



Influence of Using Geosynthetic Clay Liners on Seepage Characteristics Through an Earth Dam

Afnan Salah Ameen^{1,2*}, Raad Hoobi Irzooki³

¹ Department of Civil Engineering, Tikrit University, Tikrit, 34001, Iraq.

² Department of Civil Engineering, University of Kirkuk, Kirkuk, Iraq.

³ Dams and Water Resources Engineering Department, Tikrit University, Tikrit, 34001, Iraq.

Received 21 November 2025; Revised 24 January 2026; Accepted 01 February 2026; Published 01 March 2026

Abstract

In this study, a permeability tank and SEEP/W software were used to examine the effect of geosynthetic clay liners (GCL) on seepage discharge and the phreatic line in earth dams. Initially, the SEEP/W software was validated by comparing its results with experimental results, and the agreement was excellent. Then, various scenarios were numerically completed and studied. The results indicated that adding GCL as a full length on the upstream side of the dam reduced discharge by 99.97% as compared to a dam without GCL. The results also revealed that decreasing the uncovered GCL height, dam height, and upstream head reduced discharge and lowered the phreatic line. Conversely, a decrease in the GCL slope has the opposite effect. Additionally, reducing the dam permeability decreased discharge, but the location of the phreatic line remained constant. By decreasing the dam slope, seepage discharge increases while the observable phreatic line decreases. An empirical equation was developed to determine seepage discharge through the earth dam with only a GCL with a coefficient of determination ($R^2 = 96.4\%$). Finally, the results show that using an earth dam with a GCL ($y = 6$ cm) and a medium drain length ($L_d = 40$ cm) is an effective case to lower the seepage line, reduce seepage discharge, and prevent piping failure.

Keywords: Earth Dam; Geosynthetic Clay Liners (GCL); SEEP/W; Permeability Tank; Seepage; Phreatic Line.

1. Introduction

Dams are constructed for different purposes, such as hydropower production, flood control, irrigation, and water supply for domestic and agricultural purposes [1, 2]. Earth dams are among the earliest dam types and can be constructed more affordably using locally available natural materials [3]. Due to defective design, inadequate site investigations, improper operational management, and inadequate maintenance, earth dams are more prone to hydraulic, seepage, and structural failure [4]. The most important problems resulting from water seepage in earth-fill dams include piping, sloughing, and high pore-water pressure within the dam structure [5]. About 58.3% of earth dam failures are caused by piping within the dam [6]. Other studies have shown that internal corrosion and piping are the causes of earth dam failure, which greatly affects the downstream slope stability [7, 8]. Uncontrolled seepage can pose hazards, including economic and human losses; therefore, adopting a controlled seepage method is essential to reduce the risk and manage it effectively [9]. Two approaches can control seepage. The first approach involves using passive components for anti-seepage protection, including steel sheet piles, slurry trenches, upstream impermeable blankets, grout curtains, and

* Corresponding author: as230023en@st.tu.edu.iq; afnan.salah@uokirkuk.edu.iq

<https://doi.org/10.28991/CEJ-2026-012-03-05>



© 2026 by the authors. Licensee C.E.J, Tehran, Iran. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).

diaphragm walls. The second approach requires providing a safe outlet for seepage within the dam body or its foundations. Drains, sand drains, filters, relief wells, stone columns, and ditches may be used as effective means of reducing water seepage [10, 11]. In addition, geosynthetic clay liners (GCLs) are one of the methods that are used to control seepage. Geosynthetic clay liners (GCLs) are typically placed over soil layers to act as an effective hydraulic barrier due to their significantly low hydraulic permeability to water, installation simplicity, cost-efficiency, limited thickness, and exceptional durability against environmental cycling, including freeze-thaw and wetting-drying [12-14].

GCLs are lining systems that typically consist of a thin layer of bentonite sandwiched between two layers of geotextile and may be combined with geomembranes or geotechnical meshes to enhance their hydraulic performance [14-17]. Many studies have focused on methods for controlling seepage in embankment dams using various techniques. Hoobi Irzooki (2016) derived a novel empirical equation to estimate seepage quantities through homogeneous earth dams with horizontal toe drains using the SEEP/W software and artificial neural networks [18]. Jamel (2016) used the SEEP/W finite element software to derive an empirical equation for evaluating the seepage rate in a homogeneous earth dam without a filter [19]. Salmasi and Nouri (2017) reported that installing an upstream semi-impervious blanket with appropriate length and thickness significantly reduced seepage and increased dam stability [20]. Taghvaei et al. (2018) used experimental models to study the effect of using nano-clay as an impermeable blanket for earth dams on seepage rates. The results showed that increasing the nano-clay amount reduced the discharge rate compared to the baseline model. They also validated the numerical model using SEEP/W software with the experimental results [21]. Shakouri & Mohammadi (2019) numerically analyzed the effect of varying the penetration length of the cutoff wall within the Karkheh Dam under dynamic loading conditions [22].

El Molla (2019) analyzed the influence of sheet piles on seepage quantity in earth dams using SEEP/W software and demonstrated that the total seepage discharge decreased by increasing the height of the sheet pile [23]. Sawada et al. (2019) investigated the effect of geosynthetic clay liner placement in small earth dams on dynamic stability [24]. Ullah et al. (2019) implemented a clay blanket and a cutoff wall with a sand filter at the Baz Ali small dam to mitigate seepage discharge. The results showed that adding a 100 m-long clay blanket to the upstream side was more effective at diminishing seepage rates [25]. Al-Mansori et al (2020) investigated Khassa Chai Dam in Iraq as a case study to evaluate the effect of total head measurements and core permeability on seepage quantity [26]. Sazzad & Alam (2020) used SEEP/W software to investigate the effect of using a grout curtain as a barrier in the upstream face of an earth dam. The results indicated that the grout curtain, which was considered bentonite, was sufficient to control seepage within the dam body [27]. Attia et al. (2021) studied the influence of an internal cutoff wall within an earth dam on seepage discharge by utilizing the Hele-Shaw experimental model [28]. Kumar et al. (2022) used the SEEP/W program to study the effect of 21 homogeneous earth-dam models with impervious foundations on seepage behavior. The models were considered with and without a horizontal filter and with varying widths of the central impervious core [29]. Fawzy et al. (2023) experimentally and numerically evaluated the seepage quantity and pore water pressure through earth dams. The study included cases of grouted diaphragms with and without defects. The results indicated that a grouted diaphragm penetrating the full dam height, together with a toe drain, was the optimal solution for rehabilitating earth dams [30].

Jamel & Hassan (2024) studied the effect of different core angles and the hydraulic conductivities of shell earth dams and cores on slope stability under static conditions using SEEP/W software [31]. Haghdoost et al. (2024) studied the effects of inclination angle, number, and distance of sheet piles on seepage characteristics in an earthfill dam using SEEP/W software [32]. Hassan et al. (2024) indicated that the use of two drainpipes in the Al-Adhaim dam effectively lowered the location of the phreatic line and decreased seepage discharge [33]. Jamel and Hassan (2025) studied the seepage characteristics of an earth dam by using different angles of the central core, as well as various materials and shapes of the dam body [34]. Kidder and Behaya (2025) used a hydraulic conductivity tank to study the effects of geometry and the core position on seepage characteristics within an earthfill dam. The results indicated that the trapezoidal core was the most efficient at reducing seepage by about 62%-79% [35]. Konishi et al. (2025) investigated the impact of the implementation slope angle of geosynthetic clay liners on the seismic stability of small earth-fill dams [36]. Charrak et al. (2025) showed that using a cutoff wall in a central location with a suitable horizontal drain resulted in a significant reduction in seepage discharge and enhanced the safety of earth dams [37]. Khursheed et al. (2025) established an empirical formula for predicting the seepage discharge through a non-homogeneous earth-fill dam resting on a permeable base [38].

Previous studies have not adequately investigated the effect of geosynthetic clay liners (GCL) on seepage characteristics within earth dams using a permeability tank model. Therefore, the present study examines the effect of implementing geosynthetic clay liners on the upstream side of the earth dam on seepage discharge and the seepage line using the permeability tank model and SEEP/W software. The study experimentally examines various cases of earth dams, including different uncovered heights of GCL, GCL-covered dam slopes, and lengths of downstream drains, to assess their effects on seepage discharge and the seepage line, and compares these with those of the dam without a drain or GCL. In addition, the results of the experimental model are compared with those of the numerical model (SEEP/W software). Then, additional cases of earth dams are analyzed numerically, including variations in upstream dam slopes, dam permeability, and dam height, and their effects on seepage discharge and the phreatic line. The present paper is

organized as follows: Section 2 describes the experimental work and materials. Section 3 presents the results and discussion. Section 4 evaluates the numerical modeling. Section 5 presents the seepage discharge equation through an earth dam with geosynthetic clay liners. Section 6 summarizes the main conclusions, and Section 7 lists the references.

