

Effect of the Sheet Piles on Seepage Under the Earth Dam at Various Reservoir Water Levels

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ABSTRACT

Seepage in earth dams is one of the most challenging issues in geotechnical and hydraulic engineering, as it directly impacts dam safety and reservoir performance. Seepage may lead to internal erosion, piping, and structural failure if not effectively handled. This paper aims to study the effect of sheet pile installation at the dam body and foundation on seepage reduction at the proposed earth dam located in the Al-Khoser seasonal river basin, Mosul city, northern Iraq. The study also compares the effectiveness of sheet piles with other seepage control methods. Seepage analysis was performed using the SEEP/W submodel within the Geo-Studio package. Different Scenarios were analyzed. The first (12) Scenarios involved a homogeneous dam body without a core, exploring different configurations of blankets and foundation treatments. The final Scenario No. 13 incorporated a central impervious core. The results demonstrated that sheet piles, due to the low hydraulic conductivity of the foundation, had minimal effect on reducing seepage rates. However, an improvement was observed in Scenario No. 12, where an extended upstream blanket was used, which reduced seepage to $(1.1 \times 10^{-7} \text{ m}^3/\text{s})$ through the dam and $(1.44 \times 10^{-10} \text{ m}^3/\text{s})$ through the foundation. In Scenario No. 13, the usage of a core reduces the seepage considerably, where the seepage rate was reduced to $(8.45 \times 10^{-8} \text{ m}^3/\text{s})$ through the dam body and to $(1.35 \times 10^{-10} \text{ m}^3/\text{s})$ through the foundation, which mean that seepage decreased by 35% in the dam body and 18% in the foundation compared to the first Scenario.

Keywords:

Seepage, Al-Khoser River Basin, Earth Dam, SEEP/W, Sheet Piles.

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1. INTRODUCTION

An earth dam is a megastructure that serves as a fundamental component of recent hydraulic works and is widely used in several water resource applications, such as irrigation, flood management, potable water reservoirs, and hydroelectric power. Earth dam structures have certain advantages over concrete dams, specifically in areas with soft (or even heterogeneous) foundation soil and where industrial construction materials are not readily available. Despite these essential benefits, earth

dams are highly susceptible to seepage problems. Seepage in earth dams occurs as a result of differences in water levels between the upstream and downstream sides, which leads to the formation of a hydraulic gradient that forces water to pass through the dam body or through its foundation [1].

A major factor to consider in the design of earthen dams is seepage. Proper evaluation of the rate at which the dam body and the foundation seep is paramount from both technical and economic perspectives. The arid areas may experience high

seepage, leading to significant water loss and compromising the dam's structural stability [2].

Uncontrolled seepage is regarded as one of the key contributors to earth dam failure, because it has a direct and continuous effect on the dam's structural stability and long-term integrity [3].

Seepage measurements in earth dams can be used to identify the key parameters of the phreatic line, pore water pressure in the dam and base, the exit gradient at the downstream face, and the seepage volume passing through the dam's cross-section [4]. Seepage pressure and flow velocity of the body and the foundation of an earth dam must be at reasonable levels to ensure that there is safety and performance of the materials that were used in the construction of the dam [5].

Earth dams' seepage poses two major challenges: technical and economic. The former is precisely calculating seepage discharge rates, as there are financial consequences of water resource loss and higher operating expenses. The second problem concerns the structural integrity of the dam, where high hydraulic gradients may cause soil particles from the seepage-affected surface to migrate downstream, increasing the risk of internal erosion and leaving the dam at risk of collapse [6].

Several engineering methods were invented to mitigate the effects of seepage. These are the installation of impervious cores, upstream impervious blankets, internal drainage, and construction of vertical cutoff walls. Among such methods, sheet piles have become efficient. These are solid vertical barriers pushed into the dam base. Sheet piles increase the stability of earth dams by increasing the seepage length and decreasing the hydraulic gradient, thereby reducing seepage discharge rates and minimizing the potential for uplift pressure and internal soil erosion. The effectiveness, however, hinges on various factors, the most notable being the depth of penetration, the horizontal position, and the water level in the reservoir.

Numerical modeling has become significant for determining seepage performance under structural and hydraulic conditions. Brontowiyono et al. [7] used SEEP/W to explore the Sattarkhan Dam. They noted that extending the cutoff wall reduced seepage, uplift pressure, and exit gradient, with a more significant effect in distinct dam sections. Their results showed that the cutoff wall length is critical for minimizing these factors, and that the location of the horizontal drainage systems is also important for improving dam stability. Moreover, the sheet pile's position influenced the flow patterns, especially in the areas around the cores.

