Numerical Model of Seepage Analysis and Slope Stability for Horan Dam H4 in Iraq

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Abstract. Horan Dam H4 is an earth dam located 18 km northeast Rutba town in Anbar province in Iraq. The main objective for dam construction is to save rainfall for agriculture purposes and some household uses. In this study, a mathematical model is developed to analyze water seepage through the dam under steady state. The upstream and downstream slopes stability of the dam are also evaluated by using four methods which are: Bishop, Janbu, Morgenstern-Price, and Ordinary method. In addition, a two-dimensional finite element model was developed using GeoStudio program. The results of seepage analysis clearly show that Horan Dam H4 is safe against failure. Furthermore, the obtained factor of safety of upstream and downstream slopes stability proves that the dam body is stable based on Janbu’s method of minimum value. Moreover, it was found that the soil shear strength parameters highly influence the dam stability in steady state condition.

Key words: GeoStudio program, Horan Dam, phreatic line, Seepage, Slope stability.

1. Introduction

Dams are constructed for water storage, flood control, irrigation, energy generation, domestic water supply, industrial water supply, recreation and fishing [1]. Water seepage through earth dams might lead to catastrophic problems causing dam failure. Such problems could be in the form of piping, weak rock dissolution, excessive uplift pressure, upheaval, internal erosion, and/or saturation pressure [2]. The main factors that affect seepage are pressure gradient and soil permeability. The water ratio within the dam body mainly depends on the degree of compaction, soil properties, dam size and number of cracks or cavities within the soil. When seepage is out of the control limits, problems might initiate with water wastage due to seepage out of the dam and then exacerbate to some sort of dam failure. Piping is one sort of such failure, it occurs when the reservoir water moves from the dam upstream into the interior parts of the dam body through the voids between the soil particles [2].

The self-weight of the earth dam mass creates driving shear forces in the downward direction of the slope. While the shear strength on critical surfaces is generated by soil frictional resistance and soil cohesion. The failure generally occurs when the driving shear forces are greater than shear strength [3].

Some researchers like Li and Desai [4] studied stress and seepage in earth dams using the finite element method. Such studies tackled couple of effects. The first is the effect of external loads such as the dam body weight, surcharge and forces due to construction works. The second is the effect of seepage forces...
through steady flow of water. It has been noticed that the same finite element mesh was adequate and effective for stress and seepage analyses in which the seepage forces were directly superimposed. Furthermore, Omofunmi et al. [2] analyzed the causes of seepage and the control measures in another earth dam. The main causes were found to be: pore-water pressure, poor foundation, rodent holes and wood which, in turn, might cause piping. The control measures that were taken into consideration included: cut-off, upstream clay blanket, filter blanket, seepage drains and berms. It was recommended that careful observation should always be in action to notice any seepage increase in order to take instantaneous protective measures by lowering the reservoir water level and/or provide passages through the dam body.

Other researchers like Hnang [5] used the finite element method to study the slope stability of earth dams at maximum water level under steady state seepage. In which the factor of safety of the dam against slope stability failure was determined. Athani et al. [6], also conducted a parametric study of slope stability of an earth dam using the finite element method with different values of $E'$ and $\phi'$ parameters. It was found that the factor of safety of the dam against slope stability failure became lower when the values of $\phi'$ and $E'$ were increased.

A Lucian and O Adelina [7] studied the slope stability of Chirita earth dam and the filtration process using another program called “Galena”. The factor of safety was determined based on the soil properties ($\gamma$, $\Phi$ and $c$) and the dimensions of the dam. It was found that the new factor of safety is less than that determined 45 years ago.

Another slope stability analysis was conducted by Zewdu [8] for Koga earth dam in Ethiopia. The study had assessed the factor of safety and seepage through the main body of the dam and its foundation under various critical loading circumstances.

Furthermore, some other researchers like Gopal and Kumar [9] analyzed the compound effect of seepage and slope stability in earth dams using two methods. The First method is using Darcy’s law and Bishop Method for seepage and slope stability determination, respectively. The second method is using SEEP/W and SLOPE/W programs in the GeoStudio software. These programs were also adopted by K Anjali and Hangagekar [10] in studying the seepage and slope stability of Ujjani dam using Geo-slope software. It was found that the reservoir water level and the exit gradient followed a quadratic relationship and the dam was safe against failure because the phreatic line passes and no piping for different reservoir water levels. The phreatic line (or the saturated line) is defined as the line at the upper surface of the seepage flow at which the pressure is atmospheric (equal to zero-gauge pressure). Below the phreatic line, there is a positive hydrostatic pressure for the soil below the phreatic line is saturated. While above the phreatic line, it might be dry or moist [11].

Arshad et al. [12] also used Geo-slope software to study seepage and slope stability in Hub dam at maximum, normal and minimum water levels. The dam was found to be safe against piping and slope failure.