2. Experimental Work and Materials

Laboratory experiments were conducted to simulate the movement and flow through an earthen dam using a permeability tank. The tank consisted of a solid base with two transparent plates installed to allow direct visualization and monitoring of the earthen dam during the experiment, while the side walls were constructed from steel plates to enhance the model's stability and strengthen the tank walls. The tank was made with dimensions of 220 cm in length, 60 cm in height, and 20 cm in width. A plastic mesh was placed at the tank entrance to reduce water flow and its impact on the upstream side of the body dam during the opening of the water supply pipe. Sixteen pressure sensors and piezometers were installed along the base of the dam at a constant spacing of 12 cm to measure the distribution of the water head during a steady-state experiment. The pressure sensor HX710B was manufactured in China and has a range of 0 to 40 kPa. The Arduino board was connected to all the sensors, located inside a protective box, as shown in Figure 1. Each sensor was connected to a tube that transmits the pressure head from the measurement point to the sensor and then to the Arduino for data measurement and recording on the computer. A water inlet pipe was installed on the upstream side to provide a continuous water supply to the tank. The upstream water heads are controlled via an overflow pipe to maintain the dam's retained head. A drain pipe was used on the downstream side to measure seepage discharge through the dam body. Figure 2 illustrates an overview of the permeability tank apparatus.

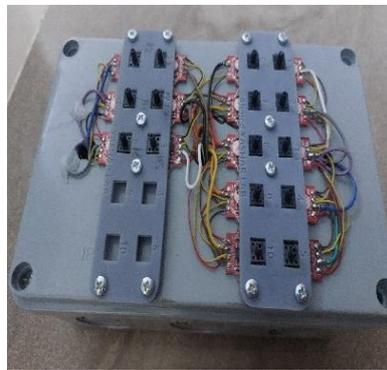


Figure 1. Connection of the Arduino board to the pressure sensors

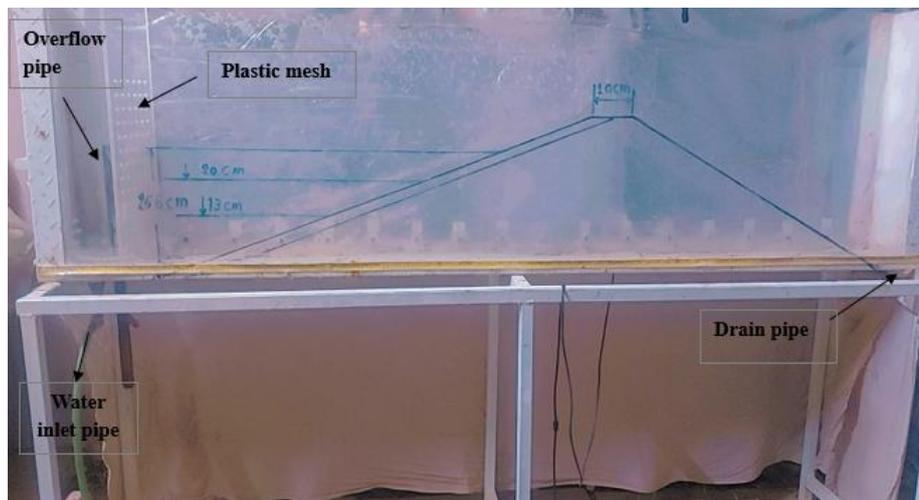


Figure 2. Permeability tank apparatus

2.1. Dimensions and Materials of the Dam Models

The real dam models with an impervious foundation were scaled down by a factor of 1:25. Avoidance and compensation techniques were adopted to scale the experimental dam model, as recommended by Heller (2011) [39] and Refaiy et al. (2021) [40]. This scaling was not applied to the soil properties and side slopes of the dam. A small-scale dam model was 34 cm in height, 10 cm in crest width, and 7.4 cm in freeboard, with upstream and downstream slopes of 3:1 and 2:1, respectively. The dam dimensions were selected according to Stringer's recommendations for small earth dams [41]. The dimensions of the real dam and the scaled model are presented in Table 1.

Table 1. Dimensions of the real dam and scaled model

Dam parameter	Real dam	Scaled model
Dam height	8.5 m	34 cm
Width of the crest	2.5 m	10 cm
Free board	1.85 m	7.4 cm
The upstream water head	6.65 m	26.6 cm
The downstream water head	0	0
The upstream slope of the earth dam	3:1	3:1
The downstream slope of the earth dam	2:1	2:1
Thickness of GCL	0.0065 m	0.65 cm
Drain lengths	3.75, 10, 16.25 m	15, 40, 65 cm

The particle-size distribution curves for the drain and dam body are shown in Figure 3. The soil type is identified as poorly graded sand by the Unified Soil Classification System (USCS) (ASTM 6913 and ASTM 2487). The shell dam and drain were used as coarse sand and poorly graded sand, with corresponding permeability coefficients of 0.00619 m/s and 0.0000907 m/s, respectively. These values are acceptable according to Das (2002) [42].

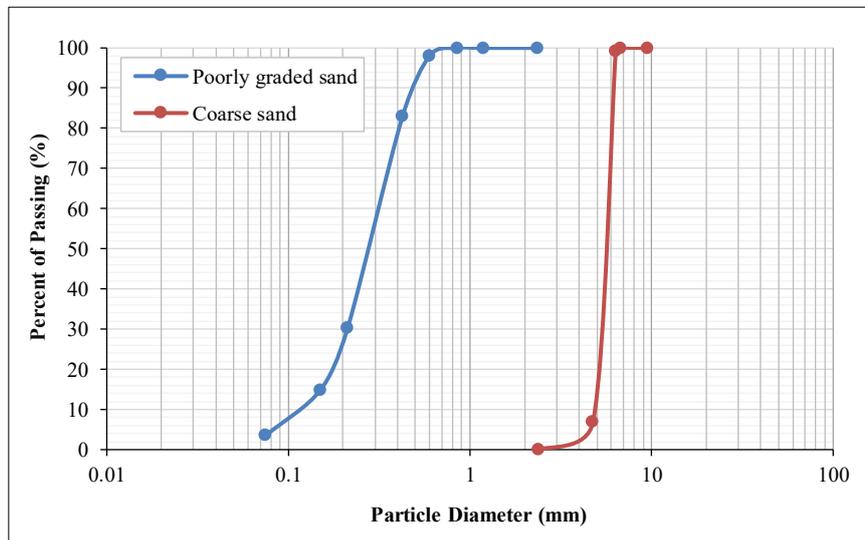


Figure 3. Grain size distribution

The dry dam material was prepared and constructed inside a permeability tank in five successive layers, each 6.8 cm thick. Each layer was compacted using a steel base to achieve a relative density of 75% at a dry density of 1.56 g/cm³, as shown in Figure 4. However, the weight of dam material required and used for each layer was calculated based on the dam body geometry and a dry density. The hydraulic conductivity test of the dam material in the laboratory was conducted using the same compaction method used during the dam's compaction inside the permeability tank. The dry density value, which corresponds to a relative density of 75%, was determined using the maximum and minimum dry density tests (ASTM 4253 and ASTM 4254). This relative density falls within the range of dense soil, according to Budhu (2010) [43].