In the study of Eyvashan earth dam, [8] explored the effects of cutoff walls on seepage patterns and the distribution of pore water pressure using numerical modeling. The researchers established a strong relationship between field measurements and their computational predictions, with R2 values of 0.9892 and 0.9834 for seepage and pore water pressure, respectively. Another notable observation was the significant decrease in pore water pressure downstream of the cutoff wall, which confirmed the correct operation of the structure. In cases where the reservoir was full, the annual seepage volume was estimated at 831,604 m³.

These analytical implications become even more relevant when assessing performance in extreme hydrological situations, a case investigated by Al-Shukur and Mahmoud [9], who studied the performance of the Al-Adhaim dam under flood conditions. They found that the embankment seepage rates may reach up to 55.1 percent of the normal maximum water level, and the safety factor declines to the critical threshold of 1.219 under extreme flood conditions.

Stability analysis of steady-state seepage conditions has been discussed by Huang [10], who devised a numerical process that combines trial-and-error techniques for calculating piezometric heads with a finite-element model based on cap models. This strategy was effectively used at the Liyuetan reservoir dam in Taiwan, demonstrating sufficient factors of safety to avoid stability failure and providing an in-depth picture of the dam's behaviour under seepage conditions.

Alternatively, geomembranes as additional seepage barriers have been examined by Weber and Zornberg [11], who studied leakage rates through geomembrane liner systems under high hydraulic heads relevant to dam applications. They determined that geomembranes are highly effective at minimizing permeability, but their construction can create defects, compromising their integrity. Therefore, they are commonly used in combination with clay liners to enhance performance, especially when the hydraulic head is high, as is the case with large dams.

In a thorough seepage and slope stability analysis of the proposed Qaim Dam on the Khosar River, Saeed et al. [12] used Artificial Neural Networks (ANN) to perform the analysis. The study designed two neural network models to forecast seepage and safety factors for upstream and downstream gradients under steady-state and rapid drawdown conditions. The research produced spectacularly accurate results, with coefficients of determination of 0.996 for seepage prediction, 0.957 and 0.925 for upstream and

downstream slope stability, respectively, and 0.976 for rapid drawdown scenarios.

Khalil [13] simulated pore-water development in a thin clay core of an earth dam using finite-element analysis in GEO-SLOPE, considering saturated or unsaturated conditions. The chimney drain was found to be effective in reducing pore pressures. In the case of the BADUSH dam, a sudden increase in water level led to a rapid accumulation of pore pressure over 8 days. Pore pressures ranged from 175 to 145 kPa in normal areas and from 25 to 50 kPa in other areas, indicating the effects of the dam height and the construction period.

Pressure peaks were in the lower core, and negative values on the crest enhanced the significance of transient and seismic analyses for dam safety.

The seepage and stability of the Duhok zoned earth dam were assessed using SEEP2D and STABIL2.3 by Ismaeel and Noori [14]. The experiment examined seepage flow, pore pressure, and slope stability in various sections. The findings indicated that when the ratio of K_x/K_y was increased, the seepage was increased and the factors of safety were decreased. Although there is a sense of incompatibility with the field piezometer data, the dam was observed to be stable in its current condition, validating the reliability of the models. Based on this, the following are the aims of this study:

- To determine the effect of the depth of the sheet piles and their position on the seepage patterns under earth dams.
- To investigate the influence of the change in water level of a reservoir on total seepage, hydraulic gradients, and distribution of pore-pressure.
- To determine the relationship between the dam body material, type of foundation soil, and seepage behavior using SEEP/W.
- The findings show that the placement of a sheet pile in the downstream (D/S) region may shift seepage flow lines towards the downstream toe. Such a reversal in flow direction will further expose the dam's structural stability and hydraulic safety to internal erosion and soil piping.

The rest of this work is organized as follows: Section 2 covers the materials and methods. Section 3 explains the seepage modeling approach. Section 4 addresses the discussion and results analysis. Section 5 gives the conclusion and the key recommendations.

2. RESEARCH MATERIALS AND METHODS

2.1. SEEP/W Application

SEEP/W, which is a computational module made part of the Geo-Studio software package. It is a finite-element numerical modeling framework specifically designed to simulate problems of groundwater seepage and the dissipation of excess pore-water pressure in porous geological formations, such as soil and rock matrices.

The software's mathematical formulation enables exploration of a wide range of hydraulic scenarios, from simple saturated steady-state conditions to complex transient scenarios that include both saturated and unsaturated flow [15].

SEEP/W has been applied to the analysis and design of infrastructure projects across multiple engineering applications, including geotechnical, civil, hydrogeological, and mining applications [16], [6], [17], [18].

