

## Research Article

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# Effect of drain pipes on seepage and slope stability through a zoned earth dam

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**Abstract:** Earth dams must be supplied with seepage control devices to prevent piping and sloughing. One such device used for this purpose is the so-called drain pipe. This study focuses on the influence of drain pipes on seepage and slope stability analysis in a zoned earth dam; here, for the specific case study of the Al-Adhaim dam, Iraq. The purpose of this study is to demonstrate the beneficial effects of drain pipes in the control of seepage and improving slope stability in zoned earth dams, thus allowing for specific recommendations for the optimal location(s) of any drain pipes. SEEP/W software was used to evaluate the steady-state seepage that occurs through and beneath the dam, and SLOPE/W software was used to analyze slope stability. In this study, two drain pipes, each with diameters of 15 cm, were used in the earth dam, with a vertical distance of 1 m between them. The effects of the drain pipes through the earth dam were investigated by varying their relative locations, specifically at  $X/B = 0.5, 0.6$ , and  $0.7$ . The results of the study showed that the presence of the drain pipes was effective in reducing the elevation of the phreatic surface line. Additionally, the drain pipes significantly reduced the seepage flow and hydraulic exit gradient while increasing the factor of safety (FOS). Based on the findings, it was concluded that the most effective position for the drain pipes was when they were located at  $X/B = 0.7$ ; in this configuration, they allowed for minimum seepage flow (70%) and hydraulic exit gradient (72%), while providing the highest FOS (17.2).

**Keywords:** Earth dam, drain pipes, seepage flow, exit gradient, factor of safety, Al-Adhaim dam

## 1 Introduction

Dams are constructed for various reasons, including the storage of water for domestic and agricultural use, control of flow, reduction of the risks of droughts and floods, and electrical power generation [1]. The structure known as an earthen dam is formed from soil particles linked to one another and mechanically compacted in layers to form the structure of the dam itself. Dams made of earth are typically trapezoidal in shape and have large bases. It was planned to be a segment with no overflow, and a separate spillway was built for it. The shear strength of the soil maintains the stability of this particular kind of dam. Homogeneous, zoned, and diaphragm earth dams are the three most common and essential forms of earth dams currently used [2,3].

When designing earth dams, seepage is a vital aspect of their operation, which has to be thoroughly analyzed and managed in order to prevent later problems. An excessive amount of seepage might pose a risk to the dam's stability, ultimately leading to its collapse. Sloughing and piping are the two most typical forms of failure that may occur in downstream seepage. Dams have a history of collapsing due to uncontrolled seepage, which has almost inevitably led to disastrous results. For example, one might consider the collapse of the Vajont dam in Italy in 1963, which resulted in 2,600 fatalities, the Teton dam in the United States in 1976, which resulted in 100 fatalities and economic losses of almost one billion dollars, or the collapse of the Gouhou dam in China in 1993, which resulted in 300 fatalities. Data analysis of 534 dam failures in 43 countries prior to 1976 reveals that these failures approximately accounted for the highest proportion of all failures in such structures, including 49% overtopping, 28% seepage through the dam, and 29% seepage through the foundations [4,5].

There are two primary issues that arise as a result of seepage *via* earth dams. The first problem pertains to assessing the quantity of seepage flow, which is always a significant cost issue for dams. The second problem is the stability of the dam in the face of high gradients, which

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may wash away soil particles along the seepage surface on the downstream side of the dam, which can jeopardize its stability. If seepage is prevented, the water might find another way through or build-up, resulting in unstable slope conditions. Dams that have been developed correctly should have a properly designed interior drainage system. Dam stability can be improved by adding drains and filters, which significantly reduce the volume of water that seeps through and prevent the erosion of soil particles. Toe drains, horizontal blanket drains, and chimney drains are three distinct types of drains that can be distinguished based on their position and form [6,7]. The proper design and implementation of drains are crucial to managing seepage in dams. By controlling seepage and preventing soil erosion, these measures contribute to the stability of the dam, reducing the risk of slope failure and other potential hazards.

