Research on Seismic Assessment of Gravity Dam Based on Performance Analysis

Xiaodong Zheng and Jianguo Hao*
College of water conservancy and hydropower, Hebei University of Engineering, Handan Hebei, 056000, China
*Corresponding author’s e-mail: haojianguo1996@163.com

Abstract: Based on the incremental dynamic analysis method, a new index (the ratio of plastic energy consumption to total deformation energy) for evaluating the seismic performance of earthquake-resistant dams is proposed. Suggestions for three levels of earthquake damage and failure classification in two extreme states of gravity dam seismic performance evaluation are given. The IDA analysis of the concrete gravity dam was carried out by nonlinear numerical analysis model. Based on this, the quantile analysis and fragility analysis were carried out. The results show that ① the peak ground acceleration PGA of each limit state in the IDA curve of the quantile analysis is larger than the peak ground acceleration of the designed earthquake, which satisfies the level of functional support and safety assurance of the gravity dam. ② Under the fragility analysis, the probability of 65.92% is in the normal use stage of the 1.5 times design earthquake, and 100% can guarantee safety. The results show that the gravity dam has good seismic performance. The results of this study provide new ideas for the seismic performance design and safety risk assessment of gravity dams.

1. Introduction
At present, the seismic design codes of various countries are based on the seismic design concept of bearing capacity, which only meets the basic design requirements of personnel safety, and requires less requirements for other indicators. However, with the continuous improvement of structural seismic design requirements, the seismic design of hydraulic structures must take into account important factors such as economic loss and post-disaster function use on the basis of ensuring personnel safety. Scholars from all over the world began to apply the performance-based seismic design concept to the high-dam seismic [1-2]. Based on this, different structural performance parameters were proposed to reflect the seismic capacity and destruction level. Kowalsky [3] first proposed a seismic design method using displacement as a structural performance parameter. Chanaat [4] first quantified the damage degree of concrete dam by seismic performance parameters such as demand capacity ratio, super stress duration and super stress range, and established a dam seismic safety evaluation model; Chen [5] based on the relative displacement of the dam crest, compared the fluid-solid coupling model and tradition additional mass model; Kong [6] selected the dam crest relative seismic subsidence rate, dam slope stability slip, panel failure index and other structural performance parameters for high-surface rockfill dam. Li [7] believed that taking the damage volume ratio and damage area ratio as the indexes to evaluate the seismic performance of the arch dam could reflect the changing trend of the damage and the seismic bearing capacity of the arch dam more clearly than the traditional ones.

In this paper, a concrete gravity dam is selected as an example. Based on the incremental dynamic analysis method, the seismic performance evaluation method of gravity dam based on energy...
consumption is proposed. The ratio of plastic energy consumption to total deformation energy \( D_p \) is taken as the structural performance index, determined the seismic damage level and seismic performance level of the gravity dam, combined with quantile analysis and fragility analysis, effectively evaluated the seismic performance of gravity dams.

2. Calculation model and parameters

2.1 Finite element modeling

The height of the dam is 81m, the width of the dam top is 10.5m, the length of the dam is 185m, and the normal storage level is 77.5m. The specific material parameters of the concrete gravity dam are shown in Table 1. The main loads such as upstream hydrodynamic pressure, uplift pressure, dam body weight and seismic load are mainly considered in the analysis. The hydrodynamic pressure is analyzed and calculated according to the specification using Westergaard’s additional mass. The finite element model is shown in Figure 1.

| Name              | Young's modulus /Gpa | Compressive strength /Mpa | Tensile yield strength /Mpa | Poisson's ratio/ \( \nu \) | Density \( \text{kg/m}^3 \) | Damping ratio |
|-------------------|----------------------|---------------------------|-----------------------------|---------------------------|------------------|---------------|
| Dam C25           | 28.0                 | 16.7                      | 1.78                        | 0.20                      | 2380             | 0.05          |
| Quartz sandstone  | 59.8                 | —                         | —                           | 0.13                      | 2650             | —             |

![Figure 1. Finite element model of gravity dam.](image)

2.2 Selection of ground motion

When performing IDA analysis, generally no less than 7 ground motion records are selected to meet the calculation accuracy requirements. Based on the site data of the gravity dam and the Standard for seismic design of hydraulic structures (GB51247-2018), six measured ground motion records matching the artificial design response spectrum were selected in the Pacific Earthquake Engineering Research Center (PEER) database and an artificial wave was applied to this study. The basic information is shown in Table 2, and the response spectrum is shown in Figure 2.