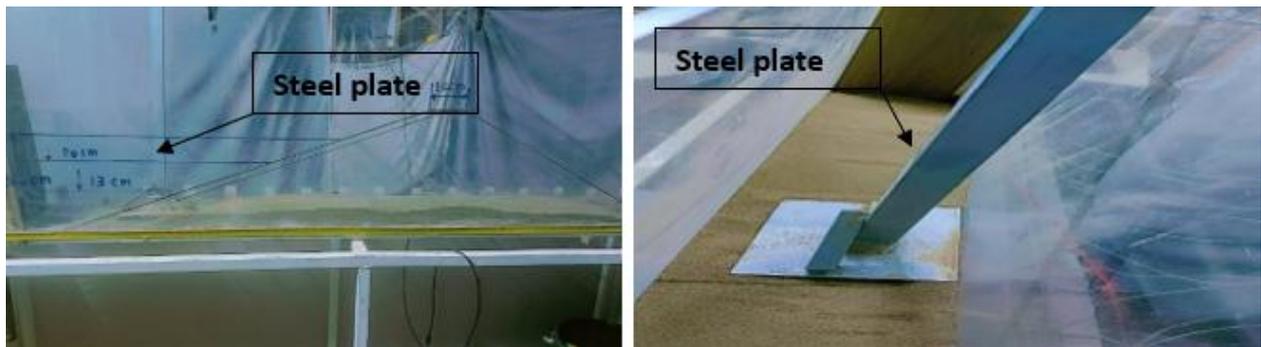


Figure 4. Steel base used for compacting the soil layers of the dam inside the tank

Geosynthetic clay liners (GCLs) with a thickness of 6.5 mm were installed on the upstream side of the earth-dam model as a barrier due to their low permeability. Silicone was used to bond the inner sides of the tank to geosynthetic clay liners, ensuring a strong bond and preventing water leakage from the edges. A geotextile was selected as a separator between the dam and the drain materials to prevent sand particles from passing through the coarse sand voids. The permeability of geosynthetic clay liners and geotextiles is 3×10^{-11} m/s and 0.095 m/s, respectively. Soil properties tests, i.e., sieve analysis, maximum and minimum dry density, and constant head permeability tests, were conducted in the Soil Mechanics Laboratory at the University of Kirkuk. The seepage discharge through the dam was determined using the volumetric approach, which measures the volume of water flowing from the dam over a specified period. The experimental procedure flowchart is shown in Figure 5.

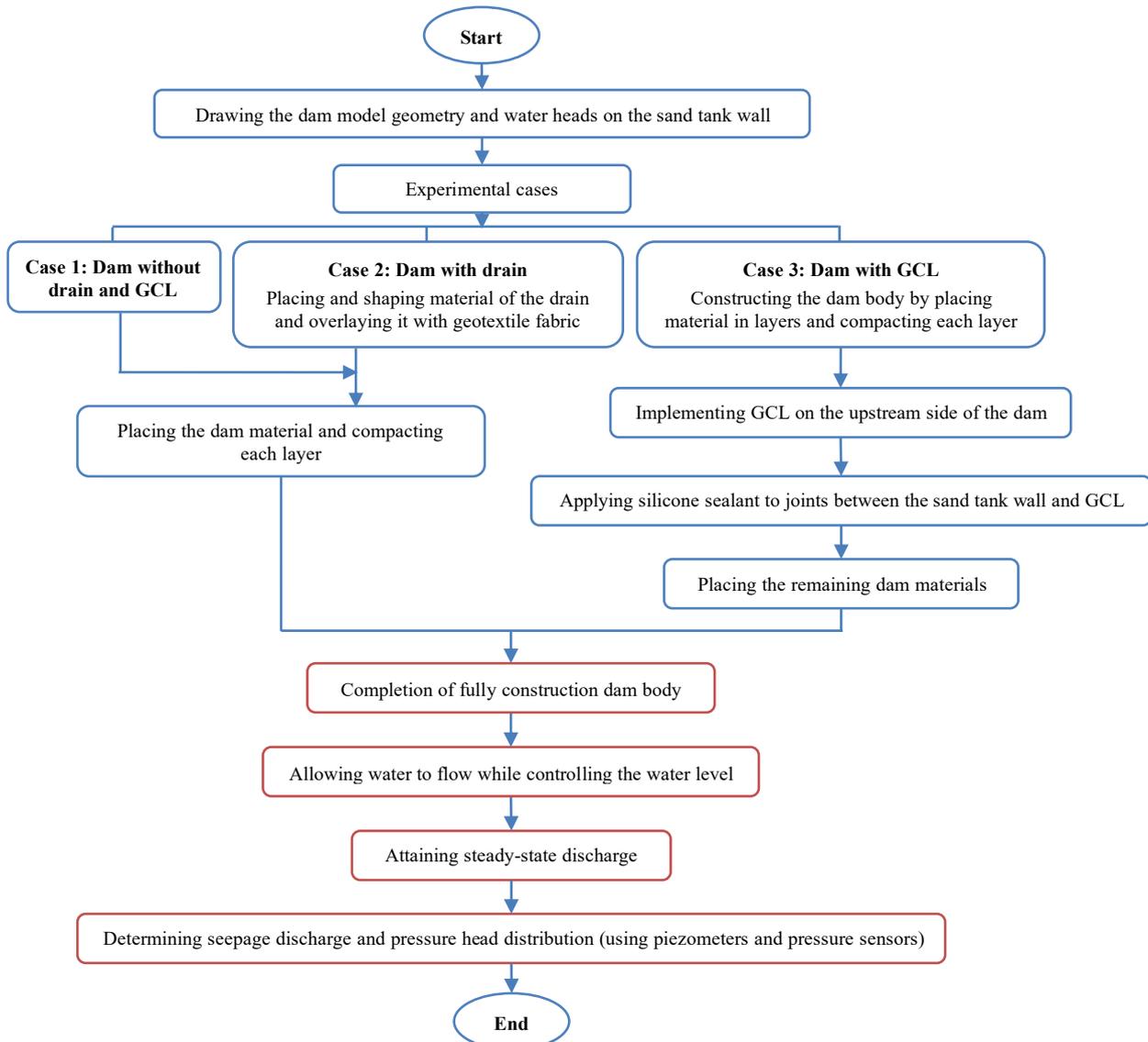


Figure 5. Flowchart of the experimental procedure

2.2. Geosynthetic Clay Liners (GCL)

In the present study, the BENTOMAT AS4000 product, a reinforced geosynthetic clay liner (GCL) manufactured by CETCO, an AMCOL company, was used. This product consists of a layer of sodium bentonite sandwiched between two geotextile fabrics (woven and non-woven). These layers were made using a needle-punching technique, which provides effective internal reinforcement that prevents the bentonite from shifting or separating, ensuring extremely low permeability and high performance in various soil and site conditions. The hydraulic permeability coefficient of GCL was 3×10^{-11} m/s according to the American standard ASTM D5887, a low value indicating high efficiency in reducing water seepage. The thickness of the GCL was 6.5 mm, and the moisture content of bentonite was 12%.

2.3. Dimensional Analysis

Dimensional analysis was used to develop empirical equations to estimate seepage discharge within a dam body. As shown in Figure 6, the variables that affect seepage discharge can be presented as follows:

$$f(q, h_w, H, h_p, y, b, b_c, k, \tan \theta, \tan \alpha, \tan \beta) = 0 \quad (1)$$

where, q : Seepage discharge through the earth dam model per unit width (L^2T^{-1}); h_w : Upstream head (L); H : Dam height, (L); h_p : Head of water in the piezometer and sensor (L); y : Vertical distance from the base of the earth dam to the end of the GCL layer (uncovered height) (L); b : Crest width (L); b_c : The distance from the starting point of the crest dam to GCL lining (L); k : Hydraulic conductivity of the shell dam material (LT^{-1}); θ : Angle of the upstream slope of the dam; α : Angle of the downstream slope of the dam; β : GCL slope angle; x : Position of the piezometer or sensor from the beginning of the upstream dam (L); and B : Base width of dam (L).

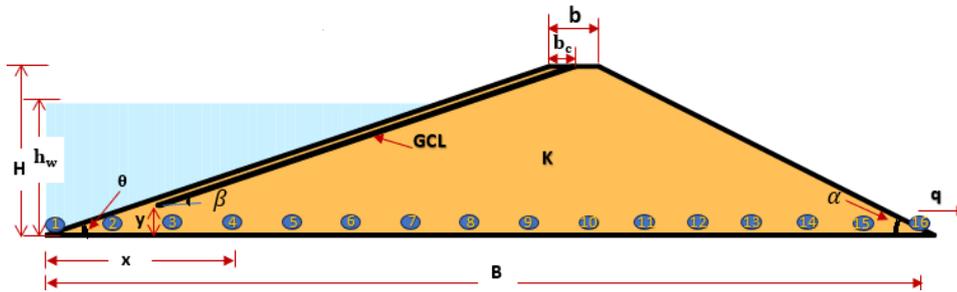


Figure 6. The investigated variables of the earth dam model with GCL

Using the Π -Buckingham theorem, the variables in the above equation can be written in terms of a set of dimensionless parameters, as follows:

$$\varphi\left(\frac{q}{h_w k}, \frac{y}{h_w}, \frac{H}{h_w}, \frac{b_c}{h_w}, \frac{b}{h_w}, \frac{h_p}{h_w}, \tan \theta, \tan \alpha, \tan \beta\right) = 0 \tag{2}$$

2.4. The Experimental Modeling

In the present study, ten earth-dam models were constructed. Three slopes of GCL, i.e., 3:1, 2.5:1, and 2:1, covering the dam body and four uncovered heights of GCL (y), i.e., 6, 10, 15, and 20 cm, were studied. GCL is located in the middle of the top of the dam and extends to the dam base. In addition, different lengths of horizontal drain (L_d) (15, 40, and 65 cm) were situated at the downstream toe of the earth dam with a thickness of 5 cm to prevent the seepage line from attaching to the downstream slope of the earth dam. These lengths represent the minimum, medium, and maximum effective lengths of the drain and were determined using the Chahar equation [44]. For each model, three upstream water heads were set at 13, 20, and 26.6 cm, while the downstream head was maintained at zero to model the worst-case seepage condition under the maximum hydraulic pressure difference between upstream and downstream. Thirty experiments were conducted to investigate the effects of various parameters on the dam's performance.