## 2 Literature review

Several research groups have concentrated their efforts on seepage behavior through earthen dams or other related topics. Mansuri and Salmasi [8] investigated the efficacy of employing horizontal drains and cut-off walls to minimize the amount of water that seeps through heterogeneous earth dams. In order to accomplish this goal, many potential lengths of horizontal drain and cut-off wall depths were investigated beneath the dam in several locations around the foundations. Seepage, exit gradient, and uplift pressure were all computed *via* numerical simulations utilizing the SEEP/W subprogram of the GeoStudio software suite. According to the findings, extending the length of the horizontal drain will lead to a minor increase in seepage flow, as well as an increase in the exit gradient. The center of the dam's foundation is the ideal place for the cut-off wall since this helps to reduce the amount of water that seeps through. Also, it has been found that seepage from earth dams and their foundations decreases when the cut-off wall is increased. Arshad *et al.* [9] developed a finite element model of a nonhomogeneous earth dam using the SEEP/W software, with the Hub dam in India chosen as the subject for their model. In order to evaluate the behavior of the dam with regard to seepage flow and hydraulic gradient, two distinct scenarios were investigated and studied: one with a cut-off wall and the other without. Additionally, the program was used to illustrate the behavior of the phreatic line in both scenarios. As a result of the simulation, it was determined that the dam is secure against piping for case 2 since the construction of the cut-off wall

was successful in terms of lowering the pore pressure of water inside the dam and its foundations. Hence, it is possible to conclude that cut-off walls in earth dams play a vital role in decreasing the internal pore pressure of water at the surface of the dam foundation, which in turn reduces the seepage flux and hydraulic gradient. Ade *et al.* [10] determined the amount of seepage for various water heads upstream of the Kas dam, which is a zoned earth dam located in India, using the GeoStudio program with the SEEP/W subprogram. In addition, an investigation into the dam's stability was performed using the SLOPE/W subprogram, with the factor of safety (FOS) thus calculated. The results indicated that the dam was not presently in any danger of collapse due to seepage, as determined by seepage analysis performed using the GeoStudio program. Attia *et al.* [11] investigated how the decrease in water head and the length of the filter were influenced by the depth of the penetration and the cut-off distance, respectively. In addition, the thickness of the previous layer that lies under the dam was analyzed to determine its influence on the length of the filter and seepage flow. The ideal location for the cut-off was also determined by analyzing the outcomes of the experiments. It was determined that the optimal location for the cut-off was the point that resulted in the least amount of seepage flow being directed toward the filter while simultaneously allowing for the greatest decrease in the phreatic surface. Additionally, it was discovered that there is no requirement to install a filter downstream; nevertheless, in order to maintain downstream safety, it is essential to build a filter on the downstream side. The depth of the previous layer is increased, which results in an increase in the water head. Torabi Haghighi *et al.* [12] developed a somewhat original approach to estimating the effectiveness of seepage control methods in earth dams using a combination of monitoring data. They validated their concept by implementing it at the Doroudzan dam in Iran, where they analyzed the effectiveness of the seepage control components. According to their findings, the total efficacy of the seepage control methods at the dam ranged between 51 and 70%, depending on the water that was released from the reservoir. The effectiveness of the seepage control methods for the chimney drain was 76–82%, for the cut-off wall was 68–74%, and for the grouting diaphragm was 16–19%. Malik and Karim [13] investigated the seepage and slope stability of the Hadith earth dam in Iraq. The SEEP/W software was used to create a flow net, which displays the phreatic, equipotential, and streamlines. Additionally, the program calculated the amount of seepage. The actual design of the dam was explored by checking the water elevation at the highest, lowest, and normal. It was concluded that the existence of an asphaltic concrete diaphragm and grout curtain

would lead to a significant reduction in the quantity of water seeping through the dam body, and the FOS for upstream and downstream fulfill the minimum requirements for such at all water elevations. Onyelowe *et al.* [14] used an optimized geostabilization numerical model for a 37 m-high slope embankment on a soft clay watershed. Their study's aim was to address slope failure, which contributes to climate change concerns and conflicts with the United Nations Sustainable Development Goals (UNSDGs) for 2050. The model considers safety, cost optimization, and environmental goals. Monitoring wells were installed, and soil samples were tested to determine water level conditions and soil properties. Seven simulation alternatives were evaluated, including slope reduction, dewatering, jet grouting, and combinations thereof. Three alternatives were discarded due to inadequate stability, leaving four alternatives for further optimization. Factors such as cost, constructability, reliability, and environmental impact were considered. Based on these factors, alternative-1, with an FOS of 1.505, was chosen as the optimal solution in terms of reliability, constructability, and environmental impact despite not being the cheapest option. Alternative-6 and alternative-7 were the most economical alternatives but ranked lower in terms of reliability and environmental impact considerations. Hassan *et al.* [15] conducted a steady-state seepage analysis and determined the downstream FOS using the modified Bishop's method for a poorly compacted earth dam. The aim of their study was to optimize the embankment of the reservoir located near Sadiyavav village in Junaga district, Gujarat, India. The analysis and optimization were conducted by introducing a double-textured high-density polyethylene (HDPE) geomembrane barrier. Two improvement techniques were studied using the limit equilibrium-finite element method (LS-FEM). The first technique involved stabilizing the HDPE membrane. The study results indicated improvements in downstream slope stability for the two alternatives, with a 3% improvement for the first alternative and a 10% improvement for the second. Fadhil and Hassan [16] addressed water seepage issues in hydraulic structures, such as concrete dams and barrages, which can lead to soil erosion, increased uplift pressure, and potential failure of the foundations. The objective was to minimize such problems by optimizing the location, number, and diameter of any drain pipes beneath the structure's foundation. Using the GeoStudio software and FEM, an optimization methodology was employed to determine the optimal position, number, and diameter of the drain pipes. The study found that the position of any drain pipes significantly affects the exit gradient and uplift pressure, particularly at specific locations along the dam's foundations. The optimal positions for the drain pipes were identified as 35 and 50% along the dam foundation, measured from the dam's