This study aims at seepage and slope stability analyses of an earth dam called Horan Dam H4 in Iraq. The effects of main parameters such as water head, pore-water pressure and soil properties (in different zones of the dam), on the factor of safety, were investigated. SEEP/W and SLOPE/W programs of the GeoStudio software were utilized to undertake the study.

2. Case Study

Horan Dam H4 is an embankment dam that is located on a valley called “Wadi Horan” (18 km) northeast of Rutba town in Iraq as illustrated in Figure 1, [13,14]. The valley extends along 485 km starting from the Iraqi-Saudi borders southwest of Iraq till the Euphrates river near Haditha town about 8 km away from Baghdad-Jordan highway [15]. The valley works as a channel that serves a specific area called “Block 7” having a catchment of (12,180 km²). The annual runoff is estimated to be (19.3×10⁶ m³) [16].
According to the primary design of Horan Dam H4, the dam body consists of a central core, shell shoulders, foundation and equipped with a filter as shown in Figure 2. It has a total height of (24.4 m) with a maximum water level that can reach up to (22.6 m). Available adjacent soil was used to construct the dam based on the recommendations of the soil investigation and geological studies report of the National Center for Construction Laboratories. Surrounding soil properties are listed in Table 1 [15]. The dam safety was considered to be acceptable according to the regulations of the British Dam Society [17] as shown in Table 2.

Table 1. Properties of the soil used in Horan Dam H4 [15]

| Part     | Unit weight (KN/m³) | Cohesion kN/m² | Angle of Friction (°) | Elastic modules E (KN/m²) | Poisson’s ratio (v) | Coefficient of permeability (m/s) |
|----------|---------------------|----------------|-----------------------|---------------------------|---------------------|----------------------------------|
| Core     | 20                  | 20             | 15                    | 20000                     | 0.35                | 2.25x10⁻⁹                        |
| Foundation | 22              | 50             | 31                    | 20000                     | 0.40                | 1x10⁻⁹                          |
| Shell    | 21                  | 0              | 32                    | 45000                     | 0.45                | 1.25x10⁻²                        |
| Filter   | 13                  | 0              | 32                    | 20000                     | 0.48                | 1.25x10⁻⁴                        |

Figure 1. Location of “Horan Dam H4” on “Wadi Horan” [13]

Figure 2. Cross section of Horan Dam H4 [14]
Table 2. Horan Dam H4 design vs. BDS safety limits [17]

| Parameter         | Horan dam (BDS) Safety limit | Dam Safety |
|-------------------|------------------------------|------------|
| Crest width       | 8 m                          | Not less than 2.0 m | Acceptable |
| Upstream slope    | 2.5:1                        | 2.5:1      | Acceptable |
| Downstream slope  | 2.5:1                        | 2.5:1      | Acceptable |
| Free board        | 1.8 m                        | Min. free board= 1.50 m | Acceptable |
| Bed width of core | 17 m                         | Not less than (H/3) = (8.133 m) | Acceptable |
| Core slope        | 1:4.33                       | 1:12       | Acceptable |

3. Seepage Flow

Based on the related boundary conditions and soil properties, a 2-D finite element model was developed to perform seepage analysis of Horan Dam H4 using GeoStudio software. The dam should be stable under all operating circumstances including different water levels and loading conditions. It should be equipped with a proper outlet on the dam's crest to avoid overtopping. In addition, the free board height should be enough to manage water seepage [18]. Seepage analysis used to be carried out based on a model or an equation that describes the phenomena using boundary conditions, hydraulic gradient and material properties [17].

The backbone of seepage analysis is Darcy’s formula [19]:

\[ Q = KA \frac{(h_1-h_2)}{L} bh \]  

where:
- \( Q \) is the rate of flow,
- \( K \) is the permeability,
- \( A \) is the cross-sectional area,
- \( h_1 \) is the water level in the inflow of the filter,
- \( h_2 \) is the water level in the outflow of the filter and
- \( L \) is the length of the filter.

According to [20], the seepage analysis undertaken in this study aimed at:
- a) Testing the phreatic surface.
- b) Estimating pore-water pressure.
- c) Estimating exit gradients and/or uplift pressures at the toe.
- d) Determination of seepage stream passing through.
- e) Determination of seepage flow intercepted by drainage facilities.

4. Slope Stability

The stability of an earth dam depends on pore-water pressure developed in the dam body, characteristics of the foundation and fill materials, geometry of the embankment and status-related factors such as the presence of water and stacking conditions. The slope stability against sliding risk is usually represented by a safety factor. This safety factor is inversely related to the value of associated soil parameters such as friction angle, unit weight and cohesion [8].
GeoStudio software is used to study the analysis of slope stability according to the critical cases of operation in steady state condition.

