Seismic Behaviour Modelling of Kualu Dam Under Earthquake Motion

Evi Nur Cahya¹, Taufiq Rochman², Suwanto Marsudi¹

¹ Water Resources Engineering Department, Universitas Brawijaya, Malang 65145, Indonesia
² Department of Civil Engineering, State Polytechnic of Malang 65145, Indonesia

E-mail: evi_nc@ub.ac.id

Abstract. As a mass structure, the seismic performance of a specified dam is importantly necessary, especially in the area which earthquake likely occur. The purpose of this study was to determine the critical areas of specified dam under earthquake motion. The dam structure was analyses with shell meshed modelling in empty condition and normal condition (operation term), as well as the seismic analysis under earthquake motion. The dynamic response analysis was carried out using response spectral acceleration under Operating Basis Earthquake (OBE) and Maximum Design Earthquake (MDE) based on earthquake records. According to the analytical results from the dynamic analyses, it was found that the shell structure members of the dam heel in the upstream were having a very large bending moment. The analysis also showed that the shell structure members in the face of downstream slopes were significantly responded the seismic motion in some certain modes. These two areas of the dam have become the critical areas of the dam which needed to be addressed in strength design of the specified dam.

Keywords: Dam structure, dynamic analysis, seismic behaviour, response spectral analysis

1. Introduction

The seismic performance of a dam is necessarily analysed, especially in the area which earthquake likely occur. Geographically, Indonesia is located among three world faults that make it vulnerable to earthquakes. According to that condition, the earthquake became one of the main considerations to guarantee the safety of dams in Indonesia.

The basic element in dam project is safety, which includes safety elements as structural safety, dam safety monitoring, operational safety and maintenance, as well as emergency planning [1]. As a strategic project, dam needs to be carefully designed to avoid damage to the environment of water reservoirs and surrounding infrastructure and human safety. In accordance with classic theoretical method and current codes, the concrete gravity dam needs to be modelled in two-and three-dimensions [2].

The construction of dams should be based on the implementation of seismic safety laws in seismically active environments. Despite the fact that dams are structures of great importance, such effective regulations have not yet been passed. In seismic modeling of these systems, approaches based on scientific research and experience are used [3].

The International Commission on Large Dams (ICOLD) gave recommendations on how to define the seismic design parameters of large dams [4]. These recommendations are the basis on which the method has been developed for defining the seismic design parameters of large dams.
Simplified methods, such as “seismic coefficient method” is often started with gravity dam seismic analysis. Earthquake load to the dam structure is assumed as a lateral force which is applied statically. The simplified methods are not used in final design stages because they are not accurate. The utilization of the finite element or boundary element method are more rigorous and refined. In the other hand, the methods are time-consuming [5].

The aim of this study was to determine the critical areas of specified dam under earthquake motion. This paper presents the stability and dynamic analysis of the gravity dam with the finite element method analysis using response spectral acceleration under Operating Basis Earthquake (OBE) and Maximum Design Earthquake (MDE) based on earthquake records.

2. Material and Methods
Kualu Dam is located on the Kualu River and build for water powerplant, in North Sumatra Province and currently under constructed. The complete technical data such as dam shape, material, and seismic parameter of the specified location were importantly needed to support the analysis. The choice of dam type is based on topographical conditions, geological conditions, dam provisions and material availability around the dam site. Based on the consideration above, Kualu Dam was planned with concrete gravity dam in 45 m high with relatively upright river cliff conditions.

2.1. Structural modelling
The dam structure was modelled using shell element in StaadPro structural analysis software, as shown in Figure 1. The model is representative for actual Kualu dam structure. Shell elements were using local axis $x$ dan $y$ which determine the direction of the bending moment $M_x$ and $M_y$, as shown in Figure 2.

2.2. Earthquake analysis
Using earthquake zone map of Indonesia with 0.2-sec spectral response acceleration for 2% 50 year with 5% damping as shown in Figure 3, with a probability exceeded 1% in 50 year (5000-year earthquake return period) [6]. The chosen value of $S_s$ is 1.3 g.

