Evaluating the effects of reservoir level and foundation depth on the dynamic behaviour of a rockfill dam using three-dimensional finite elements modelling

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Abstract. This paper presents a three-dimensional Dynamic analysis of a rockfill dam with different foundation depths by considering the dam connection with both the reservoir bed and water. ANSYS was used to develop the three-dimensional Finite Element (FE) model of the rockfill dam. The essential objective of this study is the discussion of the effects of different foundation depths on the Dynamic behaviour of an embanked dam. Four foundation depths were investigated. They are the dam without foundation (fixed base), and three different depths of the foundation. Taking into consideration the changing of upstream water level, the empty, minimum, and maximum water levels, the results of the three-dimensional FE modelling of the rockfill dam show that adding the water effect decreases the natural frequencies of the system, but not more than 45%. While, with the increase of the reservoir water level of the dam from minimum to maximum, the natural frequencies of the dam decreased, but not more than 13% in the case of maximum water level changes. The results show that the influence of changing the upstream water level affects the horizontal displacement of the dam more than the vertical displacement.

Keywords: Three-Dimensional Finite Element Modelling (FEM); ANSYS; Dynamic Analysis; Rockfill Dam; Dam-Reservoir-Foundation System

1. Introduction

Owing to several variables such as earthquakes, floods, water waves, and wind, a dam is constantly in harmonic motion. Dams may be categorized based on construction materials, dams classified into embanked (earth and rock-fill), masonry, and concrete dams. Globally, more than 80 percent of the total built dams in China are earth fill and rockfill dams, according to Bosshard [1]. While embankment dams make up approximately 73% of the total dams in Québec, Canada [2]. The majority of dam failures and accidents have occurred at embankment dam sites. Therefore, to increase the protection of the rockfill dams, further studies are needed.

By evaluating the seismic impact of the dam taking into consideration the interaction effect of the dam-reservoir-foundation system, the Dynamic behaviour of embanked dams can be assessed. The research is typically conducted using either one of these approaches or a combination of them; modelling of FE, field testing, or theoretical analysis. This article focuses exclusively on Dynamic analysis using FE modelling.

Watanabe [3] constructed two-dimensional and three-dimensional numerical models for a rockfill dam depending on FE to analyse the influence of the components (stress, strain, acceleration, displacement) at the bottom of the dam. Fenves and Chopra [4] subsequently simplified the technique for examining the basic vibration response generated by concrete gravity dams in two assumptions: (a) impounded water reservoir dams with rigid foundation rock; and (b) empty reservoir dams with flexible foundation rock. The dam
model was described as a single degree of freedom device, showing the versatility terms of the frequency-dependent hydroDynamic effect or foundation-rock, the maximum deformations caused by the earthquake, and the corresponding lateral forces that can be measured. In 1992, according to the diagrams provided by the vibration effect, defined by seismic coefficients, accelerations, displacements, and shear strain with time, the vibration impact on rock-filled dams was analysed by Gazetas and Dakoulas [5].

Bouaanani et al. [6] discovered a numerical method that depends on Fenves and Chopra's method of measuring the impact of the earthquake, including the hydroDynamic pressure applied by the upstream reservoir on rigid gravity dams to solve the problem of fluid-dam interaction by using closed-form formulas. The benefit of this study is that it can be dealt with in the case where the upstream reservoir is subject to gravity waves and/or ice cover.

Lotfi [7] investigated the influence of reservoir sizes on the Dynamic behaviour of concrete gravity dams, and the study estimated the natural frequencies of the concrete gravity dam and reservoir by using the “MAP-76” computer program. Mirccevska et al. [8] determined the Dynamic behaviour of the dam material by using a three-dimensional model of the rockfill dam using IZIIS software. One of the important results from this research is the comparison of the vertical and horizontal displacements of the crest by using linear and nonlinear analyses (direct integration method). Dynamic analysis using two-dimensional and three-dimensional models of embanked dams in ANSYS was performed by Jafari and Davoodi [9]. On the basis of situ Dynamic measurements, the soil properties were determined. The effects on the modal parameters by the depth of water, abutments, and foundation depth were investigated. The dam-foundation rock interaction was also considered. Proulx et al. studied the influence of changing the reservoir water levels on the Dynamic Response of the Émosson dam in Switzerland throughout the year (1998). Four forced-vibration tests carried out on the dam were conducted with different reservoir water levels. The Dynamic response was evaluated of the dam-reservoir-foundation system for different water levels empty, two other intermediate and full reservoir water levels). This study shows that the resonant frequencies increased with the increase of the reservoir water level [10]. While Calcina et al. [11] determined vibration properties of an arch dam depending on experimental (ambient vibration tests) and numerical (Three-dimensional finite element model) methods with two reservoir water levels. The natural frequencies of vibration of the dam were calculated by using the Spectral Ratio method. The changes of natural frequencies and mode shapes linked to water level with the experimental results.