5. Numerical Model

Numerical analysis is widely used to model different situations of seepage flow and slope stability. The most popular numerical methods are the Finite Element Method and the Finite Difference Method. The boundary conditions of seepage can be regarded using the following formula [21]:

\[
\frac{\partial}{\partial x} \left( K_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial H}{\partial z} \right) = S \frac{\partial h}{\partial t}
\]  

(2)

where,
- \( K_x, K_y, K_z \): are the coefficients of permeability in the x, y and z directions respectively,
- \( S \): is the specific yield,
- \( t \): is the time and
- \( H \): is the total fluid head which can be found by:

\[
H = \left( \frac{P}{\gamma_w} \right) + z
\]  

(3)

where,
- \( P \): is the pressure,
- \( \gamma_w \): is the unit weight of water and
- \( z \): is the elevation head.

The element characteristic matrix \([K]\), the mass matrix \([M]\), and the element applied flux vector \([Q]\) used in [22] can be expressed in the following equation:

\[
[K][H] + [M][H], t = [Q]
\]  

(4)

Under steady-state conditions, the term \(([H], t)\) is equal to zero and so the equation is simplified to:

\[
[K][H] = [Q]
\]  

(5)

Moreover, when the angle of hydraulic conductivity is zero then the hydraulic conductivity matrix can be simplified to the equation:

\[
[C] = \begin{bmatrix} k_x & 0 \\ 0 & k_y \end{bmatrix}
\]  

(6)

The factor of safety against failure according to the theory of limit equilibrium of forces and moments can be estimated using the following two independent equations and Figure 3 in which the moment equilibrium should be satisfied [23] and the horizontal force equilibrium too [22]:

\[
F_m = \frac{\Sigma(c' \beta R + (N-u \beta) (R \tan \theta'))}{\Sigma W x - \Sigma N f + \Sigma K W + \Sigma D d \pm \Sigma A a}
\]  

(7)

\[
F_f = \frac{\Sigma(c' \beta \cos \alpha + (N-u \beta) \tan \beta \cos \alpha)}{\Sigma N s i n a + \Sigma K W - \Sigma D \cos \alpha + \Sigma A a}
\]  

(8)
where,
\( A \): is the resultant external water force,
\( E \): is the horizontal inter-slice normal force,
\( N \): is the total normal force acting on the slice base,
\( S_m \): is the shear force acting on each slice base,
\( X \): is the vertical inter-slice shear force,
\( kW \): is the horizontal seismic load applied on each slice center and
\( W \): is the total weight of a slice.

(a) Circular Slip Surface  
(b) Noncircular Slip Surface

Figure 3. Forces acting on an earth slope for a circular and noncircular slip

6. Results and Discussion

6.1 Seepage Analysis

The GeoStudio software was utilized to study the seepage in the dam body (shell and core) and foundation based on the soil characteristic. The water flow crossing the embankment of Horan Dam H4 was investigated first using the finite element program SEEP/W. The seepage was modeled based on [17], using a proper equation to describe the phenomena including boundary conditions, hydraulic gradient and material properties. The boundary conditions behind and ahead of the dam are shown in Figure 4 in which the water head is (22.6 m) at the upstream side and (0 m) at the downstream side. The phreatic line was identified first to represent the top hydraulic boundary of the flow net. Figure 5 shows that the phreatic line, at steady state conditions, goes through the body dam at the downstream slope. It does not intersect the downstream face, thus it does not cause softening or sloughing of the downstream slope which might lead to consequent failure. The maximum pore-water pressure is located at the base of the upstream transition zone. This is because the initial pore-water pressure under the maximum water height of (22.6 m) is higher than its value under any other water heights. The pore-water pressure increases with increased water height, velocity vectors magnitudes (vector arrows), flow paths through particles and the average rate of flow of water through the dam’s body. The later is found to be (0.061279 m³/day).
Figure 4. Boundary conditions at steady state

Figure 5. Phreatic line, Pore-water pressure, velocity vectors, flow path and flux section

Figure 6 illustrates the values of hydraulic gradients at different distances from the dam base. It can be noticed that the supreme values of horizontal and vertical hydraulic gradients are found at the downstream exit point which are equal to (0.63) and (0.17) respectively. It can also be noticed from Figure 7 that the maximum horizontal and vertical hydraulic gradient are less than (1).

Figure 6. Horizontal and vertical hydraulic gradients at different distances
Table 3 demonstrates the results of hydraulic safety of the dam which is found to be acceptable based on the criteria of [20]. This means that, the dam is safe enough against failure in seepage at steady state.