The value of $S_1$ is obtained using 1.0-sec spectral response acceleration for 2% 50 year with 5% damping as shown in Figure 4. The chosen value of $S_1$ is 0.6 g. The value of site factor for short-period range and long-period range of acceleration response spectrum, $F_a$ and $F_v$, was obtained using Table 1 and Table 2. For $S_s$, 1.3 g, the value of $F_a$ was 0.9, while for $S_1$, 0.6 g the value of $F_v$ was 2.4.

The target for the analysis is obtaining the spectral response acceleration ($S_a$) and the fundamental vibrational period of the structure ($T$).
From Equation (1) to (6), the fundamental vibrational period of the structure (T) were obtained as $T_S = 1.231$ and $T_O = 0.246$.

$$S_{MS} = F_s \times S_S$$

(1)

$$S_{M1} = F_s \times S_1$$

(2)

$$S_{DS} = \mu \times S_{MS}$$

(3)

$$S_{D1} = \mu \times S_{M1}$$

(4)

Where,

$S_{DS}$ = acceleration response spectrum design for short period.

$S_{D1}$ = acceleration response spectrum design for 1.0-sec period.
μ = coefficient that depend on building planning regulations which is used, for example for IBC-2009 and ASCE 7-10 with 2500-year earthquake return period using μ value of 2/3 years.

Table 1. Site factor for short-period range of acceleration response spectrum, Fa.

| Site classification      | SS ≤ 0.25 | SS = 0.5 | SS = 0.75 | SS = 1.00 | SS = 1.25 |
|--------------------------|-----------|----------|-----------|-----------|-----------|
| Hard rock (Sₐ)           | 0.8       | 0.8      | 0.8       | 0.8       | 0.8       |
| Rock (S₀)                | 1.0       | 1.0      | 1.0       | 1.0       | 1.0       |
| Very hard soil and Soft Rock (Sᵥ) | 1.2       | 1.2      | 1.1       | 1.0       | 1.0       |
| Medium Soil (Sₐ)         | 1.6       | 1.4      | 1.2       | 1.1       | 1.0       |
| Soft Soil (Sₑ)           | 2.5       | 1.7      | 1.2       | 0.9       | 0.9       |

Table 2. Site factor for long-period range of acceleration response spectrum (1.0-sec), Fᵥ.

| Site classification      | S₁ ≤ 0.1 | S₁ = 0.2 | S₁ = 0.3 | S₁ = 0.4 | S₁ ≥ 0.5 |
|--------------------------|----------|----------|----------|----------|----------|
| Hard rock (Sₐ)           | 0.8      | 0.8      | 0.8      | 0.8      | 0.8      |
| Rock (S₀)                | 1.0      | 1.0      | 1.0      | 1.0      | 1.0      |
| Very hard soil and Soft Rock (Sᵥ) | 1.7       | 1.6      | 1.5       | 1.4       | 1.3       |
| Medium Soil (Sₐ)         | 2.4      | 2.0      | 1.8      | 1.6      | 1.5      |
| Soft Soil (Sₑ)           | 3.5      | 3.2      | 2.8      | 2.4      | 2.4      |
| Special Soil (S₇)         | SS       | SS       | SS       | SS       | SS       |

\[
T_S = \frac{S_{D1}}{S_{DS}} \quad (5)
\]

\[
T_O = 0.2 \times T_S \quad (6)
\]

The value of spectral response acceleration (Sa) is obtain according to the Equation (7) to (9). The result of Sa and period (T) were picture in Figure 5. The fundamental vibrational period of the structure (T) were obtained using Equation (10). With H is the height of the dam as 45 m, T is equal as 1.433 sec.

For \( T < T_O \), \( S_a = S_{DS} \left( 0.4 + 0.6 \frac{T}{T_O} \right) \) \quad (7)

Figure 5. Spectral response acceleration (Sa) vs period (T) for specified location
For $T_o < T < T_s, S_a = S_{DS}$ \hspace{1cm} (8)

For $T > T_s, S_a = \frac{2n}{T}$ \hspace{1cm} (9)

The dynamic response analysis for dam structure was carried out using response spectral acceleration under Operating Basis Earthquake (OBE) and Maximum Design Earthquake (MDE) based on earthquake records.

