Numerical modelling of dynamic stability of RCC dam

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Abstract. Stability and stress analyses are the most important elements that require rigorous consideration in design of a dam structure. In the current research, dynamic structural stability of a roller-compacted-concrete (RCC) dam was performed. The RCC dam was modeled using the finite element method to investigate the stability against sliding and the structural stability of the body of the dam. The commercially available finite element software (SAP 2000) was used to analyze stresses in the body of the dam and foundation. A linear finite element dynamic analysis was performed. Response spectrum and time history methods were used with different earthquake loads. The response spectrum of the 1995 Aqaba earthquake and a representative elastic-spectrum with smooth plateau for both Operating Basis Earthquake (OBE) and Maximum Credible Earthquake (MCE) were used in this study. The analysis was carried out assuming that no slip will occur at the interface between the dam and the foundation. The greatest tension was found to develop in the rock adjacent to the toe of the upstream slope. The factor of safety against sliding along the entire base of the dam was found to be greater than 1 ($FS > 1$), for both loading conditions.

1 Introduction

To help meet the irrigation needs of suburban parts of Amman, Jordan, a hybrid dam was built in the Mujib Canyon area, which is located about 60 km south of Amman. The dam (Mujib Dam) is owned and operated by the Jordan Valley Authority. The Mujib Dam was designed as a central Roller-Compacted-Concrete (RCC) gravity dam with adjacent earth fill dams at the valley flanks. Its maximum height reaches approximately 47 m and the total volume of the RCC structure is 720,000 m³ [1].

The dam is located in the Wadi Al Mujib, between Madaba and Al Karak. The drainage path of Al Mujib is toward the Dead Sea. The dam is a composite structure, consisting of an RCC middle section and clay core rock fill (CCR) sections at both abutments. The water intake consists of draw-off works with intakes at three levels. The reservoir will be mainly used for irrigation purposes. The catchment area is 4380 km² and the reservoir capacity is 35x10⁶ m³. The maximum height above the foundation is 67 m and the spillway is free

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overflow with stepped chute [1]. The geometric configuration of the dam is shown in Figure 1.

Fig. 1. Geometric Configuration of Mujib Dam.

2 Material properties

The properties of the material for both the dam and its foundation are shown in Table 1 [2]. Based on a comprehensive and extensive geotechnical exploration, the dam/foundation interface was characterized by strength parameters as presented in Table 2 [2]. The analyses carried out for this study used the properties and parameters listed in Tables 1 and 2.

Table 1. Properties of the dam and foundation material [2].

Condition	Material	Modulus of elasticity, E (GPa)	Poisson's ratio, ν	Unit weight (kN/m ³)	Tensile strength (MPa)	Compressive strength (MPa)
Static	Dam material	15	0.2	24	1.05	14.6
	Foundation	12	0.2	28		22
Dynamic	Dam material	19.5	0.2	24	1.58	19
	Foundation (Naur Limestone)	16.8	0.2	28		22

Table 2. Parameters of foundation [2].

Rock location	Rock formation	Friction angle (θ)	Cohesion (c)	Compression strength
Dam/foundation interface	Naure limestone	47°	425 kPa	22 MPa

3 Finite element modelling

The stress analysis was performed to accurately characterize the distribution of stresses within the dam body under dynamic loading conditions. The commercially available Finite Element Modelling (FEM) program (SAP2000) was used in the analysis [3].

3.1 Structural idealization

The dam was modeled using 2-D plain strain isoperimetric elements. Two types of elements were used: the 4-noded isoperimetric plain strain elements with 2 Degree-of-Freedom (DOF) per node, and the 3-noded Constant Strain Triangular Elements (CSTE) with 2 DOF per node. The finite element mesh of the dam cross section was developed through a mesh generation code, which was written by the authors in Fortran. The FEM analysis was performed based on the following assumptions: (i) plain strain linear elastic behavior, (ii) simplified soil-structure interaction entailing massless elastic foundation, and (iii) a uniform and homogeneous foundation. The boundaries of the foundation were fixed against translation and rotation movements. In addition, all out of plane DOFs were restrained for all nodes. A cross-section indicating a typical mesh refinement with the boundaries is shown in Figure 2.

Fig. 2. Mesh and boundaries of the foundation.

4 Seismicity

The dam site is located in latitude 32.7 N and longitude 35.822, which is about 26 km to the boundary between the Arabian and African–Sinai tectonic plates. The primary seismic sources contributing to the hazard at the dam site is the active Jordan Valley fault which extends from the dead sea of Galilee with an expected earthquake magnitude of $M=7.5$ and greater.

