FDM analysis of earth dams – end of construction and water seepage (case study: Ivshan Iran dam)

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Abstract. In this research, the Ivshan earth dam was modeled with the finite difference method (FDM) for staged construction and water seepage. A maximum settlement was 100 cm in the numerical model when construction was complete, and it occurred in the middle of the dam's height. Also, the FDM results showed consistency with field observations of the deformation instrument (inclinometer). After the reservoir's initial filling, the pore water pressure ratio changes were investigated for the dam's central axis. The results of the numerical model show relative stability in terms of pore water pressure ratio. The arching ratio is also obtained in the dam's central axis for both construction and initial filling. The lowest values of the arching ratio in the central axis of the core at the end of construction and initial filling are 0.81 and 0.80, respectively, which occurred at the height of about 41 meters and about two thirds of the height of the dam embankment. Finally, the Factor of Safety of the dam at the end of construction and initial dewatering was investigated, and the results showed the stability of the earth dam.

1. Introduction
The increasing need for the water industry, agriculture, drinking, and economical water conservation method is to construct the dam. Safety of earth dams is subject to the appropriate design, construction, and monitoring of actual behavior during the dam's construction and operation. Their role in the country's economic and construction development is undeniable. Hence, determining the expected performance evaluation of dams is critical for decision-makers.

Behavioral review and long-term dams monitoring are of particular importance. Many dams are located in the upper reaches of villages or densely populated cities, whose lack of safety will lead to irreparable dangers and losses. Considering this issue's importance, a more comprehensive study is needed to examine and predict the earth dam's behavior [1]. Behavioral history can also be an experience in designing other dams in the future [2-7].

Operation of dams needs changes in water level, which change the Factor of safety due to sliding the upstream slope of earth dams. When the reservoir level is high, hydrostatic pressures assist slope stability. The increase and decrease in water level have two effects: an increase and decrease in stabilizing external hydrostatic pressure and a change of the internal pore water pressures [8]. Considerable seepage pressure inside the dam's body resulting from the rapid increase of upstream water level may decrease downstream slope stability. The earth dam's saturation can be due to either the highwater level in upstream or seepage on the downstream slope. When drawdown occurs, soil stability's
critical conditions may threaten the upstream slope of the dam [9]. In brief, the above discussion demonstrates the importance of the dam's stability in different conditions.

2. Reference case
Ivshan earth dam lies at 1.5 km upper reaches of the Ivshan village in Golestan, Iran, and is about 57 km from Khorramabad. It is located on the Harod River and in the geographical coordinates of 48º 49' E and 33º 28' N (As shown in figure 1). This dam is a clay-core Earth Rockfill dam. The dam crown's length and width are 529 and 8 meters, respectively, and its height is 64 meters above the riverbed (stream). The maximum width of the dam's body at the river level is 240 meters. On both sides, the core slope is 2:1 while its maximum and minimum widths are 29 and 4 meters, respectively, at the height of 64 meters above the riverbed. The filter layers and the transitional areas (each 2-meters wide) are located on the core's sides [10].

![Figure 1. Location of Ivshan dam in the province and country scales.](image)

3. Numerical simulation
Various types of numerical methods, including the finite element method (FEM), finite difference method (FDM), and distinct element method (DEM) have been used by researchers to model the fluid flow in soil masses and rockfill dams. In hydrogeology, fluid flow is usually stimulated by the finite element method and finite difference method.

In this study, FLAC²D, a two-dimensional explicit finite difference code, was used for simulations. The FLAC²D is advantageous because the Lagrangian calculation program and the mixed-discretization zoning approach used in FLAC assure that plastic collapse and flow are modeled precisely. Also, since no matrices are formed, large two-dimensional calculations can be made without excessive memory [11].

The modeling strategy used in this paper is:

- Creating the geometric model of the dam and applying behavioral model and properties of materials
- Applying the boundary conditions and relevant forces
- Mesh generating
- Running
3.1. Modeling geometry and input data

The maximum width of the dam's body is 240 meters. The length, width and height of the Dam's Crest are 529, 8 and 64 meters, respectively [10]. Figure 2 illustrates the geometry and different parts of the earth dam.

