Three dimension deformation analysis of Jatigede Dam

A Minmahddun\textsuperscript{1} and E Ngii\textsuperscript{1}

\textsuperscript{1}Department of Civil Engineering, Faculty of Engineering, Universitas Halu Oleo, Indonesia

Email: edward.ngii@uho.ac.id

Abstract. In large dams, the reservoir water level will become a large hydrostatic pressure and reduce the effective stress due to the effect of seepage on the dam body. The total stress that occurs can cause deformation in the dam body to exceed the allowable deformation. Therefore, it is necessary to evaluate the deformation of the dam to know the stability of the dam. This research aimed to analyze the deformation of the dam in a steady-state seepage condition. The reservoir water level was modeled on minimum, normal, and flooded water levels. The deformation was analyzed using the three-dimension finite element method. Deformation analysis results show that the deformation increased when the reservoir water level increased. Significant deformation increase occurred in x-direction deformation i.e. 0.27 m at minimum water level, 0.55 m at normal water level and 0.55 m at flooded water level. The deformation obtained from the analysis still required the maximum deformation criteria of 2 m, which is half of the freeboard.

1. Introduction

One of the criteria of the stable dam is the deformation still meets the allowable deformation. Excessive deformation cause collapse to the dam since deformation affects the loss of freeboard, damage to complementary structures of above the dam, cracks in the dam and lead to piping and damage to dam instrumentation tools [1,2]. The deformation of the dam body depends on dam zoning and on the properties of the construction materials. In addition, deformation is also controlled by reservoir water level since it can provide hydrostatic pressure and reduce the effective stress due to the seepage on the dam body [3,4]. Reservoir Water level that is commonly analyzed in dams is the initial filling, repeated normal conditions (steady-state), and rapid drawdown [5].

The Jatigede Dam is the second largest dam in Indonesia after the Jatiluhur Dam. The dam serves to provide water for about 90,000 ha irrigation area, control flooding and supply water for Sumedang, Majalengka, Indramayu and Cirebon Regency. As one of the vital facilities, it is highly necessary to evaluate the stability of the Jatigede Dam to avoid dam collapse. Therefore, this study aimed to analyze the effect of reservoir water level to the deformation of the dam. Reservoir Water level was modeled on minimum, normal, and flooded water levels. The change of effective stress due to seepage was used to analyze the dam deformation. Seepage and deformation analysis was carried out using the three-dimensional finite element method.

2. Characteristics of Jatigede Dam

The Jatigede Dam is a rockfill dam with The height from the lowest elevation is 114 m and the length of the dam's crest is 1,715 m. Jatigede Dam is divided into 6 zones, namely zone 1 (core), zone 2A (fine filter), zone 2B (rough zone), zone 3A and 3B (rockfill material), and zone 6 (riprap). The Jatigede Dam
was constructed on a volcanic breccia and there is a grouting curtain at the bottom of the dam to minimize the uplift pressure due to seepage at dam foundation. The upstream slope is 1: 2 while the downstream slope is 1: 1.9. The plan view and cross-section of the Jatigede Dam are shown in figure 1 and figure 2.

![Figure 1. Plan view of the Jatigede dam.](image1)

![Figure 2. Cross-section A-A' of the Jatigede dam.](image2)

3. Analysis method
Dam deformation analysis was carried out with a three-dimensional model. Three dimension dam geometry was modeled based on figure 1 with some simplification in the abutment of the dam. The discretization of the dam element used Tetrahedron elements with a total of 395,000 elements. The
The engineering properties of the dam were determined by a series of primary and secondary data from the Ministry of Public Works and Public Housing as seen in table 1.

**Table 1.** Properties of dam materials.

| Zone | 1 | 2A | 2B | 3A | 3B | volcanic breccia | Grouting |
|------|---|----|----|----|----|-----------------|----------|
| Material Model | Hyperbolic | Mohr-coulomb | Mohr-coulomb |
| $\gamma$ (kN/m³) | 15 | 22 | 23 | 22 | 21.5 | 26 | 26 |
| $c$ (KPa) | 20 | 30 | 30 | 40 | 40 | 1100 | 1100 |
| $\phi$ (°) | 18 | 36 | 38 | 36 | 36 | 35 | 35 |
| $R_f$ | 0.8 | 0.83 | 0.85 | 0.74 | 0.85 | - | - |
| $K$ | 300 | 950 | 1000 | 1150 | 1200 | - | - |
| $n$ | 0.5 | 0.38 | 0.4 | 0.36 | 0.38 | - | - |
| $K_b$ | 200 | 650 | 700 | 680 | 750 | - | - |
| $m$ | 0.43 | 0.025 | -0.036 | -0.21 | -0.28 | - | - |
| $E$ (KPa) | - | - | - | - | - | $1 \times 10^6$ | $1 \times 10^6$ |
| $\nu$ | - | - | - | - | - | 0.33 | 0.33 |
| $k$ (cm/s) | $5 \times 10^6$ | $6.5 \times 10^4$ | $3.6 \times 10^3$ | 1 | 1.7 | $1 \times 10^{-4}$ | $1 \times 10^{-20}$ |

Dam fill materials were modeled using a hyperbolic model, which is a soil model that considers the non-linear behavior of the soil using the Mohr-Coulomb failure criteria [6]. The non-linear behavior of the soil was approximated by hyperbolic functions as shown in figure 3. This model was based on the stress-strain relationship in sand and clay estimated by the hyperbolic equation 1.

\[
(\sigma_1 - \sigma_3) = \frac{\varepsilon}{a + b \varepsilon}
\] (1)

With $\sigma_1$ and $\sigma_3$ are major and minor main stresses, $\varepsilon$ is a strain, and $a$ and $b$ are constants obtained from the experiment.