3. Results and Discussion

3.1. Effect of Uncovered Height of GCL (y)

When the geosynthetic clay liner was added to the upstream side of the dam with an uncovered height (y) of 6 cm and the upstream water depth of 13, 20, and 26.6 cm, the seepage discharge decreased by 30.67%, 22.89%, and 42.6%, respectively, compared to the dam without GCL (Figure 7). Consequently, the GCL acts as a low-permeability barrier, and the interaction of the bentonite layer with water causes it to swell, effectively sealing the pores and significantly reducing water movement, thereby reducing hydraulic permeability, Shirazi et al. (2010) [45]. Nevertheless, when increasing the uncovered height of GCL (y) from 6 to 20 cm, the seepage discharge was increased by about 71.05% for the upstream head of 26.6 cm. In addition, decreasing upstream head reduced seepage discharge for both earth dams with and without GCL.

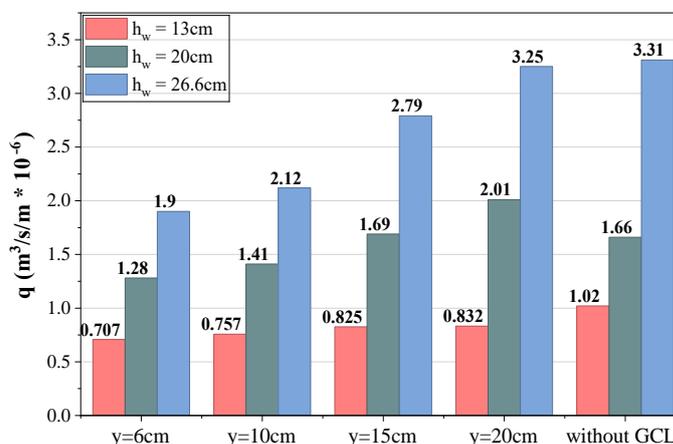


Figure 7. Seepage discharge (q) through the dam for different uncovered heights (y) of GCL and different upstream heads (h_w)

At a low upstream water level ($h_w=13$ cm), increasing the uncovered GCL height (y) from 10 cm to 20 cm insignificantly impacted the seepage line location within the dam. The location of the phreatic line for different uncovered GCL heights (10, 15, and 20 cm) remained the same as in the dam without GCL, due to the seepage flow passing beneath the GCL layer without any interaction (Figure 8-a).

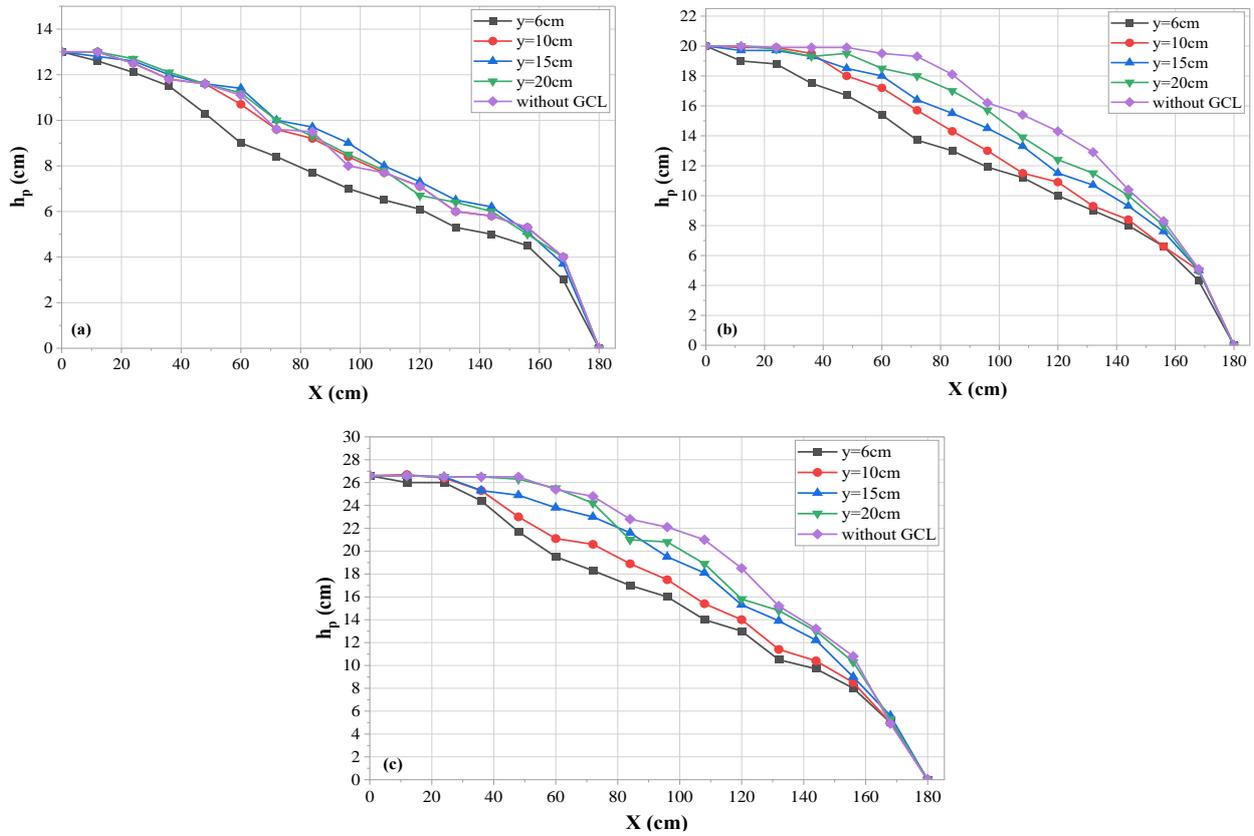


Figure 8. Location of phreatic line through the dam for various uncovered height of GCL; (a) ($h_w =13$ cm), (b) ($h_w =20$ cm), (c) ($h_w =26.6$ cm)

As shown in Figures 8-b and 8-c, it was found that the phreatic line of an earth dam with an uncovered height of 6 cm was lower than that of an earth dam without GCL. In addition, it was noted that decreasing the uncovered height (y) significantly lowered the phreatic line within the dam for upstream heads equal to 20 and 26.6 cm. However, increasing the uncovered GCL height shortened the flow path and reduced hydraulic resistance. Therefore, water moved more rapidly under the uncovered section of the GCL because the permeability of the dam body was greater than that of the GCL, resulting in increased seepage discharge and a raised seepage line. Figure 9 represents the various samples of the studied experimental dam models.