![Figure 2. The geometry and different parts of the earth dam with specific dimensions.](image)

One of the essential issues in slope stability analysis is the consideration of drained or undrained conditions of materials. In analyzes with drained conditions, drained resistances related to effective stresses are used; however, in the analysis of undrained conditions, undrained resistances with total stresses are applied. This condition applies only to the clay core, and other materials are examined in the drained state due to high permeability.

The geotechnical parameters of materials play a significant role in the stability of the earth dams. Thus, the geotechnical parameters obtained from Back Analysis were used (to determine the actual parameters of the materials used when the dam was being constructed). Table 1 shows the properties of materials used in different parts of the dam as determined by lab tests. The water bulk modulus considered with a back analysis of pore water pressure equal 20 MPa.

| Property                  | Unit weight (kN/m³) | Young's modulus (MPa) | Cohesion (kPa) | Poisson's ratio | Internal friction angle (°) | Dilation angle (°) | Permeability (cm/s) | Porosity (%) |
|---------------------------|---------------------|-----------------------|----------------|-----------------|-----------------------------|-------------------|---------------------|--------------|
| Shell (sand)              | 21                  | 43                    | 0              | 0.3             | 43                          | 6                 | 1×10⁻¹            | 30           |
| Core (clay)               | 17                  | 15                    | 20             | 0.37            | 18                          | 0                 | 1×10⁻⁷            | 37           |
| Foundation (rock)         | 22                  | 2000                  | 3000           | 0.23            | 27                          | 7                 | 1×10⁻¹¹           | 25           |
| Filter and a transitional region | 20.5              | 30                    | 0              | 0.33            | 25                          | 6                 | 1×10⁻³            | 35           |

The materials used in the Ivshan earth dam follow the Perfect Elastic-Plastic behavioral model in compliance with Mohr-Coulomb Failure Criterion (MC), the most well-known behavioral model and criterion for failure in soil materials.

3.2. Boundary conditions

In the initial stage with applying the in-situ and boundary conditions to the foundation, the Ininv-Fish code was used to create pore water pressure and initial total stress distribution. This Fish code is available in the FLAC software manual and plays no role other than facilitating the initial in situ stress
and groundwater conditions to the numerical model. According to the Terzaghi Equation \( k_0 = \frac{v}{1-\phi} \), the ratio of the effective horizontal stress to the effective vertical stress is 0.3 in the distribution of the foundation's initial stress. The groundwater level was considered to be on the foundation surface due to the river's presence in the upper reaches of the foundation. Vertical displacements in the lateral boundaries were allowed for the foundation, while horizontal and vertical displacements were restricted into account for the bottom boundaries. The following measures were taken in applying the initial and drainage boundary conditions to the dam's body. Using the Apply pp (pore pressure) sub-command, it was possible to increase the water level and initial filling of the reservoir up to 57 meters. The degree of saturation and pore pressure in the foundation and the upstream slope was considered 'fixed' due to the constant proximity to water. Finally, the hydrostatic pressure of the water on the upstream shell and foundation of the dam in boundary conditions was taken into account by using Apply Pressure command. The applied linear pressure equaled the weight of water standing 57 meters from the dam bed to the height of the upstream shell, while the hydrostatic pressure was set at zero at the height of 57 meters.

This research follows normal hydro-mechanical studies and carries out hydraulic and mechanical analyses simultaneously. Up until this stage, numerical modeling of the earth dam was made and the initial filling was done. The main goal of this study is to investigate the rapid drawdown of water trapped behind the upstream of the dam at a very high rate (the most critical condition).

### 3.3. Mesh generating

Ivshan Dam was modeled with FLAC\(^2\text{D}\) software, using a quad mesh net and a total dimension of 335x104 meters. From 75 vertical Finite Difference zone rows, 10 zone rows with a depth of 40 meters were used in modeling the dam foundation and the remaining 65 zone rows with a height of 64 meters were used in the modeling body. 65 zone rows were selected since the shape of the zones in the earth dam approaches the shape of a square and in order to avoid the rectangular zones with great length and low width, thus ensuring high quality for the zones. It should be noted that if the length/width ratio exceeds a certain value, the constructed zones may have inappropriate geometry and analysis software shows Bad Zone Geometry error. Also, since the zones are more concentrated in the upper sections of the dam body and thus may increase the chance of creating zones with geometrically inappropriate shapes, the ratio sub-command was used to gradually reduce the vertical distance of finite-difference zones for the upper sections of the dam body. According to the design provided by the consulting engineer's company, the width of the crest of the dam was determined 8 meters. The foundation was wholly constructed in one stage; then, the velocity and displacements in the main directions were set zero so that layers of the earth dam's body could be added to the model. First, the body of the dam was constructed in 15 layers, each with an approximate height of 4.2 meters, so that the staged construction of the dam body and the actual stability of the model could be achieved. The entire dam was also constructed in one stage to be compared against the staged construction method for displacements. Figure 3 shows the mesh network and the water height of the dam upstream.