The computational tool has also been extensively tested in numerous research studies. There is a rich literature showing the application to numerous seepage problems and groundwater flow analysis, such as fractured slope stability [19], earth dam hysteresis analysis [20], embankment dam seepage comparison [21], earth-fill dam optimization [22], the use of geomembrane barrier applications [23], and dam safety evaluation [24].

2.2. Site Description

The flow in the Al-Khoser River is seasonal, and the river is located on the northeastern side of Mosul, Iraq. The basin is estimated to cover approximately 654 km² and to be around 30 km long. It has a semi-arid climate with minimal and infrequent precipitation that occurs primarily during the winter months. These conditions produce seasonal surface runoff, underscoring the importance of implementing water-harvesting systems in the region.

The geospatial site that has been identified at the downstream end of the basin is a naturally occurring depression that would be used to construct a small-scale earthen dam to collect rainwater. The location is close to topographical gradients at (36°27'N) and (43°11'E), where the topography naturally assists in the collection and concentration of runoff during rainfall periods.

Studies of the soil in the basin indicate that silty clay, silty clay loam, and silty loam are the predominant surface layers. These fine-grained soils have moderate infiltration rates and a good ability to retain moisture, a factor that reduces water loss through seepage and improves reservoir performance. The farming sector in the

region relies on rainfall, and the three major crops that comprise the agricultural sector include wheat, barley, and olive production. With the emerging difficulties of varying climatic conditions and increased water demand, the creation of local rainwater harvesting systems in this basin presents significant potential to improve water security, sustain food production, and support rural sustainability. The topographical and hydrological features of the area indicate the technical and environmental suitability of applying these approaches to water management.

2.3. Dimensions of Al-Khoser RWH Dam

The dam at the Al-Khoser basin is made of compacted earth embankment built to manage the amount of water that flows seasonally in this semi-arid land. The building is 10.4 m above the foundation level, and the crest is 267 m above mean sea level. The crest width is 5.5 m, which would provide adequate space in terms of the routine monitoring and maintenance processes. Its base measures 63 m, which provides the structural stability necessary to counter hydraulic pressures.

The embankment cross-section is in a 1:3 and 1:2.5 ratio to the upstream and downstream slopes, respectively, chosen to ensure the slope is not affected by different moisture levels. The dam involves a length of about 980 m along the valley, which provides storage capacity for large amounts of catchment runoff. Reservoir maximum capacity of about 3.4 million m³ and maximum depth of 8.4 m. The impervious core comprises low-permeability clay that spans almost the entire dam height, with a crest dimension of 3 m and a bottom dimension of 10.4 m. Internal core slopes of 1:2.5 on each side will provide structural support and serve as an effective barrier against seepage.

Foundation seepage control involves the use of a cutoff trench, which lies beneath the core and is excavated to a depth of 1 m with top and base widths of 5 and 3 m, respectively. The slopes on the trench side are made at 1:1 in order to enable the integration of the foundation materials and reduce the subsurface flow paths. The flood management employs an Ogee spillway that can handle peak discharges of 1084 m³/s, corresponding to the 100-year flood event. The hydraulics of the spillway profile dissipate energy effectively, enabling discharge to be measured during high-intensity rainfall. The design approach is applicable in rural semi-arid areas, as it is a compromise between hydraulic design, geotechnical soundness, and construction cost.

3. SEEPAGE MODELING

3.1. Methods of Controlling Seepage

- A Sheet Pile is a set of barrier panels fitted in the dam foundation, which are made of concrete or steel plates placed vertically, to cut off seepage paths. Such installation causes the flow lines to follow longer paths, and with increased path length, the hydraulic gradient decreases; consequently, water pressure in the downgradient regions is reduced. This, in turn, increases the stability of earthen dams and eliminates soil piping.

- A blanket is an impervious, non-permeable layer, usually made of clay. This layer is applied by engineers on the upslope slope of the dam body, on the top of the reservoir floor above the foundation, or on both. The blanket is employed to stop or greatly mitigate seepage through the dam body and foundation, thus enhancing the general stability of the dam without affecting the storage capacity of the reservoir water.

- A Core is an impervious or low-permeability central object located in the interior of a structure of an earthen dam. Such a core is made of materials with minimum permeability properties, like well-compacted clay. It is a system of internal barriers that aims to prevent or significantly reduce water seepage through the dam body and to improve structural stability.

3.2. Study Scenarios

To analyze the scenarios presented in the study, steady-state seepage conditions were simulated using the Seep/W GeoStudio software, including a dam body saturation scenario in which the boundary conditions remain constant over time and the seepage entering the dam body equals that exiting it. The analysis was conducted under two reservoir levels: first, at a depth of 8.4 m, representing the full reservoir capacity; and second, at a height of 4 m, representing half the reservoir volume.