| number | Earthquake name | years | Magnitude | PGA/g | duration /s |
|--------|-----------------|-------|-----------|-------|-------------|
| 1      | NorthRidge      | 1989  | 7.1       | 0.568 | 24.58       |
| 2      | Imperial valley | 1979  | 6.9       | 0.313 | 39.99       |
| 3      | Friuli          |       | —         | 0.479 | 20          |
| 4      | Kobe            | 1995  | 7.2       | 0.345 | 24.79       |
| 5      | Sakaria         |       | —         | 0.628 | 19.98       |
| 6      | Koyna           | 1967  | 6.3       | 0.474 | 11          |
| 7      | Artificial wave |       | —         | 0.15  | 20          |
2.3 Seismic performance level and damage level

Based on ABAQUS, nonlinear time-history analysis of concrete gravity dam, output plastic energy consumption, total deformation energy and relative displacement of dam crest and dam foundation. On the basis of this, the IDA curve generated by the maximum relative displacement and the ratio of plastic energy to total deformation energy ($E_D$) as the structural performance parameter is compared and analyzed, as shown in Figure 3.

In the analysis of structural performance parameters with $E_D$, the IDA curve can be divided into three stages by the two inflection points as the ground motion intensity increases. The first inflection point is near the $E_D$ value of 0.2 and the second inflection point is near at the $E_D$ value of 0.7. The seismic damage of the gravity dam is divided into three phases: normal use phase, damage control phase and prevention collapse stage.

In the analysis of the relative displacement of the dam top as the structural performance parameter, according to the study of the definition of the seismic limit state by Vamvatsikos et al[8], the point at which the slope is 80% elastic slope is defined as the serviceability limit state, and the slope in 20% elastic slope is defined as the bearing capacity limit state, as shown in Figure 3b.

Compared the PGAs corresponding to the two limit states under different structural performance parameters. It can be seen that when the PGA is small, the structural performance parameter $E_D$ is close to the Serviceability limit state corresponding to the maximum relative displacement. When the PGA is large, the PGA corresponding to the maximum relative displacement as the structural performance index is much larger than that with $E_D$ as the DM. Therefore, when using $E_D$ as the structural performance index, the safety performance of the gravity dam is higher.

2.4 Selection of IDA analysis parameters

The IDA analysis process is based on ABAQUS finite element analysis software. Each seismic wave adjusted the peak ground acceleration (PGA) to 0.1g~0.8g according to a certain ratio, and introduced...
into the model for nonlinear analysis, forced the structure from elastic response to final overall damage. Thereby plotting the relationship curve between the structural performance parameter (DM) and the ground motion intensity parameter (IM). In this paper the ratio of plastic energy consumption to total deformation energy \( (D_z) \) is taken as DM, and the PGA is used as IM.

3. Analysis of results

It can be seen from Figure 4 that 0<PGA ≤ 0.1g then \( D_z \) are 0, indicating that the dam is not destroyed; when 0.1g<PGA ≤ 0.5g, \( D_z \) is exponentially increasing, indicating that the damage is growing fast of the dam at this stage under the action of moderate earthquakes; when PGA>0.5g, the growth trend of \( D_z \) gradually slows down and the dam body is nearly completely destroyed.

3.1 Quantile analysis

For the quantile analysis of the IDA curve, the 16%, 50%, 84% and mean value curve and the corresponding normal use limit state point and bearing capacity limit state point on each quantile curve are shown in Table 3 and Figure 5. Taking 16% of the quantile as an example (with 84% guarantee rate at this time), the dam body is in the normal use stage when the peak ground acceleration is 0.253g, which meets the functional guarantee level; the dam body is in the damage control stage when the peak ground acceleration is 0.461g, which meets the safety guarantee level.

![Figure 4. IDA curve cluster.](image1)

![Figure 5. IDA curves for different quantiles.](image2)

**Table 3. PGA corresponding to each limit state under different fractile probabilities.**

| Quantal probability | Serviceability limit state | Limit state of bearing capacity |
|---------------------|---------------------------|--------------------------------|
| 84%                 | 0.219g                    | 0.421g                         |
| 50%                 | 0.235g                    | 0.442g                         |
| Mean                | 0.230g                    | 0.431g                         |
| 16%                 | 0.253g                    | 0.461g                         |

3.2 Fragility analysis

According to the IDA analysis results of the gravity dam, the probability of the gravity dam exceeding the limit state under different seismic intensities is calculated respectively. The direct fitted method can draw the seismic vulnerability curve of the gravity dam, as shown in Figure 6.
Figure 6. vulnerability curve.