heel side. By installing the drain pipes at these locations, a notable reduction of approximately 50% in the exit gradient and a 48% decrease in uplift pressure could be achieved compared to the reference condition, that is, without drain pipes. Furthermore, the study revealed that increasing the number and diameter of the drain pipes would lead to a considerable reduction in uplift pressure head and exit gradient.

This article focuses on investigating the impact of drain pipes on the seepage and slope stability of the Al-Adhaim dam in Iraq, which is an earth dam with zoned construction. The GeoStudio software was utilized for simulations via its SEEP/W and SLOPE/W subprograms to compare the results between scenarios with and without drain pipes [17]. Figure 1 shows the step sequence in which this study was conducted, from beginning to end.  $X$  represents the horizontal position of the drain pipes from the upstream, and  $B$  represents the base width of the dam. SEEP/W is a numerical modeling tool used for analyzing groundwater flow and seepage problems, while SLOPE/W is employed in slope stability analysis. These software programs were used to assess how the presence of drain pipes might influence seepage patterns and the overall stability of the earth dam. The methodology involved developing a numerical model of the dam in GeoStudio, considering its geometric and material properties. The results obtained from the simulations were compared and evaluated to determine the effects of the drain pipes. The presence of drain pipes in an earth dam can enhance

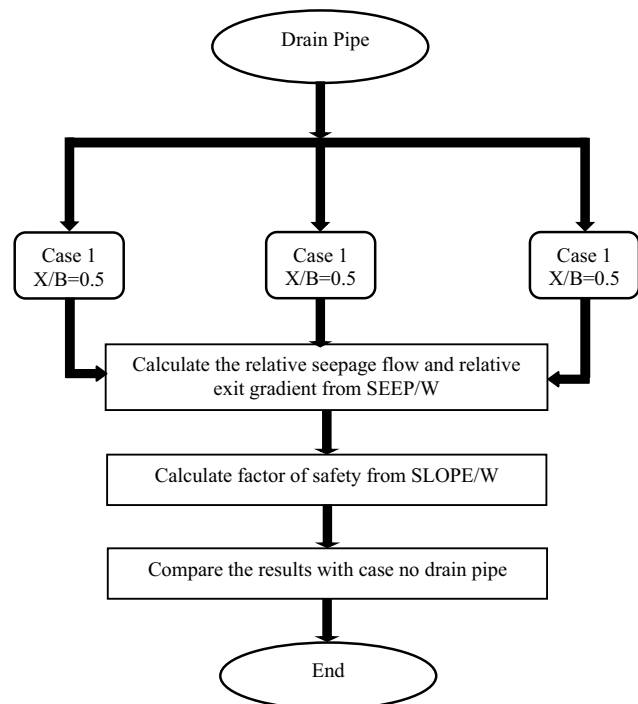


Figure 1: Flow chart of Geo-Studio model.

its seepage characteristics by providing an additional route through which water can flow and dissipate pore pressures. This can potentially reduce the risk of internal erosion and improve the overall stability of the dam, as per the following:

1. Prevention of water seepage: The pipes redirect the flow of water away from the outer slope of the dam, reducing the risk of water away from surrounding areas.
2. Protection against corrosion: Water can cause corrosion and erosion of the soil and materials used in dam construction. Using drain pipes thus reduces exposure to potential sources of corrosion.
3. Maintenance of dam stability: The drainage system helps maintain the stability of the dam. When the water seeps into the dam and exceeds allowable levels, its weight increases and may affect the stability of the dam as a whole, in turn increasing the risk of collapse. By using drain pipes, seepage water can be controlled, and dam stability can be effectively preserved.
4. Preservation of surrounding land: By properly directing the flow of water, the negative impacts on the land surrounding the dam can be minimized. This includes reducing land excavation, soil erosion, and changes to the ecosystem.
5. Water redirection for agricultural or industrial use: Drainage pipes can be used to redirect water discharged from the dam for agricultural or industrial purposes. This helps maximize the utilization of available resources and meet the water needs of surrounding communities.