5 Design criteria

According to the International Commission on Large Dams, 1989 (ICOLD) [4], the operating basis earthquake (OBE) should have a 50 % probability of non-exceeding in a 100 years lifetime of structures. For the dam, this represents a return period of 145 years, and a design acceleration of 0.13 g.

The Maximum Design Earthquake (MDE) is expected to produce the maximum level of ground motion according to which the dam should be designed or analyzed. The MDE or the Maximum Credible Earthquake (MCE) will be represented by the earthquake that is determined by using the probabilistic procedures with a 50 % or higher probability of not being exceeded in a large number of years. During such seismic activity, the water retention capacity of the dam should be safely maintained. The ICOLD guidelines do not define the "large number", whereas the United Kingdom (UK) guide, which is largely based on the ICOLD principles, assigns various return periods for the safety evaluation earthquake (SEE) according to dam category or risk class. The SEE is defined as the earthquake which produces

the most severe level of ground motion under which the safety of the dam should be insured. The SEE is equivalent to MDE at the design stage, dependent on the dam category, and may be based on a return period. Thus, the peak ground acceleration for OBE and MCE selected for this study were 0.13 g and 0.28 g, respectively.

6 Earthquake load

The seismic loading was represented as response spectra for the OBE at 0.2 PGA and the MCE at 0.5 PGA (Peak Ground Acceleration). A response spectrum is a plot of the peak response of a single DOF system to an earthquake motion against the natural period of oscillation for that system at a given level of damping. The transverse component acceleration time history recorded at Aqaba Hotel Station of the 1995 Aqaba Earthquake was used in this study, as shown in Figure 3. This earthquake record was used to generate response spectra for OBE and MCE loading. The seismic loading was applied in the horizontal direction only.

Fig. 3. The Transvers Component Acceleration Time History at Aqaba Hotel Station of the1995 Aqaba Earthquake (Ref 2).

7 Results of analysis and discussion

Frequency analysis was performed to find the significant modes. The results of this analysis are summarized in Table 3. In addition, Figure 4 illustrates the first 4 significant modes.

Table 3. Summary of first 5 vibration modes.

Mode	Frequency (Hz)	Period (sec)
1	0,23944	4,176412
2	0,14537	6,878998
3	0,10488	9,639485
4	0,10374	9,63948
5	0,09628	10,38637

Fig. 4. Signifiant Modes (a) Mode (1), (b) Mode (2), (c) Mode (3) and (d) Mode (4).

Response-spectrum and time-history methods were used with different earthquake loads to perform the dynamic analysis. The dynamic analysis includes the estimation of the principal and shear stresses along the base of the dam for both OBE and MCE cases in addition to calculation of factor of safety for principal stresses and shear stresses for both OBE and MCE cases. The results of the stress analysis of dynamic loading for Maximum Principal Stresses (S11) and shear stresses along the base of the dam for both OBE at 10 % damping ratio and MCE cases are shown in Figures 5 to7, respectively. Using Eq.1 and the normal stresses calculated from the dynamics analysis, the factor of safety against sliding was calculated for both cases OBE and MCE. Figures 8 and 9 show the variation in factor of safety. As shown in Figures 8 and 9, the factor of safety against sliding for both OBE and MCE cases was found to exceed 1 along the base of the dam. Also, it was found that the dynamic tensile strength (1.58 MPa) and dynamic compressive strength (19 MPa) of the dam material were not exceeded at any section along the base of the dam. Therefore, the design satisfies the “fail safe” criterion for stability of an RCC dam (i.e., the FS against sliding is greater than 1 for all load conditions). [5].

Sliding or shear failure is the most common failure for dams constructed on rocks [6]. Factor of safety against sliding was calculated as the ratio of the shear strength of the rock determined from Mohr-Coulomb criterion and the applied shear stress along the base of the dam at each node. The shear strength of rock is given by Eq.1.

$$\tau_f = c' + \sigma_n' \tan \phi'$$

(1)

Where:

- τ_f is the shear strength of foundation
- c' and ϕ' are the shear strength parameters of the foundation
- σ_n' is the effective normal stress along the base of the dam.

Fig. 5. Max principal stresses for massless foundation OBE, 10% damping ratio.

Fig. 6. Maximum principal stresses (MCE)

Fig. 7. Shear stresses for massless foundation (OBE), 10% damping ratio

Fig. 8. Factor of safety for horizontal shear stresses (dynamic loads OBE)

Fig. 9. Factor of safety for horizontal shear stresses, dynamic loading (MCE)

8 Conclusion

The stability of the Mujib Dam against sliding and under dynamic loading conditions was evaluated through 2D-FEM analyses. The calculated stress levels were compared with the strength of RCC and rock foundation. Also, the factor of safety against sliding was analyzed. The analyses indicated that under all loading conditions, the factor of safety along the base of the dam was greater than 1.0.

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