The flow measurement location was designated at point (60,0) and divided into two sections: the first for measuring flow in the dam foundation only from (60,0) to (60,10), and the second for measuring flow in the dam body only from (60,10) to (60,17.5). Thirteen scenarios were generated in this research: 12 scenarios where the dam body was homogeneous (without a core) and one Scenario using a core as shown in Table 1.

The first five scenarios studied conditions at full reservoir capacity, where scenario 1 discusses a dam without sheet pile addition, scenario 2 discusses the dam with sheet pile addition in the dam foundation at U/S with 4 m depth, scenario 3 explore the dam with sheet pile addition in the dam foundation at U/S with 8

m depth, scenario 4 involves adding sheet pile at both D/S and U/S with 4 m depth, and scenario 5 studies the dam with sheet pile installation with 8 m depth, as shown in Figures (1-5). These scenarios are important for studying the dam's hydraulic behavior under various structural configurations. The findings of these analysis can be determined on the best and most cost-effective seepage-control system to use in similar geotechnical environments.

Table 1: Description of Study Scenarios.

Scenario No.	Description	Reservoir Level (m)
1	Dam without sheet pile addition.	8.4
2	Dam with a sheet pile at the upstream (U/S) foundation, 4 m depth.	8.4
3	Dam with a sheet pile at the upstream (U/S) foundation, 8 m depth.	8.4
4	Dam with sheet piles constructed at both upstream (U/S) and downstream (D/S) foundations, 4 m depth.	8.4
5	Dam with sheet piles constructed at both upstream (U/S) and downstream (D/S) foundations, 8 m depth.	8.4
6	Dam without sheet pile addition.	4.0
7	Dam with a sheet pile at the upstream (U/S) foundation, 4 m depth.	4.0
8	Dam with a sheet pile at the upstream (U/S) foundation, 8 m depth.	4.0
9	Dam with sheet piles constructed at both upstream (U/S) and downstream (D/S) foundations, 4 m depth.	4.0
10	Dam with sheet piles constructed at both upstream (U/S) and downstream (D/S) foundations, 8 m depth.	4.0
11	Dam with a blanket layer added at the upstream side	8.4
12	Dam with a blanket layer covering the reservoir floor and the upstream slope of the dam body	8.4
13	Non-homogeneous dam with a central impervious core.	8.4

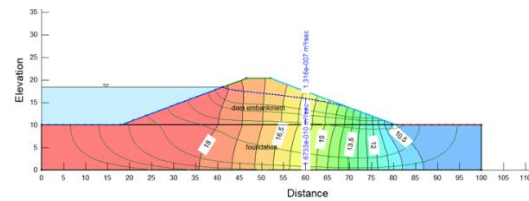


Fig. 1 Flow net and total head distribution for homogeneous dam (Scenario 1).

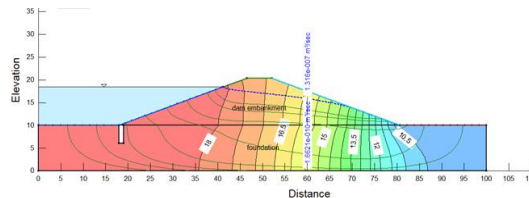


Fig. 2 Flow net and total head distribution of the homogeneous dam with sheet pile (Scenario 2).

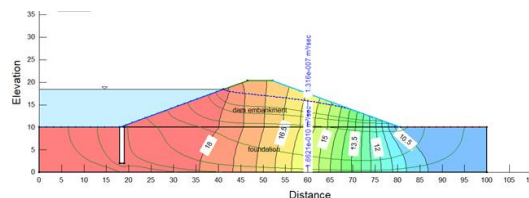


Fig. 3 Flow net and total head distribution for the homogeneous dam with sheet pile (Scenario 3).

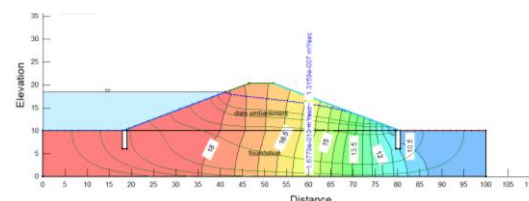


Fig. 4 Flow net and total head distribution of the homogeneous dam with sheet pile (Scenario 4).

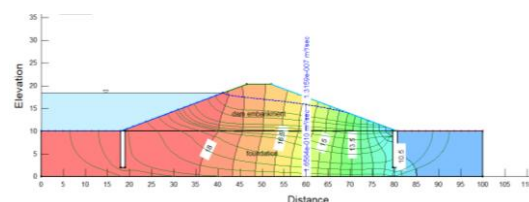


Fig. 5 Flow net and total head distribution of the homogeneous dam with sheet pile (Scenario 5).