### 3 Seepage analysis

The difference in water elevation between the upstream and downstream sides of the earth dam, combined with the hydraulic conductivity of the respective embankment material, is used to inform the calculation used to estimate the quantity of seepage flow that occurs through earth dams. The quantity of seepage flow through a saturated soil media can be calculated *via* the Darcy law as follows [18,19]:

$$Q = K i_e A, \quad (1)$$

where  $Q$  represents seepage flow *via* porous media ( $\text{m}^3/\text{s}$ ),  $k$  is the hydraulic conductivity of the soil ( $\text{m/s}$ ),  $i_e$  is the hydraulic exit gradient, and  $A$  is the cross-sectional area ( $\text{m}^2$ ).

The purpose of the Darcy law is to calculate flow rates through saturated soil. According to subsequent studies, it can also be used to determine the seepage rate across unsaturated porous media [20–23].

The theory of fluid flow *via* porous materials can be used to calculate the amount of water that seeps through the earth dam as well as the distribution of water pressure. The two-dimensional differential equation known as the Laplace equation can be used to predict the seepage flow as follows [24–26]:

$$\frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + Q = \frac{\partial \theta}{\partial t}, \quad (2)$$

where  $H$  represents the total head ( $\text{m}$ ),  $k_x$  and  $k_y$  are the hydraulic conductivities in  $x$  and  $y$  directions ( $\text{m/s}$ ), respectively,  $Q$  is the seepage rate ( $\text{m}^3/\text{s}$ ),  $\theta$  is the volumetric water content, and  $t$  is the time ( $\text{s}$ ).

Under steady-state flow, storage changes are unaffected by time, and continuity requires the quantity of flow entering and leaving the element volume to be equal. If the flow through the earth dam is steady and the dam materials are anisotropic, Equation (2) can be expressed as follows [27]:

$$\frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + Q = 0. \quad (3)$$

The SEEP/W software uses the FEM to find the solution to (3) [24,28].

### 4 Slope stability analysis

In the field of geotechnical engineering, the general limit equilibrium analysis is employed to evaluate the slope stability of earth dams. The traditional technique of analysis when determining slope stability is to calculate the FOS. The FOS is defined as the ratio of the total resistance of shear to the total shear that has been generated for individual slices [17,20].

$$\text{FOS} = \frac{\tau_f}{\tau_d}, \quad (4)$$

where the FOS represents the factor of safety against sliding,  $\tau_f$  is the total shear strength of the soil ( $\text{kN/m}^2$ ), and  $T_d$  is the total shear stress generated along the surface that could fail ( $\text{kN/m}^2$ ).

Cohesion and friction are the two main components contributing to the soil's shear strength, which can be represented as:

$$\tau_f = c + \sigma' \tan \phi, \quad (5)$$

where  $c$  represents cohesion ( $\text{kN/m}^2$ ),  $\phi$  is the friction angle, and  $\sigma'$  is the normal stress on the surface of potential failure ( $\text{kN/m}^2$ ).



SLOPE/W uses the theory of limit equilibrium of forces and moments to find the FOS [29]. Various GLE methods have been used to calculate the FOS, such as the Bishop, Morgenstern-Price, Spencer, Janbu simplified, and Corps of Engineers approaches. This research uses the Spencer method to compute the FOS; this method assumes that all forces from the side are sloped at the same angle and the normal pressure at the slice bottom operates at the base center. Thus, this method meets all the criteria for the equilibrium of forces and moments [30–33].

## 5 Case study

The case study selected was the Al-Adhaim dam, shown in Figure 2, which represents a zoned earth-type dam. The location of the dam is around 100 km northeast of Baghdad, Iraq. The dam itself is located about 1.5 km from the confluence of two rivers, the Tuz Jay and the Taq Jay, which join to create the Al-Adhaim River [34]. The reservoir's surface area is 270 km<sup>2</sup> at an elevation of 143.5 m and 122 km<sup>2</sup> at a



Figure 2: Al-Adhaim dam (Al-Labban, [30]).

level of 132 m. The maximum capacity of the Al-Adhaim dam is 3,750 km<sup>3</sup> at an elevation of 143.5 m [30,35].