**Table 3.** Horan Dam hydraulic safety based on (USBR, 2014) criteria

| Safety Factor Against Heave | Horan Dam | (USBR, 2014) Safety Limits | Safety Status of the Dam |
|----------------------------|-----------|-----------------------------|-------------------------|
| $l_{exi} = 0.05$           | $FS_H = (1.0/0.05) = 20.0$ | 4.0                         | Acceptable              |

### 6.2 Slope Stability Analysis

Several Limit Equilibrium methods were developed for slope stability analysis including: Bishop, Janbu, Morgenstern-Price and Ordinary method. All these methods were utilized in running the finite element program SLOPE/W. They are based on certain assumptions concerning the inter-slice normal forces ($E$) and shear ($T$). The basic difference between these methods is the way of forces determination or assumption. Table 4 lists the adopted assumptions of these forces [24,25].

**Table 4.** Assumptions of Limit Equilibrium methods used

| Methods                | Circular | Non-Circular | $\Sigma M = 0$ | $\Sigma F = 0$ | Assumptions for $T$ and $E$ |
|------------------------|----------|--------------|----------------|----------------|----------------------------|
| Ordinary               | ✓        | -            | ✓              | -              | Neglects both $E$ and $T$  |
| Bishop                 | ✓        | (*)          | ✓              | (**)           | Considers $E$, but neglects $T$ |
| Janbu                  | (*)      | ✓            | ✓              | ✓              | Considers $E$, but neglects $T$ |
| Morgenstern-Price      | ✓        | ✓            | ✓              | ✓              | Defined by $f(x), T=f(x),\lambda, E$ |

(*') Can be used for both circular and non-circular failure surfaces.<br/>
(**) Satisfies vertical force equilibrium for base normal force.

Design and safety evaluation of embankment dams should satisfy the recommended criteria of some recognized agencies in the field of embankment dams design such as: the U.S. Army Corps of Engineers [26] and the British Dam Society [17]. Among the aforementioned methods, Janbu method yielded the lowest factors of safety in both upstream and downstream slopes as shown in Figures 8 and 9. On the other hand, the Bishop method yielded the highest factors of safety in both upstream and downstream slopes as shown in Figures 10 and 11. The results obtained using all methods are acceptable when
compared to the limits of [26] and [17] as shown in Table 5. All the values of the factor of safety obtained are higher than (1.3), so, the dam is considered stable at steady state (no slop failure is expected).

In general Morgenstern-Price method is considered as the best for its ability to be used for both circular, non-circular failure surfaces and satisfies vertical force equilibrium for base normal force.

**Figure 8.** Factor of safety for upstream slope by Janbu method (2.874)

**Figure 9.** Factor of safety for downstream slope by Janbu Method (2.121)

**Figure 10.** Factor of safety for upstream slope by Bishop method (3.811)
Figure 11. Factor of safety for downstream slope by Bishop Method (2.831)

Table 5. Factor of safety vs. (USACE, 2003) and (BDS, 1994) Limits

| Method          | Critical stability condition at steady-state |
|-----------------|---------------------------------------------|
|                 | Upstream slope     | Downstream slope   |
| Bishop          | 3.811              | 2.831              |
| Janbu           | 2.874              | 2.121              |
| Morgenstern-Price| 3.521              | 2.711              |
| Ordinary        | 3.181              | 2.398              |
| Criteria (USACE, 2003) | 1.5                | 1.5                |
| Criteria (BDS, 1994)  | (1.3-1.5)          | (1.3-1.5)          |
| Judgment        | Stable             | Stable             |

7. Conclusions

In this study, the Geo-Studio software was quite suitable for seepage and slope stability analyses using SEEP/W and SLOPE/W programs. The analyses of seepage and slope stability were carried out using the Finite Element technique. Four different methods of limit equilibrium slope stability were used to analyze the upstream and downstream slopes of the dam. The methods which are used for slope stability of earth dam are; Bishop, Janbu, Morgenstern-Price, and the Ordinary method.

No internal erosion because the phreatic line was found to be inside the downstream side of the earth dam. The total seepage quantity through the foundation and main body of the dam at the maximum reservoir level (22.6 m) is (0.061279 m³/day). The outlet hydraulic gradient seems to have a quadratic relationship with the reservoir water level. The dam is also safe against piping for all reservoir water levels. The results showed acceptable accuracy compared with [20] safety limits. Horan Dam H4 was found to be safe toward failure via seepage analysis.

SLOPE/W program was used to analyze the static slope stability of the embankment under various loading conditions. The results revealed that the upstream and downstream sides of the dam section directly effect
on the factor of safety. The analysis was carried out in terms of sufficient stress conditions. The performance of stability analysis indicated that the downstream and upstream slopes are critical at steady-state. The Janbu method allowed the minimum factor of safety at both upstream and downstream slopes. The factors of safety of slope stability at both upstream and downstream sides satisfy the minimum limits in all four methods.

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