Numerical Modeling of Sliding 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. Stability of dams against sliding is crucial due to the substantial horizontal load that requires sufficient and safe resistance to develop by mobilization of adequate shearing forces along the base of the dam foundation. In the current research, the static sliding stability of a roller-compacted-concrete (RCC) dam was modelled using finite element method to investigate the stability against sliding. A commercially available finite element software (SAP 2000) was used to analyze stresses in the body of the dam and foundation. A linear finite element static analysis was performed in which a linear plane strain isoperimetric four node elements was used for modelling the dam-foundation system. The analysis was carried out assuming that no slip will occur at the interface between the dam and the foundation. Usual static loading condition was applied for the static analysis. 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 static loading conditions.

1. Introduction
In the Mujib Canyon, some 60 km south of Amman, Jordan, a hybrid dam was constructed. The dam (Mujib Dam) is owned by the Jordan Valley Authority and 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 south of Jordan in the Wadi Al Mujib, south of Madaba and north of Al Karak as shown in Figure 1. The Al Mujib drains toward the Dead Sea. The dam is a composite dam, consisting of a 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 overflow with stepped chute [1]. The geometric configuration of the dam is shown in Figure 2.
2. Material properties
The properties of the dam material as well as those of the foundation material are shown in Table 1. [2].
Also, based on a comprehensive and extensive geotechnical exploration, the dam/foundation interface was characterized by the strength parameters presented in Table 2. [2]. The analyses carried out for this study used the properties and parameters listed in Tables 1 and 2.

| Condition | Material          | Modulus of elasticity, $E$ (GPa) | Poisson's ratio, $ν$ | Unit weight ($kN/m^2$) | Tensile strength ($kN/m^2$) | Compressive strength (MPa) |
|-----------|-------------------|----------------------------------|----------------------|-------------------------|-----------------------------|-----------------------------|
| Static    | Dam material      | 15                               | 0.2                  | 24                      | 1.05                        | 14.6                        |
|           | Foundation        | 12                               | 0.2                  | 28                      | 22                          |                             |

| Rock location           | Rack formation   | Friction angle ($φ$) | Cohesion (c) | Compression strength |
|-------------------------|------------------|----------------------|--------------|----------------------|
| Dam/foundation interface| Naure limestone | $47^°$               | 425 kpa      | 22 kPa               |

3. Finite element modelling
The stress analysis was performed to obtain accurately characterize the distribution of stresses within the dam body under static loading conditions. The commercially available FEM program (SAP200) was used in the analysis [3].

4. Structural idealizations
The dam was modelled using 2-D plain strain isoperimetric elements. Two types of elements were used; the 4-noded isoperimetric plain strain elements with 2 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 mesh generation code, which was written by the authors in Fortran-Lahey77 Programming Language, in order to control the dimensions of the dam cross section.
and to carry out a mesh refinement. The FE 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 movement. In addition, all out of plane DOFs were restrained for all nodes. A typical mesh refinement and boundaries of the dam cross section are shown in Figure 3.

**Figure 3.** Mesh and boundaries of the foundation.

5. Static loading components

Static loading components comprises of: a) self-weight of the dam, b) hydrostatic uplift pressure: uplift at the concrete/rock interface assumed to vary as a straight line from full headwater pressure at the heel to 0 water pressure at the toe, over 100% of the base area, and put these values at the node in the finite element model to get the nodal uplift forces, c) hydrostatic pressure: a linear distribution of the static water pressure acting normal to the surface of the dam was applied varies from 0 at the water face to \((W \times h)\) at the dam base, then the values of hydrostatic nodal force were calculated and used in the analysis, and d) silt pressure: weight of accumulated silt resting up to 10 m on the upstream face

6. Results of analysis and discussion

The definition of dam failure usually refers to partial collapse or movement of a dam or its foundation that hinders the water-retaining ability of the dam [4]. Sliding or shear failure is the most common failure for dams constructed on rock [5]. Sliding occurs when the horizontal forces exceed the frictional resistance. Sliding can be divided into three different kinds of failures; failure in the interface between concrete and foundation, failure in weak planes of the foundation, such as cracks, and failure in the solid foundation [6]. In this present research the potential failure along the interface plane was investigated for the Mujib Dam. The results of stress analysis of static loading for Maximum Stress (S11), normal stresses in x and y direction and shear stress along the base of the dam are shown in Figures 4 to 6, respectively. It was found that the maximum tensile stress (0.9 MPa) is developed in the rock adjacent to the toe of the slope. All calculated stresses were found to be within the compressive strength (22 MPa) and tensile strength (2 MPa) of the foundation rock and the compressive capacity of the RCC (14.6 MPa).

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 at the along the base of the dam at each nodes. The shear strength of rock is given by equation (1).

\[
\tau_f = c' + \sigma_n' \tan \phi'
\]

Where:
- \(\tau_f\) is the shear strength of foundation
- \(c'\) and \(\phi'\) are the shear strength parameters of the foundation
- \(\sigma_n'\) is the effective normal stress along the base of the dam.

The factor of safety against sliding is given by equation (2).

\[
FS(\text{Sliding}) = \frac{\tau_f}{\sigma_n'}
\]
Where:

$S_{12}$ is the applied shear stress along the base of the dam.

**Figure 4.** Envelope maximum stresses ($S_{11}$) (Static Loads Condition)

**Figure 5.** Normal stresses in X-Direction across the base of the dam (Static Load).

**Figure 6.** Shear stresses across base of the dam (Static Loads).

Using the cohesion of rock as 0.425 MPa and angle of internal friction as 47° the FS against sliding can be calculated using equation (2). The results of FS are shown in Figure 7. As shown in the figure the FS is above 1 at all nodes along the base of the dam. Most design criteria require a minimum FS against sliding of 2 to 4, based on normal high headwater and low tailwater conditions. This can drop to 1.5 to 2 under flood conditions, and typically is defined as greater than 1 for seismic loads. Although it is not considered by most codes and authorities, a true “fail safe” criterion for stability of an RCC dam is that the FS against sliding is greater than 1 for all load conditions [7].
7. Conclusion
The stability of Mujib dam against sliding was carried out using 2D-FEM. The calculated stress levels were compared with the strength of RCC and rock foundation. Also, the factor of safety against sliding was analysed and it was found that under static loading conditions, all values of FS along the base of the dam exceeded 1.

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Figure 7. Factor of safety for horizontal shear stresses, Static Loads.