![Figure 3. The mesh network and the water table of the dam.](image-url)
In the following, a summary of the results of numerical modeling and deformation instrumental field observations (inclinometer) of the earth dam is presented; in four subcategories of displacements, safety factor, arching ratio, and pore water pressure.

4.1. Earth dam displacements

Figures 4 to 7 show the dam’s vertical displacement (subsidence) contours at the end of construction, initial filling of the reservoir. Comparing the subsidence values for staged and non-staged construction of the dam body (figures 4 and 5), it is found that in the case of staged construction, the maximum downward subsidence of the dam occurs in the middle of the dam’s height that is in accordance with instrumental field observations. In contrast, in the non-staged construction, maximum subsidence occurs at the dam’s crest that does not correspond to field observations. Concerning the subsidence contours in figure 6, once the reservoir is initially filled and water begins to infuse the core, increased pore water pressure and decreases effective stresses result in swelling of the middle and lower parts of the dam body and, over time, the subsidence dominates the swelling as the excess pore water pressure wears away. The maximum subsidence measured in Ivshan Dam at the end of the construction and initial filling are 100 and 90 cm, approximately 1.5% and 1.4% of the dam height and at altitudes of 46 and 45 meters, respectively. Considering that the maximum subsidence range is 3% of the dam height, the subsidence values for Ivshan Dam fall within the acceptable range.

Figure 4. Vertical displacement contour at the end of construction (staged construction).

Figure 5. Vertical displacement contour at the end of construction (non-staged construction).

Figure 6. Vertical displacement contour at the initial filling of the reservoir.

Figure 7 shows settlement results of numerical modeling and instrumentation data at the end of construction. According to figure 7, the maximum subsidence recorded by instrumentation for dam core is 97 cm, indicating the accuracy of the settlement values predicted in the numerical modeling of the FLAC.
Figure 7. Dam’s vertical displacement at the end of the construction, results of FLAC modeling, and instrumentation data (inclinometer).

Figures 8, 9 show horizontal displacement contours at the end of construction, initial filling of the reservoir. Concerning figure 8, the dam core's horizontal displacement is not noticeable at the end of the construction while the upstream and downstream shells display upward and downward horizontal displacements, respectively; this indicates that the dam is inclined to opening. The maximum value of the dam’s horizontal displacement at the end of the construction is also 100 cm in the downstream shell that is very small compared to the dam height with 64 meters. As the horizontal displacement contours indicate (figure 9), the horizontal displacement of the core is increased toward the crest after filling. The maximum horizontal displacement is 125 cm and is observed approximately at 23 meters height of the dam body. Small horizontal displacement indicates the stability and safety of the dam.

Figure 8. Horizontal displacement contour at the end of construction.
4.2. Factor of safety

The static stability of an earth dam means maintaining balance and preventing the movement of the components of an earth dam against static forces. In other words, an earth dam is in equilibrium or stable when the result of the applied stresses in each part of the dam is less than the resistance mobilized in that part. Therefore, it is observed that the stability of the earth dam is a relative issue and depending on the relative change in the values of destructive forces and resistive forces, there can be different degrees of stability.

Figure 10 shows the Ivshan earth dam's safety factor in the initial filling of the reservoir obtained using numerical modeling based on the strength reduction created in the material. As shown in Figure 10, the safety factor obtained with the cohesion and internal friction reduction is equal to 1.19 and is a small value at the initial filling of the reservoir. Suppose the shear strain increment downstream of the dam is considered in the figure. In that case, it can be seen that the shear strain increment in this area covers a very small part of the body and therefore, it can be said that the obtained Factor of safety is local and cannot affect the stability of the entire dam.