**The main objective of this paper is to provide an assessment for the selected rockfill dam**. The results of two dimensional and three-dimensional numerical models of the dam body was compared with the forced vibration test results.

2. Dam's description

The Temenggor rockfill dam is located in the narrow valley of Sungai Perak, in Gerik, Perak, Malaysia, about 200 km northeast of Ipoh. The three-dimensional evaluation of the dam's behaviour affected by Dynamic forces is crucial. Table 1 and Figures 1, 2, and 3 show the important information pertaining to the Temenggor rockfill dam, which is crucial towards the construction of a three-dimensional finite element model. This information has been obtained from the dam's site visit. All other information related to this dam can be found in the link mentioned in Table 1.

| Table 1. Dimensions of Temenggor Dam [https://en.wikipedia.org/wiki/Temenggor_Dam]. |
|----------------------------------------|--------|
| **Dimension**                          | **Unit (m)** |
| Min. U/S.W.L (ASL)                     | 236.5   |
| Max. U/S.W.L (ASL)                     | 248.42  |
| Crest width                            | 18      |
| Crest length                           | 258     |
Height 127
D/S.W.L (ASL) 142

Figure 1. Top view and location of Temenggor rockfill dam.

Figure 2. Temenggor rockfill dam.
Figure 3. Temenggor dam-reservoir-foundation system model.

3. Three-dimensional dam modelling
The methodological approach through a flowchart is shown in Figure 4 below.

![Flow Chart of the Proposed Methodology](image)

According to the shape of the Temenggor rockfill dam, its three-dimensional form has a linear appearance and behaviour. Four cases were used for foundation modelling, where the first model is a fixed base without the foundation. The second, third, and fourth models of depths 23 m, 50 m, and 123 m,
respectively, were constructed with the homogeneous foundation assumption similar to that used by Abed M S and Azzubaidi R Z [12]. Figures 5 and 6 outlines the three dimensional FE model of the Temenggor rockfill dam with a fixed base is empty and full reservoirs cases respectively. Figure 7 shows the three-dimensional FE model of the dam with a rock-bed foundation (d = 123 m).

The tetrahedron mesh was used because of the complexity of the computational domain, whereas the computational domain of the Temenggor dam model includes a foundation, upstream reservoir, and the left and right embankments.

**Figure 5.** Three-dimensional FE model of the Temenggor rockfill dam with fixed base & empty reservoirs.

**Figure 6.** Three-dimensional FE model of the Temenggor dam with a fixed base and full reservoir.
In this work, the mode shape and the natural frequency of Temenggor rock-fill dams were evaluated using four cases of foundation with three depths of upstream water levels (empty, minimum, and maximum) have been considered for this analysis as follows:

1. Fixed base of the dam and three depths of upstream water levels.
2. Rock-bed foundation (d = 23 m) for the dam and three depths of upstream water levels.
3. Rock-bed foundation (d = 50 m) for the dam and three depths of upstream water levels.
4. Rock-bed foundation (d = 123 m) for the dam and three depths of upstream water levels.

The model formulation is presented and the approach is implemented in ANSYS by linking the static structural component with the model component. The self-weight of the dam-foundation-reservoir system affected by the hydrostatic pressure were taken into consideration. The technique applied and the results for this dam compared to the related corresponding results.

4. Dynamic analysis

Using ANSYS, the three-dimensional model was generated to measure the natural frequency and mode form of the dam-reservoir-foundation structure, taking into account the empty case, with the shift of water levels from minimum to maximum upstream reservoir level. The soil and water properties of the dam-foundation have been taken from Ali A et al. [13] as listed in Table 2.

| Table 2. The physical properties of the dam-reservoir-foundation system materials [13]. |
|---------------------------------------------------------------|
| **Property** | **Unit** | **Water** | **Soil 1** | **Soil 2** | **Soil 3** |
|----------------|-----------|------------|------------|------------|------------|
| Poisson’s Ratio | -         | 0.49       | 0.3        | 0.3        | 0.3        |
| Mass density   | kg/m³     | 1000       | 2100       | 2400       | 2700       |
| Modulus of Elasticity for soils and water | GPa | 2.07 | 12.5 | 25 | 50 |

5. Results and discussion

The natural frequencies of the first four modes of the three-dimensional FE models in empty, maximum and minimum upstream water levels are presented in Table 3.