2.3. Loading condition

The loading condition is considered under certain different condition. The first condition to be considered is normal condition for long term loading, which includes dead load of the dam, live load in the term of wind load, active and passive soil pressure, uplift, and water pressure.

The earthquake load is added to the normal condition, to investigate the earthquake motion to the dam structure. In this step, hydrodynamic loading of water pressure was also included in the analysis. The last load condition is considering the flood cases as load due to the increasing water level in the upstream of the dam, which is not necessarily for earthquake load to be added.

3. Result and Discussion

Linear and nonlinear time-history seismic analyses were used to investigate the dam seismic behavior analysis under Operational Basis Earthquake (OBE) and Maximum Design Earthquake (MDE), as well as linear and nonlinear static analyses for different flood cases. The result of dynamic analysis was shown in Figure 6 dan 7 in several different modes for OBE and MDE.

![Figure 6. Modes of spectral response acceleration at the Maximum Design Earthquake (MDE)](image)

It can be seen that the shell of the dam structure members in the face of downstream slopes were significantly responded the seismic motion in some certain modes. In the 6th mode of the spectral response acceleration, the shell structure members of the dam heel in the upstream were deformed at both Operating Basis Earthquake (OBE) and Maximum Design Earthquake (MDE).
The structural behavior of dam structure under earthquake load is shown from the bending moment dan shear force at certain condition of the loading. The bending moment in Mx direction for normal water level condition and empty condition at both the Operational Basis Earthquake (OBE) are can be seen in the Figure 8. From the figure, it is clearly seen that the shell structure members of the dam heel in the upstream were having a very large bending moment at Operating Basis Earthquake (OBE). Meanwhile, at the Maximum Design Earthquake (MDE) in the Figure 9, the analysis has shown that dam toe structure at the downstream is having medium bending moment compare to the previous figure.

Figure 7. Modes of spectral response acceleration at the Maximum Design Earthquake (MDE)

Figure 8. Bending moment in Mx direction for normal water level condition and empty condition at the Operational Basis Earthquake (OBE)
Figure 9. Shear force for normal water level condition and empty condition at the Maximum Design Earthquake (MDE)

4. Conclusions
This paper has presented the results of research in structural modelling of concrete dam under earthquake motion in certain dam condition. The seismic analysis was carried out using response spectral acceleration under Operating Basis Earthquake (OBE) and Maximum Design Earthquake (MDE) based on earthquake records. According to the analytical results, it was found that the shell structure members of the dam heel in the upstream were having a very large bending moment and deformed in the mode of spectral response acceleration at both Operating Basis Earthquake (OBE) and Maximum Design Earthquake (MDE). The analysis also showed that the shell structure members in the face of downstream slopes were significantly responded the seismic motion in some certain modes. These two areas of the dam have become the critical areas of the dam which needed to be addressed in strength design of the specified dam.

References
[1] Wieland M 2016 Safety Aspects of Sustainable Storage Dams and Earthquake Safety of Existing Dams, Engineering vol 2, 325–331
[2] Zaccheia E, Molinab J.L., Brasile R.M.L.R.F., 2017 Seismic Hazard and Structural Analysis of the Concrete Arch Dam (Rules Dam on Guadalfeo River), Procedia Engineering vol 199, 1332–1337
[3] Stamatovska S.G. 2010 Seismic Design Parameters for Large Dams - ICOLD METHOD, 14th European Conference on Earthquake Engineering 14
[4] Committee on Seismic Aspects of Dam Design 2019 Selecting Seismic Parameters for Large Dams –Guidelines, ICOLD
[5] Alembagheri M, 2016 Earthquake Damage Estimation of Concrete Gravity Dams using Linear Analysis and Empirical Failure Criteria, Soil Dynamics and Earthquake Engineering Vol 90, 327-339
[6] Indonesian Earthquake Sources and Hazards Map 2017 Research and Development Center for Housing and Regency, Research and Development Agency, Ministry of Public Works and Public Housing