In scenarios 6-10, the same configuration as in scenarios 1-5 was applied. However, in these scenarios, the reservoir was set at half capacity with a water level of 4 m, as illustrated in Figures 6-10. On the other hand, in scenario 11, as shown in Figure 11, a homogeneous dam was used without sheet pile installation; instead, a blanket layer was installed on the upstream side (U/S) of the reservoir floor. In Scenario 12, as illustrated in Figure 12, the dam is also homogeneous. Still, the blanket layer is extended to cover both the

reservoir floor and the upstream slope of the dam body, enhancing seepage control. In contrast, scenario 13 in Figure 13 represented a non-homogeneous dam with a central impervious core located at the base of the dam body.

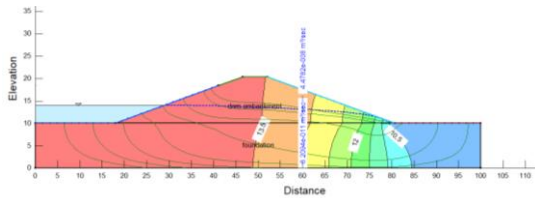


Fig. 6 Flow net and total head distribution of the homogeneous dam (Scenario 6).

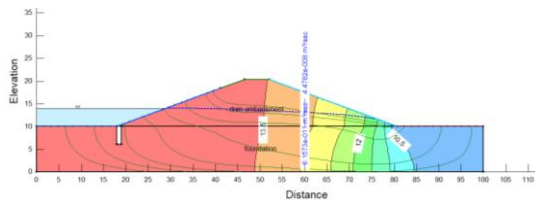


Fig. 7 Flow net and total head distribution of the homogeneous dam with sheet pile (Scenario 7).

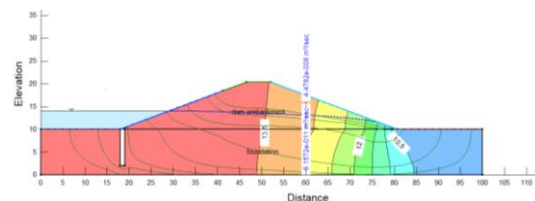


Fig. 8 Flow net and total head distribution of the homogeneous dam with sheet pile (Scenario 8).

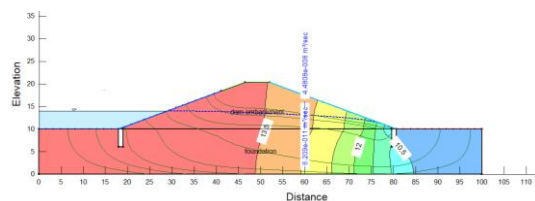


Fig. 9 Flow net and total head distribution of the homogeneous dam with sheet pile (Scenario 9).

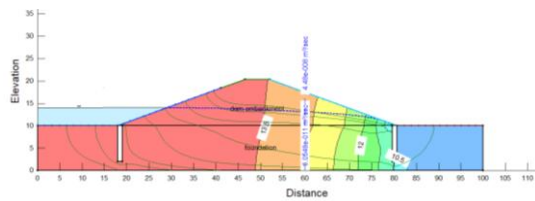


Fig. 10 Flow net and total head distribution of the homogeneous dam with sheet pile (Scenario 10).

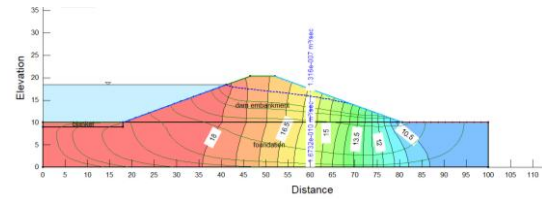


Fig. 11 Flow net and total head distribution of the homogeneous dam with a blanket layer (Scenario 11).

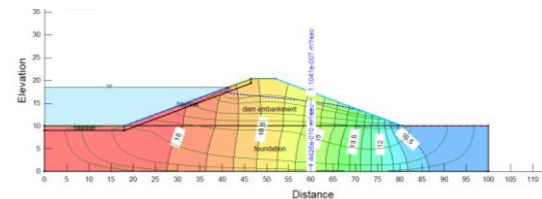


Fig. 12 Flow net and total head distribution of the homogeneous dam with a blanket layer (Scenario 12).

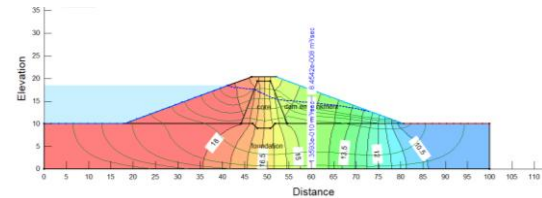


Fig. 13 Flow net and total head distribution for the dam with core (Scenario 13).