| Table 3. Natural frequencies of different models (Hz). |
|---------------------------------------------------------------|
| **Mode** | **Fixed base** | **Foundation / Bed rock level** |
|----------|----------------|---------------------------------|
| d = 0 m  |                | d = 23 m       | d = 50 m    | d = 123 m  |
The results in the empty condition show that the natural frequency of the first mode decreases from 3.481 Hz to 3.079 Hz as the depth of the foundation increases. These observations are also true for modes 2, 3, and 4. The trends in the decrease of the natural frequencies are to be expected due to the increase of the total mass of the dam-foundation-reservoir system. Similarly, the decrease in natural frequencies is apparent for all the modes for changes in upstream water levels (from empty to maximum). However, the changes in natural frequencies for all modes are insignificant for minimum and maximum upstream water levels cases with increases in depth of foundations. This observation is probably due to the mass of water are much larger than the foundation and quite significant for all 4 depths of foundation cases. The three-dimensional mode shapes of the dam with a rock-bed of 123 m and empty reservoir are presented in Figure 8. This range of frequency is similar to that obtained by Vahid Lotfi [7] and Jean Proulx et al [10].

|         | 1   | 2   | 3   | 4   |
|---------|-----|-----|-----|-----|
| Empty   | 3.418 | 3.267 | 3.173 | 3.079 |
| Min.    | 2.097 | 2.102 | 2.093 | 2.085 |
| Max.    | 2.200 | 2.289 | 2.279 | 2.270 |
|         | 3.555 | 3.417 | 3.348 | 3.282 |
|         | 2.200 | 2.289 | 2.279 | 2.270 |
|         | 3.830 | 3.651 | 3.538 | 3.411 |
|         | 2.446 | 2.440 | 2.434 | 2.428 |
|         | 2.528 | 2.531 | 2.527 | 2.523 |
|         | 1.884 | 1.884 | 1.880 | 1.875 |
|         | 2.030 | 2.030 | 2.087 | 2.078 |
|         | 2.236 | 2.236 | 2.225 | 2.219 |
|         | 2.343 | 2.343 | 2.342 | 2.341 |
Figure 8. The first four mode shapes of the Temenggor dam with 123 m rock-bed and empty reservoir.

The calculation for the components of the displacements at the midpoint of the crest of the dam was done by taking into consideration the gravity weight and the hydrostatic pressure and defining the water-solid interface. This is done to find the effect of changing upstream water levels and foundation depths of the deformed shape of the dam. Figure 9 outlines the positive displacement directions at the midpoint of the crest of the dam.
Figure 9. Temenggor dam body showing midpoint of the top crest with the positive direction of displacements.

Figures 10 and 11 show the horizontal and vertical displacements, respectively at the midpoint of the top crest of the dam for all cases of study. The horizontal displacements increase about 0.5 mm from empty condition to minimum water level for both rock bed levels 50 m and 123 m. While the vertical displacements increase with the depths of the foundation, it remains almost constant for different upstream water levels, because the hydrostatic pressure affects the dam in the direction of flow (horizontal direction).

Table 4 shows the increment percentage between the full and empty cases in horizontal and vertical displacement in the midpoint of the crest of the dam. The displacement results show similar results to those obtained by Violeta J. et. al. [15].
Figure 10. Horizontal displacement at the midpoint of the crest of the dam.  

Figure 11. Vertical displacement at the midpoint of the crest of the dam.

Table 4. The increment percentage between the full and empty cases in the midpoint of the crest

| displacement | The increment percentage | Fixed base | Foundation / Bed rock level |
|--------------|--------------------------|------------|-----------------------------|
|              |                          | d = 0 m    | d = 23 m                   | d = 50 m | d = 123 m |
| horizontal   | %                        | 79         | 38                         | 356      | 102       |
| vertical     | %                        | 2          | 11.5                       | 2        | 1.5       |

6. Conclusion
A study on the Temenggor rockfill dam in Malaysia including analysing using a three-dimensional numerical model was performed successfully. Based on the FE model results, the following conclusions can be derived:
1. Including the water effect to the model of the dam-foundation-reservoir system increases the mass, which in turn decreases the natural frequencies of the system, but not more than 45%.
2. By changing the water level upstream of the dam from minimum to maximum, the natural frequencies of the dam decreased, but not more than 13% in the case of maximum water level changes.
3. By increasing the water level from minimum to maximum, the increase of horizontal displacement at the midpoint of the crest of the dam range from 0% to 49% and in vertical displacement from 1.4% to 3.2%.
4. The increase in foundation depth leads to decreases in the natural frequencies.
5. When the upstream water level increased to the maximum level and the foundation depth equal to the Temenggor dams’ height, the mass of the dam-reservoir-foundation system increased which lead to a decrease in the natural frequencies of the system.

Acronyms and Abbreviations

3-D: Three dimensional.
ASL: Above sea level.
d: Depth
D/S.W.L: Downstream water level
FE: Finite Element
FEM: Finite Element Modelling
GPa: Giga Pascale
Hz: Hertz
Kg: Kilogram
km: Kilometer.
M: Meter
Max.: Maximum
Min.: Minimum
U/S.W.L: Upstream water level
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