The maximum flood design level of the dam is 143.5 m. The dam's base elevation is 70 m above sea level, while the dam's crest height is 146.5 m. The dam's primary components are the shell, core, and filters, while its foundation soil consists of slope layers and a series of overlays, marl, and sandstone of varying thicknesses [30].

## 6 Al-Adhaim dam components

The Al-Adhaim earth dam, illustrated in Figure 3, is filled with three basic layers: filters, shell, and core. The thicknesses of these infills vary with the height of the dam, being thickest at the base and progressively decreasing as height increases. The dam height varies according to the ground level, ranging from some meters to several tens of meters, such as at 70 m [30,36]. The shell consists of sand and gravel, with a top width of 12 m and side slopes of 1:2.5 and 1:2 for upstream and downstream, respectively. The core is made up of silty clay, which slides upstream with slopes of 1:1 and 1:2. The form of the core section is that of a chimney, having a thickness of 8 m at a height of 143.5 m. This thickness gradually increases to 33 m at an elevation of 70 m. It may be noted that the core thickness at any point is 50% of the water level at that point, which is ideal to prevent water from leaking. At a level of 70 m, the core and marl soils have been combined to produce an obstacle to stop water from seeping under the dam. The drainage system is composed of vertical and horizontal filters. The core is protected by utilizing a vertical filter composed of two layers. The first layer, referred to as filter (F), has a 2 m thickness, while the second layer, referred to as filter (T), also has a 2 m thickness. The horizontal drainage is made up of three layers: the first layer is filter

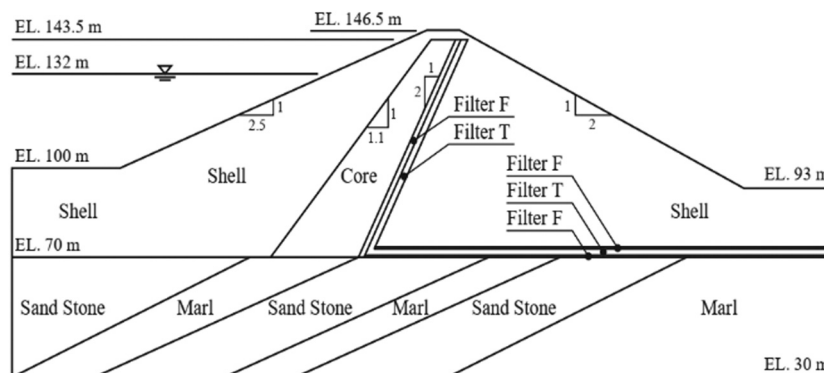


Figure 3: Cross-section of the Al-Adhaim dam [30].

**Table 1:** Material permeability of the Al-Adhaim dam [37]

| Material   |            | Permeability coefficient (m/s) |                       |
|------------|------------|--------------------------------|-----------------------|
|            |            | Horizontal ( $k_x$ )           | Vertical ( $k_y$ )    |
| Shell      |            | $1.25 \times 10^{-5}$          | $1.25 \times 10^{-5}$ |
| Core       |            | $2.25 \times 10^{-10}$         | $1 \times 10^{-10}$   |
| Filters    | Filter (F) | $1.2 \times 10^{-3}$           | $1.2 \times 10^{-3}$  |
|            | Filter (T) | $1 \times 10^{-2}$             | $1 \times 10^{-2}$    |
| Foundation | Marl       | $1 \times 10^{-10}$            | $1 \times 10^{-10}$   |
|            | Sandstone  | $5.5 \times 10^{-6}$           | $5.5 \times 10^{-6}$  |

(F) with a thickness of 0.3 m, the second layer is filter (T) with a thickness of 2.5 m, and the third layer is filter (F) with a thickness of 0.5 m. The material properties of the Al-Adhaim dam are summarized in Tables 1 and 2.

## 7 Analysis of seepage and slope stability of the Al-Adhaim dam

The steady-state seepage that occurs through and beneath the Al-Adhaim dam was evaluated utilizing the SEEP/W