![Figure 10. The Factor of safety contour based on the strength reduction method at the initial filling of the reservoir.](image)

4.3. Arcing ratio

It is possible for earth dams constructed of heterogeneous materials to settle more (due to the embankment's weight) than the dam's hard shell, which transfers most of the core to the shell next to it. This means that in the neighbouring shell, the vertical stress of the core would be less than that of the overhead. This weight transfer is known as the arcing phenomenon from the dam to the shell. The arcing ratio of Equation 1 is:

\[
AR = \frac{\sigma_v}{\gamma h}
\]

where \(\sigma_v\) is the total vertical stress and \(\gamma h\) is the soil overburden pressure at the point.
Figures 11, 12, and 13 show the total vertical stress contours. According to these figures, the drop in total vertical stress throughout the core is indicative of the occurrence of the arching effect. As the filling begins, total stresses increase due to the weight of water and an increase in unit weight of materials. The total vertical stresses in the dam’s central axis are not significantly different during the initial filling of the reservoir.

The arching ratio graphs in the central axis of the dam body (presented in figure 13) belong to the end of construction, initial filling of the reservoir. These graphs indicate a decrease in the arching effect in the core and an increase in the dam safety against hydraulic fracturing during filling that can be accounted for by the pressure of the upstream shell on the core after applying reservoir water load. The probability of hydraulic fracturing in Ivshan Dam is low due to the small arching effect. According to the figures, the minimum value of the arching ratio in the central axis of the core during the end of the construction and initial filling is 0.81 and 0.80, respectively, which occur at about 41 meters and about two-thirds of the dam body height.

**Figure 11.** Total vertical stress contour at the end of construction.

**Figure 12.** Total vertical stress contour in the initial filling of the reservoir.

**Figure 13.** The arching ratio in the central axis of the dam body at the end of construction, initial filling of the reservoir.
4.4. Pore water pressure
Figure 14 shows the pore pressure ratio to total stress from the numerical model in the dam's central axis during the initial filling of the reservoir. This figure shows that in the case of the initial filling of the reservoir, the pore pressure ratio condition is favorable in the dam's central axis except for an altitude of 59 m. According to Figure 15, a distribution of the pore water pressure has been created in the earth dam's body. As can be seen from this figure, the explanation of the pore water pressure in the core of the earth dam decreases and the water head in the core of the dam decreases. This function indicates the correct operation of the core and the drainage part of the earth dam body.

Figure 14. Pore water pressure ratio for different altitudes in the dam body's central axis during the initial filling of the reservoir.

Figure 15. Pore water pressure contours for the initial filling of the reservoir.

5. Conclusion
Numerical analysis of the hydro-mechanical behavior of the Ivshan earth dam indicated that the numerical method and FLAC explicit finite difference code are reasonably able to model the variations in stress and deformation of the dam's body during construction, end of construction and initial filling of the reservoir.

The numerical model results also showed that the maximum settlement values calculated for the Ivshan dam at the end of construction and during the initial filling are approximately 1.5% and 1.4% height of the dam. At altitudes of 46 and 45 meters, respectively. Considering that the acceptable settlement is near 3% of the dam's height, the settlement values are acceptable and within the acceptable range. The maximum settlement calculated by deformation instrumentation at the dam's central core is 97 cm, indicating the accuracy of settlement values given by numerical modeling.
One of the criteria for controlling hydraulic rupture potential in earth dams is the arching ratio. The lowest values of arching ratio in the central axis of the core at the end of construction and initial filling of reservoir are 0.81 and 0.80, respectively, which occurred at a height of about 41 meters and about two thirds of the height of the dam embankment. In the case of the initial filling of the reservoir, the arching ratio increases and the intensity of curvature is reduced.

Another criterion for evaluating the stability of an earth dam in the initial filling condition is to evaluate the pore pressure ratio. At all altitudes, the pore pressure ratio is less than 0.6 and only at the height of 60 meters is close to 0.7, and shows the relative stability of the earth dam in terms of pore water pressure. Moreover, the Factor of Safety in the earth dam approached 1.19 at the initial filling of the reservoir. Most of the shear strains occur in the local area and cannot affect the dam's stability globally.

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