4. RESULTS AND DISCUSSIONS

Comparative analysis of the seepage rate in scenarios 1-5, with maximum reservoir level conditions (8 m), displayed no significant change in the rate of discharge. This was regardless of the installation location of sheet piles, either at the upstream (U/S) or the downstream (D/S) side of the dam, and whether they are embedded with depths of 4 m or 8 m. The same observations were demonstrated in scenarios 6-9, whereby the level of the reservoir was lowered to 4m, or about half of the total storage capacity.

Conversely, it was observed that there was an exception in scenario 10, in which sheet piles were used with a depth of 8 m at both the upstream and downstream areas. This setup yielded only a significant 4% less foundation seepage than the level in scenarios 6-9. Although this is the slightest improvement, the size of the reduction is deemed too small to warrant the large expenditure of excavation and sheet piling installation. The results indicate that, at the current geotechnical and hydraulic conditions, the performance of sheet pile installation is therefore limited, especially in foundations with low hydraulic conductivity. The factor that led to the minimal seepage recorded at the study site lies in the soil density used to construct the dam

foundation, which considerably lowers hydraulic conductivity and, consequently, seepage rate.

In this case, geotechnical conditions do not consider the use of sheet piles economically effective; a more cost-effective and hydraulically efficient solution can be implemented by laying a blanket over the reservoir bed and the slope before the dam. In scenario 11, in which the blanket was applied only to the upstream foundation, the measured discharge rates were virtually identical to those in scenario 1, where no blanket treatment was applied. This may be explained by the migration of seepage paths from the dam body into the foundation at the bottom of the structure, extending to the downstream toe, as illustrated in Figure 11. The blanket in this arrangement can only act as a barrier to infiltration into the reservoir bed and therefore has little impact on the overall seepage rates.

In comparison, scenario 12 was more detailed and included a blanket treatment that spans the entire face of the dam body and foundation. This design successfully restricted water intrusion at both the reservoir bed and the dam structure, resulting in a significant decrease in seepage compared to scenario 11. In particular, discharge by the dam body was minimized by 15%, and foundation seepage was minimized by 14%, as depicted in Figure 12.

In case 13, further improvement was achieved by the installation of a centrally impervious core. This installation produced the greatest decrease in seepage rate, with a 35% reduction in rate through the dam body and 20% reduction in rate through the foundation, as shown in Figure 13, compared to the baseline in scenario 1 with no core installed.

5. SEEPAGE MODELING

5.1. Total head

The Seepage analysis was done as a total head considering the first five different scenarios, where these scenarios were performed with the reservoir water level at 8.4m, as shown in Table 1, which was the maximum reservoir capacity. Figures 1-5 indicate that flow line patterns vary based on the presence or absence of sheet piles and vary based on the location and length of the sheet piles. Nonetheless, there is no difference in the direction of the phreatic line in terms of its direction in any of these scenarios.

The total head distribution shows the change in head between upstream and downstream across the dam body and foundation, with downstream values ranging from 18m upstream to 10.5m downstream. This head difference creates 1.31×10^{-7} m³/s discharge rates through the dam body and 1.67×10^{-10} m³/s through the dam

foundation. It is important to note that discharge values are identical in all the scenarios 1-5, which proves that there is no difference in the flow rates regarding the sheet pile being installed at the upstream or downstream positions or the depth of the sheet pile. The studied scenario involved a high-density foundation soil, resulting in low hydraulic conductivity. As a result, installing sheet piles in the foundation does not significantly affect the seepage rate, though it alters the seepage flow directions. As determined, the presence or absence of sheet piles has no effect on seepage through the dam body. On other hand in the 6-10 scenarios which we analyzed with a reservoir water level of 4 m, or a level nearly half of the reservoir level as in Figures (6-10), we found that the values of total head between 13.5 m upstream and 10.5 m downstream were such that the discharge rate across the dam body was 4.47×10^{-8} . The flow rate across the foundation was 6.15×10^{-11} . However, the rate of discharge was also constant in all scenarios, regardless of the location and depth of the sheet pile, which is consistent with the results with 1-5 scenarios. Based on the obtained results, other seepage reduction scenarios were investigated, including placing a blanket over the dam base at the upstream scenario 11, which offered seepage rates 1.31×10^{-7} and 1.67×10^{-10} across the dam body and foundation, respectively. The discharge rates of seepage obtained for each analyzed scenario are illustrated in Table 2.

Table 2: Seepage discharge rates at the dam body and foundation within the studied scenarios.