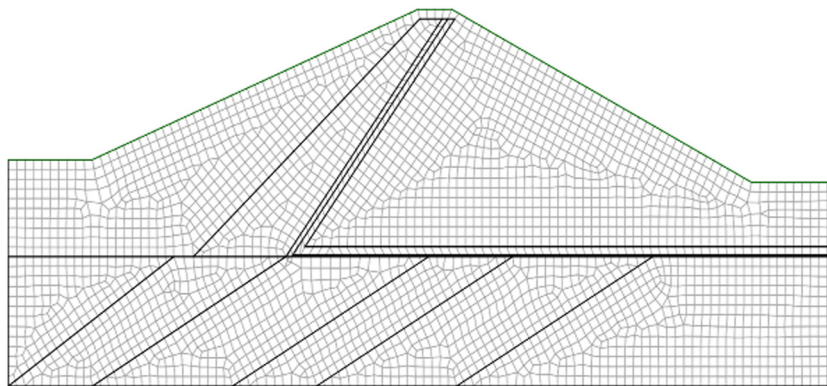
software, while SLOPE/W was used to analyze the slope stability. Figure 4 illustrates the finite element mesh that was utilized in this study. The total number of nodes is 3,167, whereas there are 3,050 elements. The boundary nodes upstream were defined as head boundaries, with the total head equal to the reservoir's water of 132 m. In contrast, the boundary nodes downstream were defined as the tail boundaries with a total head of 93 m. The nodes at the foundation's bottom edge have been designated as zero discharge (no flow) [38,39]. A saturated/unsaturated method was employed for material models of the shell and the core soils, respectively. The completely saturated option was chosen for the foundation and the filter soils.

## 8 Results and discussion

This section presents the analysis of the Al-Adhaim dam section under various scenarios, including the presence or absence of drain pipes, with different positions for the drain pipes. In all cases, the use of two drain pipes was assumed; the first was located at coordinates (X,73), while the second was located at (X,74), passing through the dam.

**Table 2:** Material properties of the Al-Adhaim dam [30]

| Material  | Unit weight ( $\gamma$ )<br>(kN/m <sup>3</sup> ) | Hydraulic conductivity ( $k$ )<br>(m/day) | Cohesion ( $c$ ) (kPa) | Elastic modulus<br>( $E$ ) (kPa) | Friction angle ( $\phi$ ) (°) |
|-----------|--------------------------------------------------|-------------------------------------------|------------------------|----------------------------------|-------------------------------|
| Shell     | 17                                               | 1.08                                      | 0                      | 19,000                           | 37                            |
| Core      | 17                                               | $1.944 \times 10^{-5}$                    | 0                      | 9,000                            | 25                            |
| Filter F  | 20                                               | 1.0368                                    | 0                      | 19,000                           | 35                            |
| Filter T  | 16                                               | 8.64                                      | 0                      | 19,000                           | 35                            |
| Marl      | 19.5                                             | $8.64 \times 10^{-6}$                     | 600                    | 350,000                          | 10                            |
| Sandstone | 19.5                                             | $4.752 \times 10^{-3}$                    | 0                      | 300,000                          | 38                            |

**Figure 4:** Al-Adhaim dam finite element mesh.

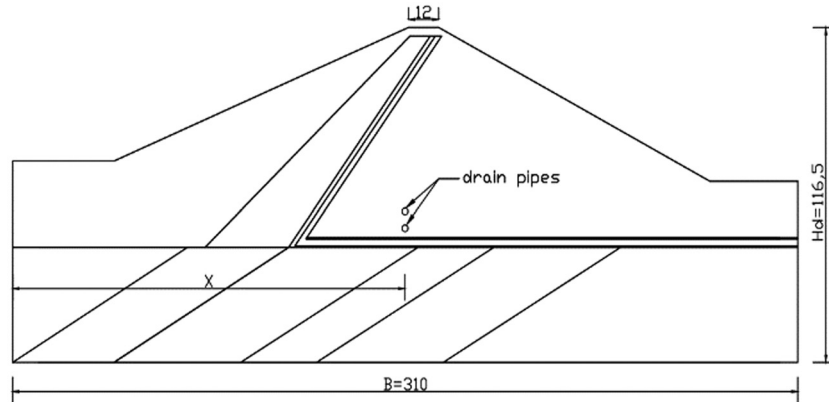


Figure 5: Al-Adhaim dam section when using drain pipes.

The horizontal position of the drain pipes varied, represented by relative position  $X/B$  with values of 0.5, 0.6, and 0.7. Here,  $X$  represents the horizontal position of the drain pipes upstream, and  $B$  represents the base width of the dam, as shown in Figure 5. The diameter of the drain pipes used in all cases was 15 cm. Figure 6 illustrates the different scenarios, demonstrating how the installation of drain pipes through the earth dam leads to a lowering of the phreatic surface line. The effects of the drain pipes' presence on seepage flow ( $Q$ ), exit gradient ( $i_e$ ), and FOS were investigated and compared to the case without drain pipes.

