      | 3 sets of waves   |                  | Qualityless foundation |                  |
| 6                 |                               |                   |                  |                  |                  |
| 7                 | Steel pipe with full water    | 3 sets of waves   |                  |                  | time history method |
| 8                 |                               |                   |                  |                  |                  |
| 9                 | √                              | 3 sets of waves   |                  |                  | Ground radiation damping |
| 10                | √                              | 3 sets of waves   |                  |                  |                  |
3. Calculation results and analysis

Table 2 shows the results of the controlled stress and displacement of the dam under the combined static and dynamic action of the bottom outlet dam section when the mode decomposition response spectrum method and the massless foundation time history method are adopted. The two stress results are in good agreement from the comparison results, the displacement results are slightly different, the overall performance is that the displacement of mode decomposition response spectrum method is slightly larger than that of massless foundation time history method.

**Table 2.** The static and dynamic comprehensive stress and displacement of bottom outlet dam section (MPa, cm)

|                                    | Design earthquake | Check earthquake |
|------------------------------------|-------------------|-------------------|
|                                    | response spectrum method | time history method1 | time history method2 | time history method3 | mesponse spectrum method | time history method1 | time history method2 | time history method3 |
| Displacement of the dam crest along the river | 5.35 | 4.96 | 4.98 | 4.59 | 6.48 | 5.96 | 5.99 | 5.48 |
| Tensile stress near downstream face and guide wall | 3.65 | 2.68 | 3.52 | 3.23 | 5.21 | 4.02 | 5.13 | 4.75 |
| Maximum tensile stress on upstream surface | 2.50 | 2.59 | 2.26 | 2.25 | 3.53 | 3.70 | 3.20 | 3.23 |
| Maximum tensile stress on downstream surface | 3.65 | 2.68 | 3.52 | 3.23 | 5.21 | 4.02 | 5.13 | 4.75 |
| Maximum compressive stress on downstream surface | -6.84 | -7.16 | 6.63 | -6.28 | -8.48 | -8.89 | 8.21 | -7.73 |
| Maximum tensile stress of dam heel | 6.09 | 4.45 | 4.94 | 5.33 | 8.18 | 6.26 | 6.92 | 7.43 |

**Figure 2.** Comprehensive maximum principal stress diagram (Response spectrum method under check earthquake)
Figure 3. Comprehensive maximum principal stress diagram (Time history method3 under check earthquake)

Because the static and dynamic stress response calculated by the mode decomposition response spectrum method for bottom outlet dam section is relatively large, an analysis of the influence of the radiation damping effect of the infinite foundation on the dynamic response of the dam section under the action of different seismic waves is supplemented. Table 3 shows the comparison of the influence of radiation damping on the dynamic response of the dam under the action of the design earthquake and the check earthquake. It is found that when considering the radiation damping effect of the infinite foundation, the dynamic response of the dam body is significantly reduced.

Table 3. The static and dynamic comprehensive stress of bottom outlet dam section (MPa)

|                          | Design earthquake | Check earthquake |
|--------------------------|-------------------|------------------|
|                          | response          | artificial       | artificial | artificial |
|                          | spectrum method   | wave1            | wave2      | wave3      |
| Tensile stress near      | 3.65              | 1.16             | 1.54       | 2.10       |
| downstream face and      |                   |                  |            |            |
| guide wall               |                   |                  |            |            |
| Maximum tensile stress   | 2.50              | 1.51             | 1.02       | 1.02       |
| on upstream surface      |                   |                  |            |            |
| Maximum tensile stress   | 3.65              | 1.16             | 1.54       | 2.10       |
| on downstream surface    |                   |                  |            |            |
| Maximum compressive      | -6.84             | -5.18            | -5.18      | -4.28      |
| stress on downstream     |                   |                  |            |            |
| surface                  |                   |                  |            |            |
| Maximum tensile stress   | 6.09              | 2.93             | 3.27       | 3.10       |
| of dam heel              |                   |                  |            |            |
| Maximum compressive      | -23.38            | -12.83           | -12.49     | -13.54     |
| stress of dam toe        |                   |                  |            |            |
| Tensile stress near      | 5.21              | 2.01             | 2.50       | 3.23       |
| downstream face and      |                   |                  |            |            |
| guide wall               |                   |                  |            |            |
| Maximum tensile stress   | 3.53              | 2.29             | 1.64       | 1.64       |
| on upstream surface      |                   |                  |            |            |
| Maximum tensile stress   | 5.21              | 2.01             | 2.50       | 3.23       |
| on downstream surface    |                   |                  |            |            |
| Maximum compressive      | -8.48             | -6.25            | -5.38      | -5.14      |
| stress on downstream     |                   |                  |            |            |
| surface                  |                   |                  |            |            |
| Maximum tensile stress   | 8.18              | 4.21             | 4.66       | 4.44       |
| of dam heel              |                   |                  |            |            |
| Maximum compressive      | -26.32            | -13.93           | -13.48     | -13.52     |
| stress of dam toe        |                   |                  |            |            |
4. Conclusion
The three-dimensional linear finite element model is established for the bottom outlet dam section of concrete gravity dam. Mode-superposition response spectrum method and massless foundation time history method are adopted to analyze the static and dynamic comprehensive stress response and displacement response of the dam under the action of the standard response spectrum of the design earthquake or the corresponding artificial wave under the action of design earthquake and check earthquake. The results show that the dam works well in seismic condition.

In the design earthquake and check earthquake conditions, the static and dynamic comprehensive stress analysis of the bottom outlet dam section is compared with the influence of radiation damping by the time history method, and the dynamic response changes of the dam body under different seismic waves are studied. It is found that after considering the radiation damping effect of the infinite foundation, the dynamic response of the dam body is significantly reduced.

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