Scenario No.	Pressure head under the toe (m)	Discharge rates at dam body (m ³ /s)	Discharge rates at dam foundation (m ³ /s)
1	2	1.316×10^{-7}	1.673×10^{-10}
2	2	1.316×10^{-7}	1.662×10^{-10}
3	2	1.316×10^{-7}	1.662×10^{-10}
4	2	1.315×10^{-7}	1.677×10^{-10}
5	2	1.315×10^{-7}	1.656×10^{-10}
6	2	4.478×10^{-8}	6.209×10^{-11}
7	2	4.478×10^{-8}	6.157×10^{-11}
8	2	4.478×10^{-8}	6.157×10^{-11}
9	2	4.480×10^{-8}	6.209×10^{-11}
10	2	4.480×10^{-8}	6.054×10^{-11}
11	2	1.316×10^{-7}	1.673×10^{-10}
12	2	1.104×10^{-7}	1.442×10^{-10}
13	2	8.454×10^{-8}	1.359×10^{-10}

5.2. Blanket

The upstream blanket installation was a practical method for reducing the rate of water infiltration in the dam foundation to the reservoir bed.

However, the foundation remained with seepage at the origin of the dam body. The reason for this is that the dam structure had a large base width (62.7m) and an internal flow sufficient to retain water, with no water escaping into the foundation, stabilizing the discharge rate.

According to the constraints in the previously discussed scenarios, the blanket design was used in scenario 12. The design also involves the extension of the blanket, and it would cover the reservoir bed, upstream slope, and the upstream face of the dam body. The empirical findings showed that seepage control was greatly improved, and discharges decreased to $1.1 \times 10^{-7} \text{ m}^3/\text{s}$ at the dam body and $1.44 \times 10^{-10} \text{ m}^3/\text{s}$ at the foundation.

The constant cover provided by the blanket effectively limited the inflow of water into the reservoir and the dam feature, thereby improving overall hydraulic performance, as shown in Figure 12. The above results indicate that scenario 12 has a more effective seepage-reduction strategy than scenario 11.

5.3. Core

A core was installed within the dam body in scenario 13 and evaluated in comparison with scenario 12 to determine the optimal seepage control strategy. As illustrated in Figure 13, this configuration resulted in a significant reduction in seepage, with discharge rates reaching $8.45 \times 10^{-8} \text{ m}^3/\text{s}$ through the dam body and $1.35 \times 10^{-10} \text{ m}^3/\text{s}$ into the foundation.

These results indicate that scenario 13 represents the most effective treatment among all scenarios analyzed in this study. Notably, the phreatic line intersects with the core area, and the high density and low permeability of the core material contribute to a deflection in pressure head, where the seepage decreased by 35% in the dam body and 18% in the foundation compared to the first scenario.

5.4. XY-Gradient

We notice, as in scenario 5, that the installation of the sheet pile in the downstream region causes flow lines to intersect with the sheet pile, creating a flow obstruction that leads to an increased hydraulic gradient in this area, resulting in water rising upward and moving toward the toe region. Figure 14 shows the change in hydraulic gradient across scenarios 1-5, which increases the likelihood of soil piping around the sheet pile. Figure 15 shows the relationship between the x-y

hydraulic gradient and horizontal distance (x m). The x-y hydraulic gradient was computed at 10m elevation at the base of the earthen dam and the top of the foundation. Seven horizontal checkpoints were taken from $x=70$ to $x=80$ as shown in Figure 14 for Scenario one and compared with corresponding values in Scenario 5, to determine the effect of the downstream sheet pile on flow and hydraulic gradient variations caused by sheet pile installation. We observed equal x-y gradient values at the initial curve positions up to $x = 75$, where the influence of the sheet pile begins. The hydraulic gradient x-y gradient values increase gradually as we approach the sheet pile, reaching values of 0.37 for scenario 1 and 0.41 for scenario five at a distance of $x = 79$. These points were located at a horizontal distance $x = 79$ (at the toe point), as shown in Figure 16 for both scenarios 1 and 5, to determine the effect of the downstream sheet pile on flow and hydraulic gradient variations resulting from sheet pile installation. Figure 17 shows the relationship between the x-y hydraulic gradient and vertical distance (Y m). The x-y hydraulic gradient was calculated from a 10m elevation at the bottom of the dam body down to the end of the foundation, vertically, using seven checkpoints.