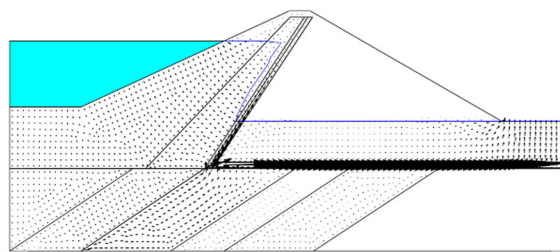
The information shown in Figure 7 illustrates the effects of different drain pipe positions on various parameters in specific cases as follows:

For case 1, when the drain pipes are located at  $X/B = 0.5$ ,

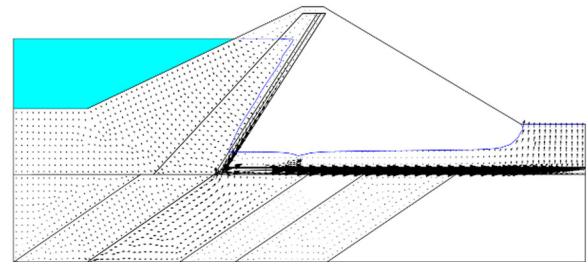
- The relative seepage flow ( $Q/kH_d$ ) (where  $H_d$  represents the height of the dam) is reduced by approximately 60%.
- The relative exit gradient  $i_e(B/H_d)$  is decreased by around 72%.
- The FOS is increased by nearly 16%.

For case 2, when the drain pipes are located at  $X/B = 0.6$ ,

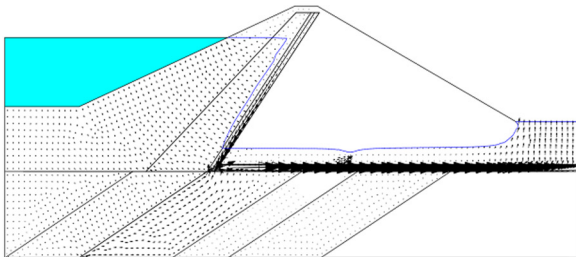
- The relative seepage flow ( $Q/kH_d$ ) is reduced by approximately 66%.