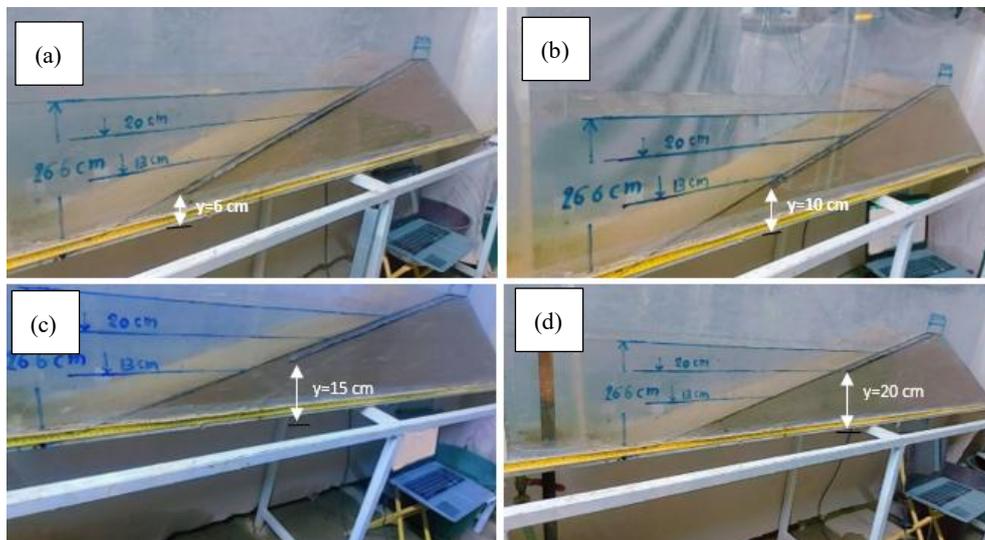


Figure 9. The experimental model for different uncovered heights (y) and GCL slope of (3:1); (a) ($y=6$ cm), (b) ($y=10$ cm), (c) ($y=15$ cm), (d) ($y=20$ cm)

3.2. Effect of Upstream Slope of Geosynthetic Clay Liners

Based on the experimental results, increasing upstream heads increased the seepage discharge for earth dams with various GCL slopes, while the uncovered height of the GCL remained constant at 6 cm, as shown in Figure 10. Furthermore, the results demonstrated that when the GCL slope was changed from 3:1 to 2:1, the seepage rate increased by 3.25%, 9.38%, and 17.89% for upstream water heads of 13, 20, and 26.6cm, respectively. The increase in seepage discharge is attributed to the short seepage path, which allows water to move easily.

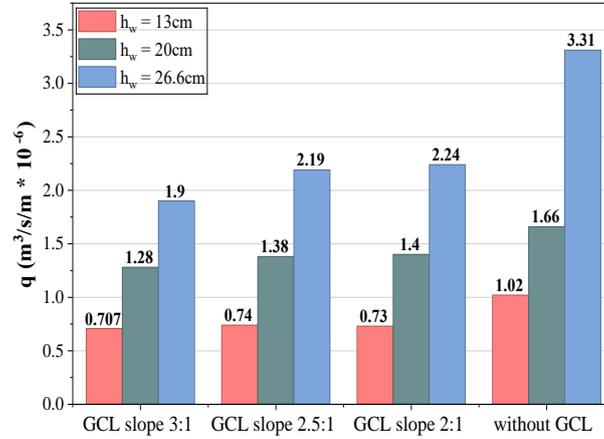


Figure 10. Seepage discharge (q) through the dam for different upstream slopes of GCL and uncovered height (y=6 cm)

Based on Figures 11-a to 11-c, it was noted that changing the slopes of the GCL layer while maintaining a constant uncovered GCL height (y) of 6 cm insignificantly impacted the location of the phreatic line for all upstream water heads. Thereby, the geosynthetic clay liner contributes to its effectiveness as a barrier, preventing water from passing through due to its low permeability. Consequently, the phreatic line remained stable despite variations in the slope of the GCL. In addition, the phreatic line of a dam without GCL was higher than that of a dam with GCL.

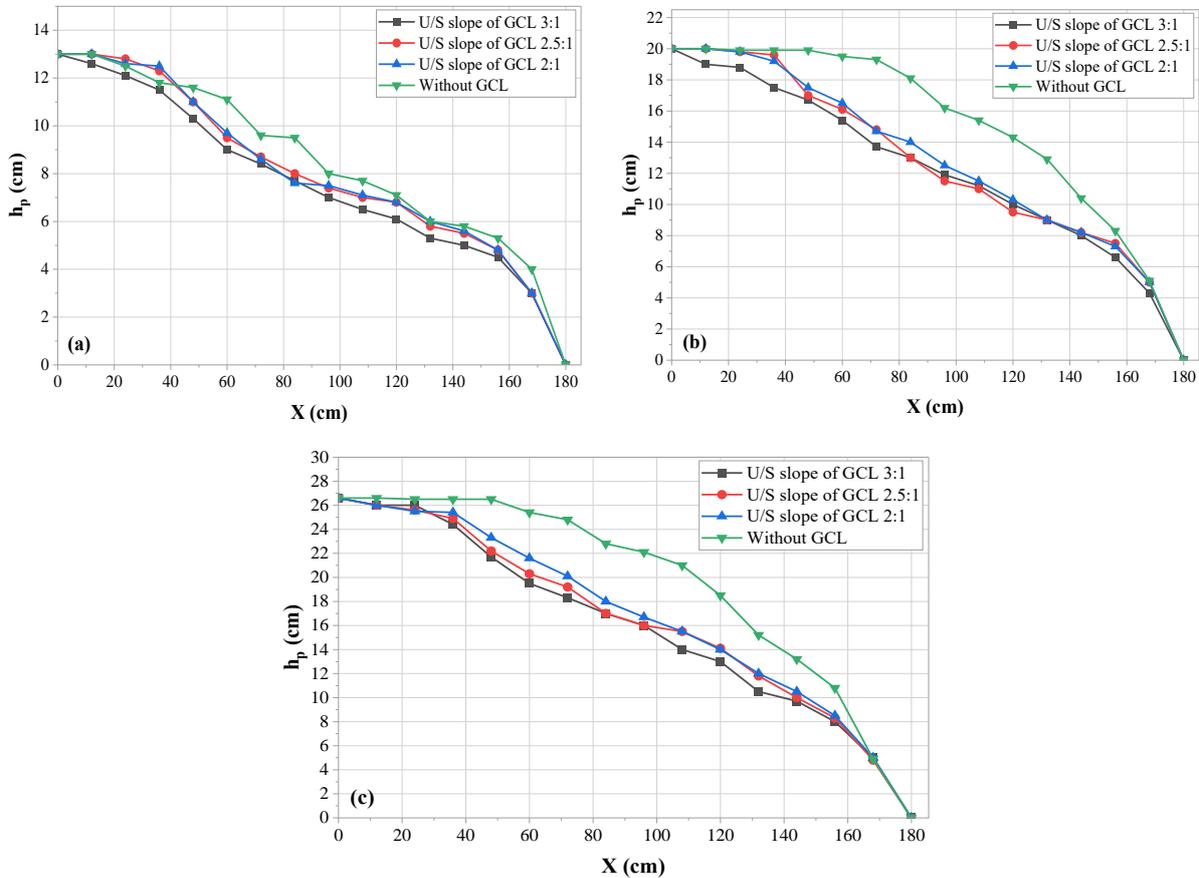


Figure 11. Location of phreatic line through the dam for various upstream slopes of GCL and uncovered height (y=6cm); (a) (h_w =13 cm), (b) (h_w =20 cm), and (c) (h_w =26.6 cm)

Thus, it is more efficient and practical to install the geosynthetic clay liners from the dam crest's center and parallel to the dam's slope. This configuration provides enhanced accessibility for inspections and maintenance in the event of damage, thereby improving system reliability and minimizing long-term maintenance expenses.

3.3. Effect of Downstream Drain Length (L_d)

Figure 12 presents the relationship between the quantity of seepage (q) through a dam without a drain and the various downstream drain lengths (L_d) for all upstream heads (h_w). Figure 12 shows that seepage and drain lengths are positively correlated; i.e., seepage discharge increases with both drain length and reservoir head. However, for a maximum water level of 26.6 cm, it was found that the seepage discharge of an earth dam with a maximum drain length was approximately 160.4% higher than that of an earth dam without a drain. The seepage discharge increased as the drain length increased from 15 cm to 40 cm and 65 cm by 16.26% and 42.28%, respectively, for an upstream water depth of 13 cm, 25.68% and 65.76%, respectively, for an upstream water depth of 20 cm, and 51.95% and 97.25%, respectively, for an upstream water depth of 26.6 cm. The correlation between pressure head (h_p) and the distance (x) for different drain lengths and upstream water depths is shown in Figure 13. It was found that the seepage line of the dam with a 15 cm drain length was higher than that of the 40 cm and 65 cm ones. On the other hand, the seepage line of an earth dam with a drain was lower than that of an earth dam without a drain. Therefore, the findings of the present study are consistent with several previous studies [40] that indicate that increasing the drain length results in higher discharge and a lower seepage line.