**Figure 3.** Stress-strain in a hyperbolic model.
The relationship between stress and strain in the hyperbolic form can be seen in figure 3. It shows that \(1/b\) is the asymptote of the value \((\sigma_1 - \sigma_3)\). The final equation of the hyperbolic model is the tangent modulus \((E_t)\) value of the curve determined by the following equation 2.

\[
E_t = \left[ 1 - \frac{R_f (1 - \sin \phi) (\sigma_1 - \sigma_3)}{2c \cos \phi + 2\sigma_3 \sin \phi} \right]^2 \cdot K Pa \left( \frac{\sigma_3}{Pa} \right)^n
\]

with:
- \(R_f\) = Ratio between \(\sigma_1 - \sigma_3\) during collapse and ultimate
- \(c\) dan \(\phi\) = Mohr-Coulomb shear strength parameters
- \(Pa\) = Atmospheric pressure as a reference
- \(K_n\) = Modulus constant
- \(n\) = Exponential coefficient

The hyperbolic model is commonly used in analyzing the deformation of the rockfill dam. The result shows that with the Duncan model, deformation analysis of the dam is close to the actual condition [7,8,9].

4. Result and discussion

The analysis was carried out to determine the displacement that occurs in dams due to the load acting on the dam. The load acts on the dam were the gravitational load due to the dam fill material and hydrostatic pressure on three water level conditions, namely the minimum water level (elevation +230 m), normal water level (elev. +260 m) and flood water level (elev. +262 m). The effect of seepage on each water level condition is also considered in the analysis. Figure 4 shows the dam deformation pattern at flood water level and table 2 shows the results of the displacement analysis of the dam in the x-direction, y-direction, and z-direction.

Figure 4. Results of displacement analysis of the dam on the flooded water level condition.
Table 2. Results of displacement analysis of dam body.

| Water level            | Displacement (m) |
|------------------------|------------------|
|                        | x-direction      | y-direction | z-direction |
| Minimum water level    | 0.27             | 0.20        | 0.81        |
| Normal water level     | 0.50             | 0.13        | 0.98        |
| Maximum water level    | 0.55             | 0.12        | 0.98        |

One factor that controls the value and direction of dam deformation is the geometry factor [10]. The upstream slope of the dam will move downward as does the downstream slope. Meanwhile, the dam body above the left and right abutments will go down following the abutment’s slope as shown in figure 5. This explains the displacement of the x-direction as shown in figure 4 was concentrated in the center of the dam.

![Figure 5](image)

**Figure 5.** The general pattern of surface movement of the dam.

Analysis results in Table 2 show that the x-direction displacement values increased when the reservoir water level increased. The displacement that occurred at the normal water level was almost twice the displacement at the minimum water level condition due to the large difference in water level that reached 30 m. The largest displacement location was on the downstream side of the dam because the dam tends to move upstream and downstream due to gravity. Hydrostatic pressure on the upstream surface of the dam increases the resisting force on the slope thereby reducing the upstream slope movement due to the opposite direction of the force. On the other hand, the hydrostatic pressure is an additional driving force on the downstream slope, causing displacement of the downstream slope to be greater than the upstream slope.

Displacement of the y-direction as shown in table 2 shows the magnitude of displacement tended to decrease when the reservoir water level increased. The direction of displacement that occurs in the dam body is caused by a movement that occurs at the top of the dam as seen in Error! Reference source not found.. In addition, the upstream and downstream slopes of the dam also experience movement due to the influence of gravity. The abutment on the upstream side had smaller displacement than the
downstream slope due to the hydrostatic pressure which added resisting force to the upstream slope which was not found on the downstream slope of the dam.

Analysis results in Table 2 show that the z-direction displacement increased when the reservoir water level increased but the increase was not significant as the x-direction displacement. In z-direction (settlement), the main factor that controls settlement was the weight of the dam itself. The largest displacement occurs at the end of the construction period due to overburden pressure. The water level of the dam still influences the displacement because the hydrostatic pressure on the surface of the dam was projected in the x and z-direction but the magnitude towards x-direction is more dominant. The deformation that occurred was still meet the allowable deformation, which is 2 m (half of the freeboard).

5. Conclusions
The analysis result shows that the reservoir water level affects the deformation of the dam body. The changes in effective stress due to seepage and hydrostatic pressure influencing dam deformation. In the case of lateral deformation, the effect of hydrostatic pressure is very large in influencing deformation. Hydrostatic pressure adds the resisting force on the upstream slope at the same time become a driving force on the downstream slope, causing greater x-direction displacement on the downstream side of the dam.

Even though the displacement increased when the reservoir water level rose, the increase that occurred was not significant. The main factor that affects settlement in the dam is overburden pressure. The results of deformation analysis at minimum, normal, and flooded water levels show that the deformation still meets the required standards.

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