The x-y hydraulic gradient was calculated from a 10m elevation at the bottom of the dam body down to the end of the foundation, vertically, using seven checkpoints. The analysis shows that in scenario 1, the hydraulic gradient rises gradually from 0.18 at $Y = 2 \text{ m}$ to 0.38 at $Y = 10 \text{ m}$. In contrast, Scenario five records higher values, increasing from 0.34 at $Y = 2 \text{ m}$ to 0.41 at $Y = 10 \text{ m}$, indicating the difference between the upper and lower levels of the sheet pile. We also notice irregular changes in hydraulic gradient values in scenario five, which are high at the lowest point of the sheet pile, then gradually decrease to reach 0.08 at an elevation of 5.2 m before rising again to the highest point, where the sheet pile is located near the dam body at the toe.

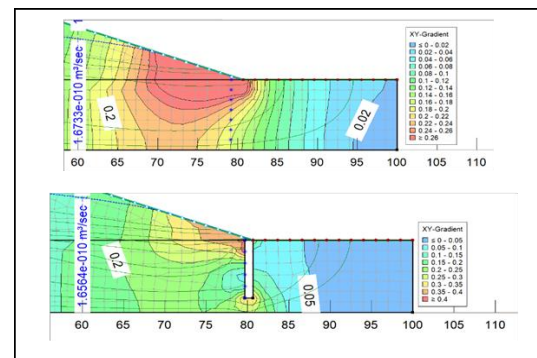


Fig. 14 Flow net and XY-Gradient distribution for Scenarios 1 and 5 (comparison points in the horizontal direction).

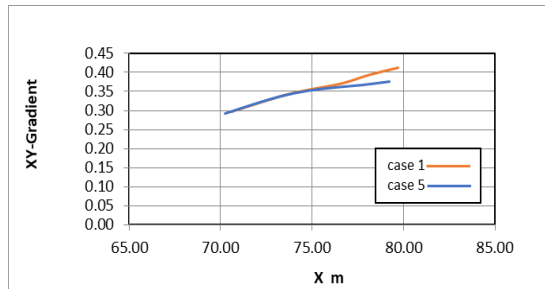


Fig. 15 Comparison of XY-gradient distribution of Scenarios (1 and 5) in the horizontal direction, at the location of the sheet pile ($x = 79$ m).

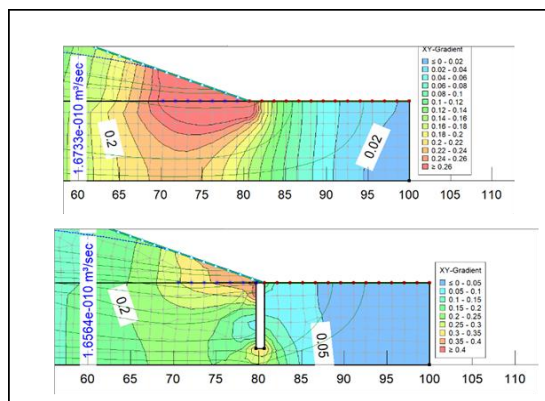


Fig. 16 Flow net and XY-gradient distribution of Scenarios 1 and 5 (comparison points in the vertical direction).

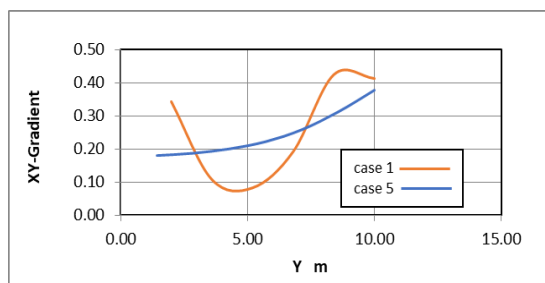


Fig. 17 Vertical distribution of XY-gradient at sheet pile location ($x = 79$ m) for Scenarios (1 and 5).

6. CONCLUSION

This work evaluated the effectiveness of sheet pile systems for seepage control in earth dams under varying reservoir conditions and concluded that core implementation within the dam body, as in scenario 13, provides the most effective seepage reduction strategy. The experimental results also indicated that seepage decreased by 35% in the dam body and 18% in the foundation compared to the first Scenario.

The obtained results revealed that the installation of Sheet piles at both upstream and downstream positions failed to achieve a significant seepage reduction at either the maximum reservoir capacity or at intermediate

water levels of 4m and 8m across all analyzed scenarios. This limited seepage control occurred due to the overall density and the low hydraulic conductivity of the dam foundation. It was also observed that installing a blanket in the upstream area of the reservoir base had only a limited impact on reducing seepage; therefore, a more effective approach is to place the blanket both on the reservoir bottom and along the downstream slope of the dam. Furthermore, the results indicated that the installation of a sheet pile in the downstream (D/S) area can lead to the deflection of seepage flow lines toward the downstream toe area. This shift in flow direction increases the possibility of internal erosion and soil piping, which may lead to structural instability and reduced hydraulic safety of the dam.

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