It can be seen from Table 4 that under the action of designing earthquakes, the probability that the gravity dam exceeds the normal use limit state is 3%; In the case of 1.5 times design earthquake, the probability that the gravity dam exceeds the normal use limit state reaches 65.92%; Under the influence of 2 times design earthquake, the probability that the gravity dam exceeds the normal use limit state reaches 96.83%, and the probability of exceeding the bearing capacity limit state is 3.14%.

From Table 5, the probability that the gravity dam is in a state of failure grade at different seismic intensity levels can be calculated, as shown in Table 5. Under the design earthquake, the gravity dam is basically non-destructive, 97% of the probability is in the normal use stage, 3% is in the damage control stage; Under the action of 1.5 times design earthquake, the probability of the dam body in the normal use stage is 65.92%, The probability in the damage control phase is 34.08%; In the case of 2 times design earthquake action, the probability of being in the normal use phase is 3.17%, the probability of being in the preventing collapse phase is 3.14%, and the probability is 93.69% in the damage control phase.

| Fortification standard /g | Surpass probability /% |  |
|--------------------------|------------------------|---|
|                          | Functional protection point | Security guarantee point |
| 0.1                      | 0                      | 0                          |
| 0.15                     | 3                      | 0                          |
| 0.2                      | 16.70                  | 0                          |
| 0.225                    | 34.08                  | 0                          |
| 0.3                      | 96.83                  | 3.14                      |
| 0.4                      | 100                    | 16.70                     |
| 0.5                      | 100                    | 95                         |
| 0.6                      | 100                    | 0                          |
| 0.7                      | 100                    | 0                          |

| Fortification standard /g | Failure probability /% |  |  |
|--------------------------|------------------------|---|---|
|                          | Normal service phase   | Damage control phase | Prevent collapse stage |
| 0.1g                     | 100                    | 0                          | 0                          |
| 0.15g                    | 97                     | 3                          | 0                          |
| 0.2g                     | 83.30                  | 16.70                     | 0                          |
| 0.225                    | 65.92                  | 34.08                     | 0                          |
| 0.3g                     | 3.17                   | 93.69                     | 3.14                      |
| 0.4g                     | 0                      | 83.30                     | 16.70                     |
In summary, for the quantile analysis, the peak ground acceleration PGA of each limit state in the IDA curve of the quantile analysis is larger than the peak ground acceleration of the design earthquake, thus satisfying the functional guarantee level and safety guarantee level of the gravity dam. For the fragility analysis, under the design earthquake, the probability of being in the normal use phase is close to 100%; and under the action of 1.5 times the design earthquake, the probability of 65.92% is in the normal use phase, and 100% can guarantee safety. In the case of 2 times design earthquake, the probability of 93.69% is in the damage control phase, meeting the safety requirements. The results show that the gravity dam has good seismic performance and the possibility of global failure is small.

4 Conclusion

(1) The seismic performance of concrete gravity dam was evaluated by IDA method. Established a method for estimating the seismic performance of gravity dams using the ratio of plastic energy consumption to total deformation energy consumption ($D_p$) as DM. The reasons and basis for using $D_p$ as the structural performance parameter are discussed, Suggestions are given for the three-stage failure state (normal use phase, damage control phase and collapse prevention phase) based on the seismic performance of the gravity dam and two limit state points (normal use limit state and bearing capacity limit state). It provides a new idea for evaluating the seismic performance of gravity dams.

(2) Applying the above method to evaluate the seismic performance level of a gravity dam, the results show that: ①The results of quantile analysis show that the PGA under both extreme states is greater than the PGA of the design earthquake of the gravity dam, and the applicability and safety of the dam can be guaranteed. ②In the fragility analysis, under the design earthquake, the dam is in the normal use stage; The probability of the dam being in normal use under the action of 1.5 times design earthquake is greater; the probability of the dam being in the damage control stage is greater under the action of 2 times design earthquake. Through the above analysis, it can be concluded that the gravity dam has good seismic performance.

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