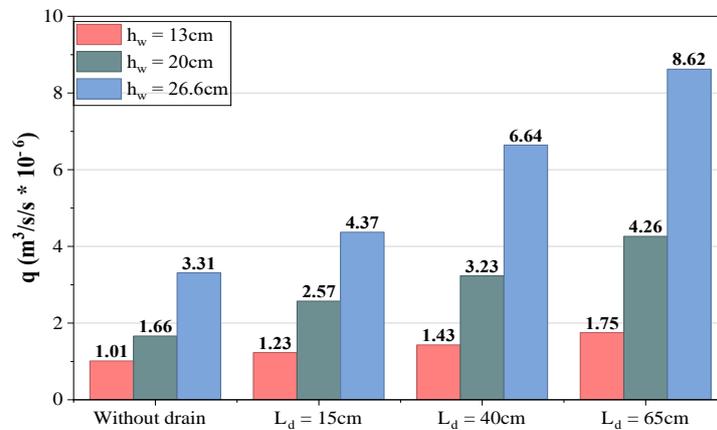


Figure 12. Seepage discharge (q) through the dam having downstream drain and without drain

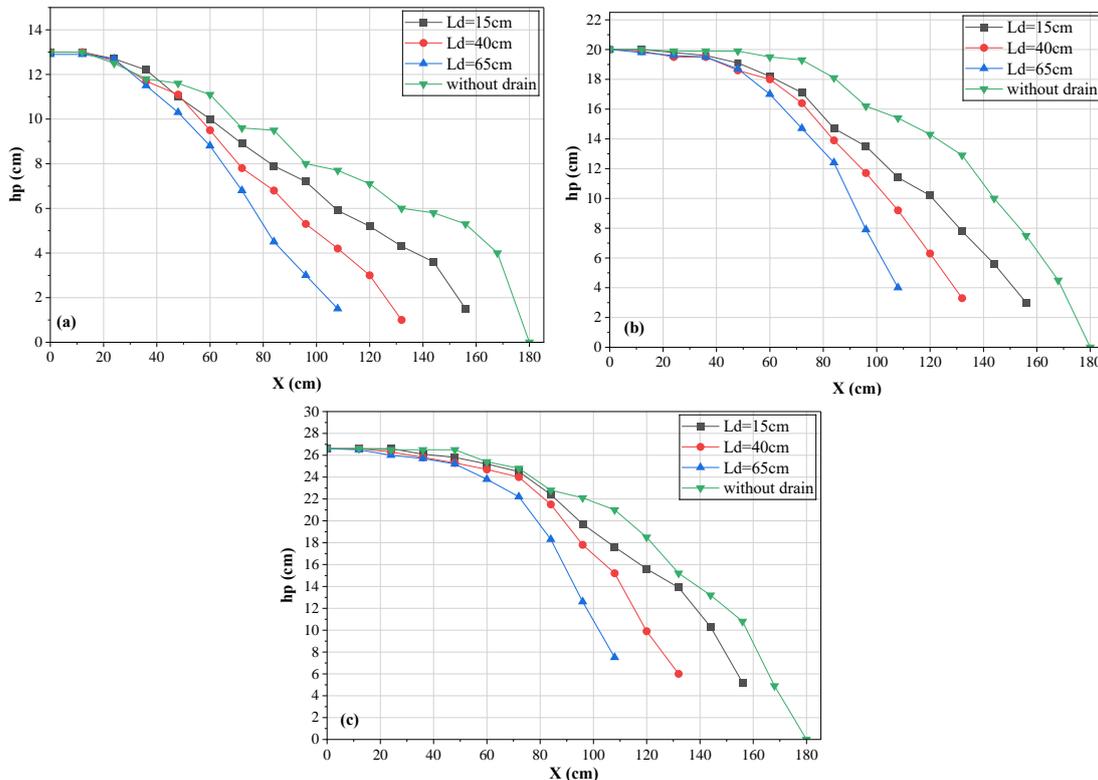


Figure 13. Location of phreatic line through the dam with various drain lengths in comparison to a dam without GCL; (a) ($h_w = 13$ cm), (b) ($h_w = 20$ cm), and (c) ($h_w = 26.6$ cm)

It was observed that the earth dam with a minimum drain length of 15 cm decreased seepage discharge, raised the phreatic line, and moved it adjacent to the downstream slope face of the dam, leading to increased soil saturation in the area and weakening the downstream slope stability. On the other hand, using a maximum drain length of 65 cm increased the seepage discharge, reducing the seepage line distance from the downstream slope of the dam and ultimately enhancing stability. Therefore, a medium drain length was the optimal choice to control seepage, as noted by Al Janabi et al. (2020) [46]. The earth dam models studied with varying drain lengths are depicted in Figure 14.

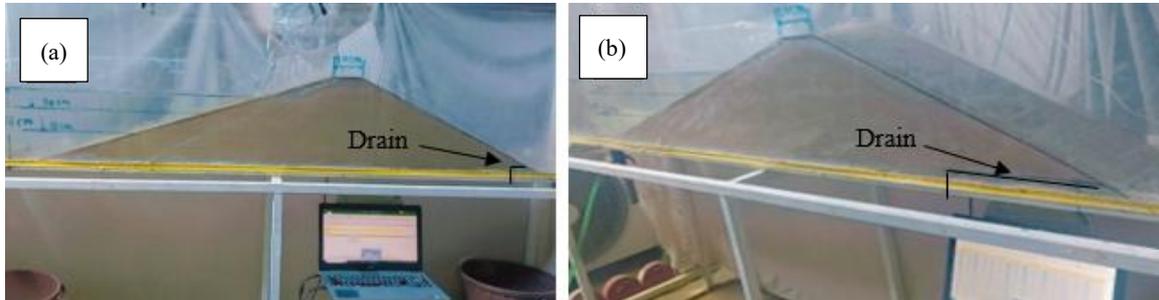


Figure 14. The experimental model with different downstream drain; (a) ($L_d=15$ cm) and (b) ($L_d=60$ cm)

4. Numerical Modeling

SEEP/W is a finite-element software package for simulating water flow through porous media. It is used to analyze groundwater flow in steady and transient conditions. It also applies Darcy’s Law to simulate groundwater flow through saturated and unsaturated states [47]:

$$Q = KIA \tag{3}$$

where, Q is the seepage discharge, K is the permeability, I is the hydraulic gradient, and A is the flow cross-section.

SEEP/W software employs partial differential equations to model and calculate water movement through the dam, enabling it to analyze seepage and flow patterns. Solving these equations enables SEEP/W to evaluate the dam’s behavior under steady-flow conditions. The equations take the following form [48]:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial H}{\partial y} \right) = 0 \tag{4}$$

where k_x and k_y are the horizontal and vertical permeability values, and h is the total water head. The seep/w software implementation flowchart is depicted in Figure 15.

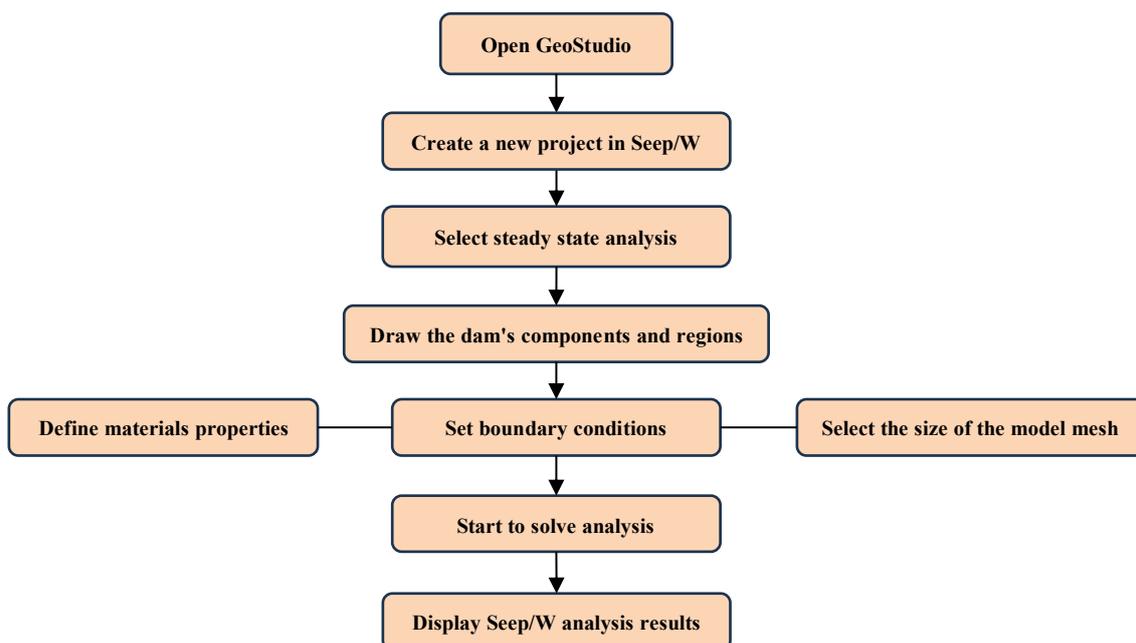


Figure 15. Seep/w software implementation flowchart

In the present study, the SEEP/W (2022) software was used to simulate seepage discharge and the phreatic line through the earth dam under steady-state conditions. The exact experimental dimensions and conditions were used for all the earth dam models. Different earth dam models were studied, including uncovered height (y), upstream (U/S) GCL slope, soil permeability, upstream (U/S) dam slope, dam height, and downstream (D/S) drain length. The process diagram of the numerical models used is illustrated in Figure 16.