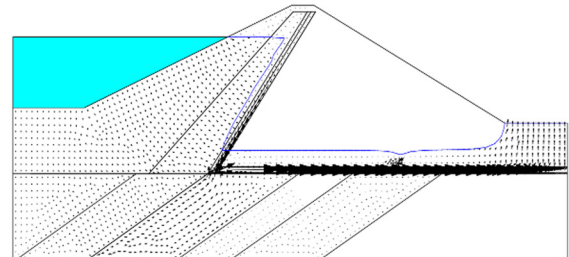
Without drain pipe



Case 1: With drain pipe at location  $X/B = 0.5$

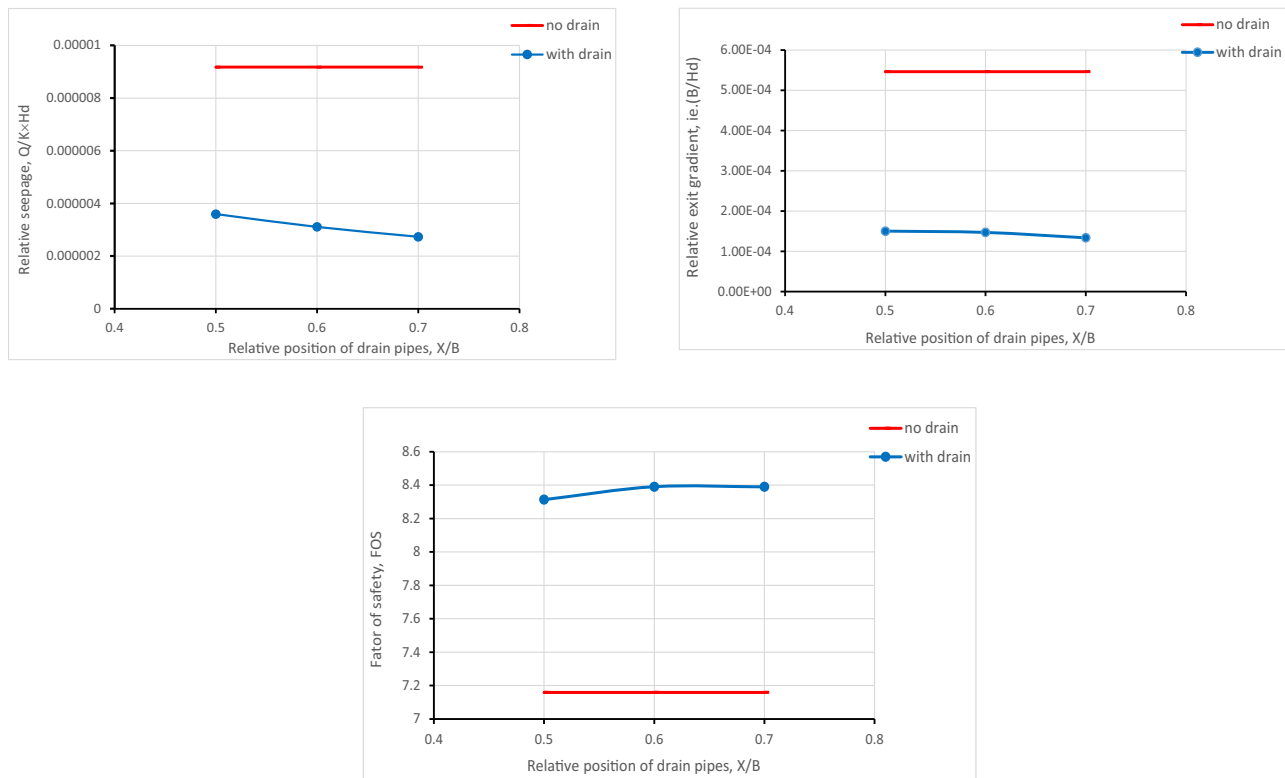


Case 2: With drain pipe at location  $X/B = 0.6$



Case 3: With drain pipe at location  $X/B = 0.7$

Figure 6: Cases of the Al-Adhaim dam with and without drain pipes.



**Figure 7:** Influence of drain pipes.

- The relative exit gradient  $i_e(B/H_d)$  is lowered by around 73%.
- The FOS is increased by nearly 17.2%.

For case 3, when the drain pipes are located at  $X/B = 0.7$

- The relative seepage flow ( $Q/kH_d$ ) is reduced by approximately 70%.
- The relative exit gradient  $i_e(B/H_d)$  is lowered by around 75%.
- The FOS is increased by nearly 17.2%.

Based on previous results, it seems that the presence of drain pipes in an earth dam has a positive effect in terms of reducing seepage flow and enhancing the stability of the dam. For all cases shown in Figure 6, there are significant reductions in the relative seepage flow ( $Q/kH_d$ ). This means that the drain pipes effectively intercept and divert the seepage flow, preventing excessive water from flowing downstream through the dam. By reducing seepage flow, the drain pipes help mitigate the potential for excessive pore water pressure within the dam. This is beneficial because excessive pore water pressure can have adverse effects on the dam's stability and performance. By implementing the use of drain pipes, the seepage flow can be managed, reducing the risk of pore water pressure buildup and its associated consequences. Also, it may be noted that there is a decrease in the relative exit gradient  $i_e(B/H_d)$ . The

exit gradient refers to the slope of the seepage path as it exits the dam. A lower exit gradient indicates a flatter seepage path, which means that the drain pipes help distribute the seepage flow more evenly and prevent concentrated flow paths. This can help reduce the potential for erosion and development of preferential flow channels, further contributing to improved slope stability. In addition, it can be seen that the FOS increases in each case, where an increase in such indicates an improvement in the stability of the dam. The drain pipes help to reduce the pore water pressure, which can decrease the effective stress acting on the soil particles and increase the overall stability of the dam.

## 9 Conclusions

Based on the seepage and slope stability analysis of the Al-Adhaim dam using the FEM, the following conclusions can be drawn:

- The presence of drain pipes in the earth dam has beneficial effects on seepage flow ( $Q$ ) and hydraulic exit gradient ( $i_e$ ). The drain pipes help to lower these values, indicating a reduction in the amount of water seeping through the dam and the hydraulic gradient.



- The installation of drain pipes through the earth dam significantly reduces the phreatic surface line. This means that the drain pipes effectively lower the water table within the dam, minimizing the potential for seepage-related issues.
- The presence the drain pipes through the earth dam results in an increase in the FOS on the earth dam. This means that the dam is less prone to slope failure and can withstand external loads and hydraulic pressure more effectively.
- The analysis shows that the best location for the drain pipes within the dam is when the relative position is  $X/B = 0.7$ . At this location, the dam experiences the lowest seepage flows ( $Q$ ) and hydraulic exit gradient ( $i_e$ ), including minimal water seepage and hydraulic pressure. Additionally, this location corresponds to the highest FOS, including the highest level of slope stability. Therefore, placing the drain pipes at  $X/B = 0.7$  within the dam is recommended to ensure optimal seepage control and slope stability.

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**Data availability statement:** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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