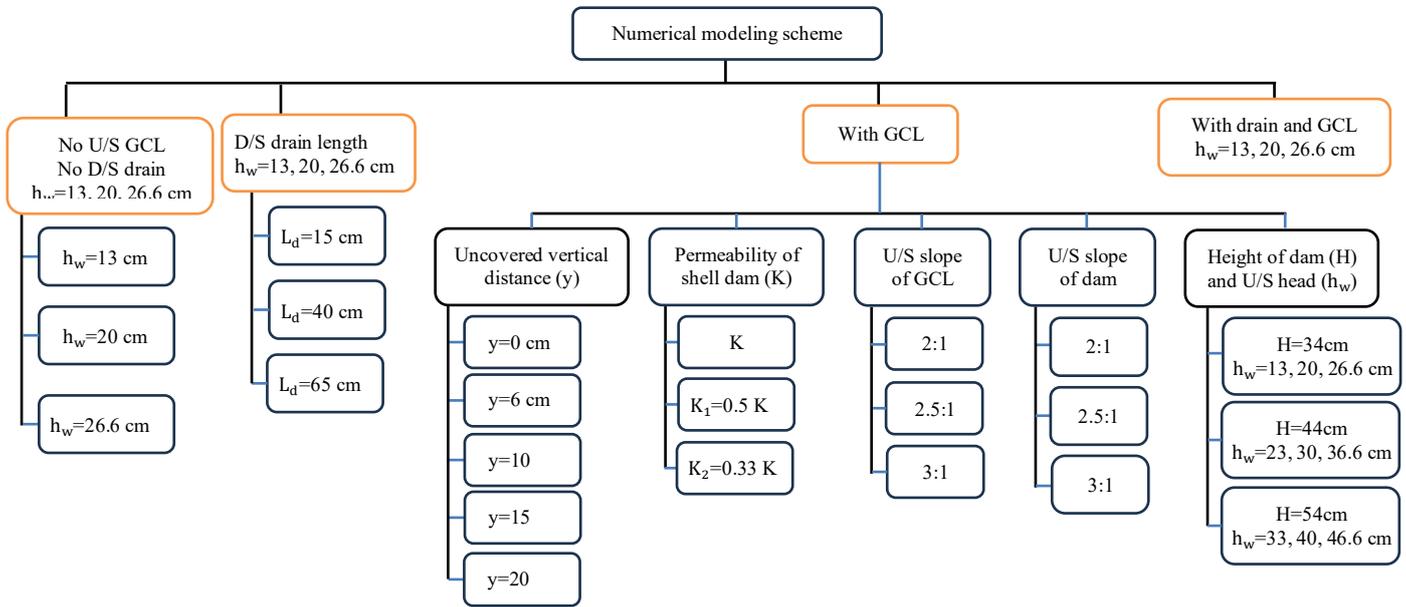


Figure 16. Process diagram of numerical models used

4.1. Validation of SEEP/W Numerical Software

The numerical model was run using the same experimental parameters and conditions described in the experimental setup section to verify its reliability and accuracy by directly comparing its results with the experimental data. A comparison was performed between the experimental and numerical results for different cases to examine the effect of each case on the seepage discharge and the seepage line within the dam body. The cases included an earth dam that has no drain on the downstream side and no GCL on the upstream side. The second case involved the earth dam, featuring various uncovered heights (y) and GCL slopes. The final case included an earth dam with varying lengths of the downstream drain (L_d).

Figure 17 compares water pressure heads along the dam base, calculated by numerical modeling, with those measured in the experimental model. In addition, the comparison of other cases was illustrated in Table 2. The comparison between experimental and numerical modeling shows excellent agreement, with the determination coefficient (R²) ranging from 0.9895 to 0.1. The values of the coefficient of determination for all models were found using the following equation [49]:

$$R^2 = 1 - (\sum_{i=1}^n (y_i - \hat{y}_i)^2 / \sum_{i=1}^n (y_i - \bar{y})^2) \tag{5}$$

where, y_i: The values computed from experimental model; \hat{y}_i : The values estimated from numerical model; and \bar{y} : Average values obtained from experimental model.

Table 2. The determination coefficient values (R²) between the numerical and experimental pressure head distributions

Type of earth dam model	Values of determination coefficient (R ²) %		
	h _w = 13 cm	h _w = 20 cm	h _w = 26.6 cm
Without drain and GCL	99.15	99.86	99.87
With GCL (y=10cm, U/S slope of GCL= 3:1)	99.49	99.82	99.85
With GCL (y=15cm, U/S slope of GCL= 3:1)	99.67	99.89	99.89
With GCL (y=20cm, U/S slope of GCL= 3:1)	99.39	99.89	99.91
With GCL (y=6cm, U/S slope of GCL= 2.5:1)	99.39	99.83	99.89
With GCL (y=6cm, U/S slope of GCL= 2:1)	98.95	99.92	99.87
With drain (L _d =15cm)	99.35	99.67	99.78
With drain (L _d =40cm)	99.15	99.86	99.83
With drain (L _d =60cm)	99	100	99.73

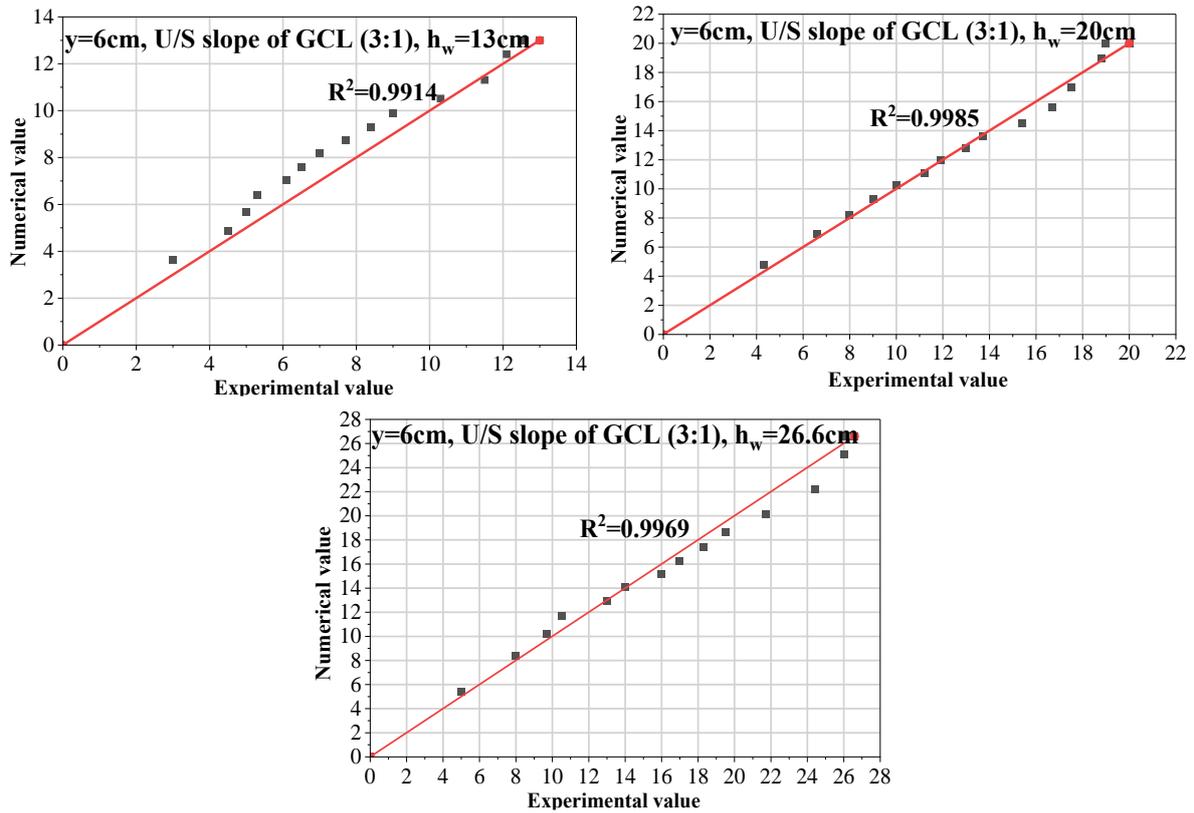


Figure 17. Comparison between the experimental and numerical pressure head (hp) distribution along the dam base

After validating the numerical software, many different cases of seepage through earth dams were tested using this software, which had not been conducted in the laboratory, to generate a variety of information that could be used to derive an empirical general equation that could be applied to predict the amount of seepage passing through earth dams containing GCL.

4.2. Effect of Uncovered GCL Height (y) with Different Upstream Slopes of the Dam

As mentioned above, the practical experiments were conducted on an earth dam with an upstream slope of 3:1. Based on the verification of experimental test results and for the purpose of generalizing the study results, a theoretical seepage test was performed, using SEEP/W software, on dams with different upstream slopes than those experimentally tested in the present study. As shown in Figure 18, a comparison between earth dams with and without geosynthetic clay liners revealed that when a full-length geosynthetic clay layer was incorporated. The seepage discharge decreased significantly by 99.92%, 99.95%, and 99.97% for dams with slopes of 3:1, 2.5:1, and 2:1, respectively, compared to dams of the same upstream slope but without GCL. Furthermore, it was shown that seepage discharge decreased as upstream dam slopes increased, a finding accepted by researchers [18, 29, 50, 51], who observed this reduction using a dam with different seepage control methods. Moreover, it was observed that decreasing the uncovered height of GCL from 20 cm to 6 cm results in a decrease in seepage discharge by about 41.69% at the upstream slope of dam 3:1. The decrease in uncovered height caused significant losses in the hydraulic head due to the high resistance imposed by the geosynthetic clay liners on the flow. The numerical modeling of seepage and the phreatic line within a dam with GCL is shown in Figure 19.

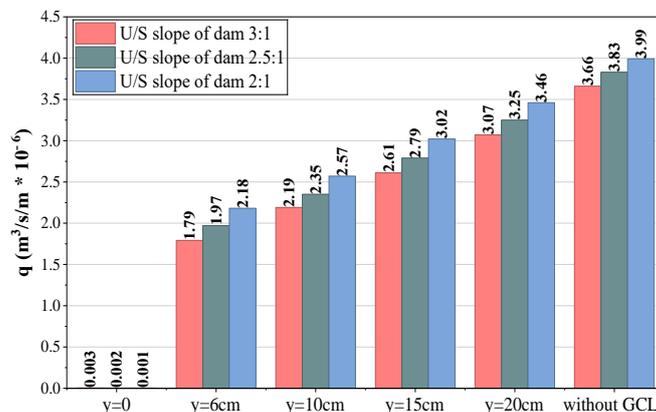


Figure 18. Effect of the dam upstream slopes (U/S slopes of dam) on seepage discharge for different uncovered GCL heights, permeability of soil (K), and upstream head 26.6cm

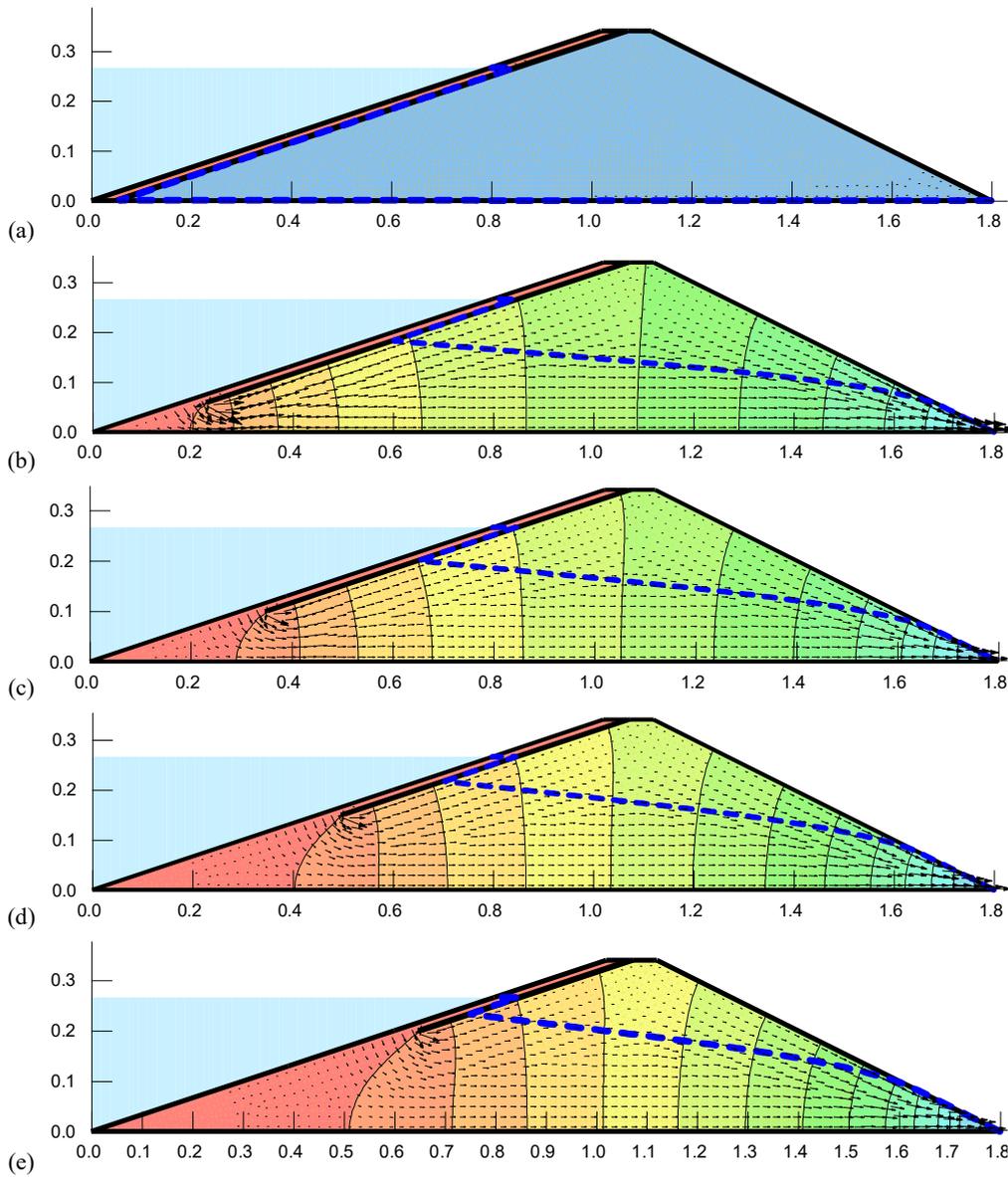


Figure 19. The numerical modeling of seepage and phreatic line through earth dam with GCL for upstream slope 3:1, and permeability of soil (K); (a) (y=0 cm), (b) (y=6 cm), (c) (y=10 cm), (d) (y=15 cm), and (e) (y=20 cm)

As shown in Figure 20, for the same upstream dam slope, the results indicated that the earth dam with GCL significantly reduced the phreatic line compared to the earth dam without GCL. Moreover, decreasing the uncovered height (y) significantly reduced the seepage line along the base of the dam and the pressure head distribution, which became nearly zero.

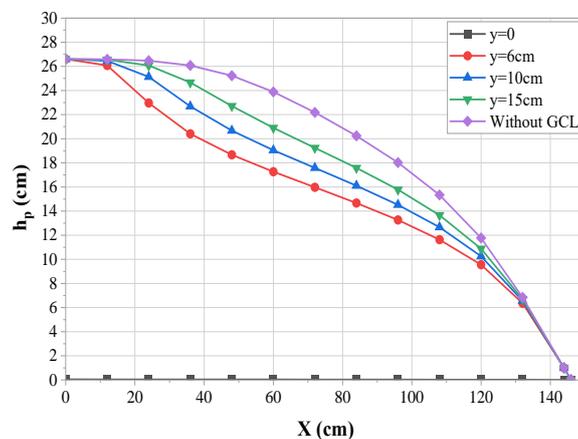


Figure 20. Location of phreatic line along the dam for different uncovered heights of GCL, $h_w=26.6$ cm, upstream slope dam 2:1 (U/S slope dam), slope of GCL 3:1, and permeability of soil (K)

Figure 21 shows that changing the upstream slope from 3:1 to 2:1 lowered the phreatic line when the upstream head and the uncovered height of the GCL remained constant. When the dam slope increased, it created a longer seepage path through the dam body, raising the seepage line, decreasing seepage discharge, and thereby enhancing the dam's safety.

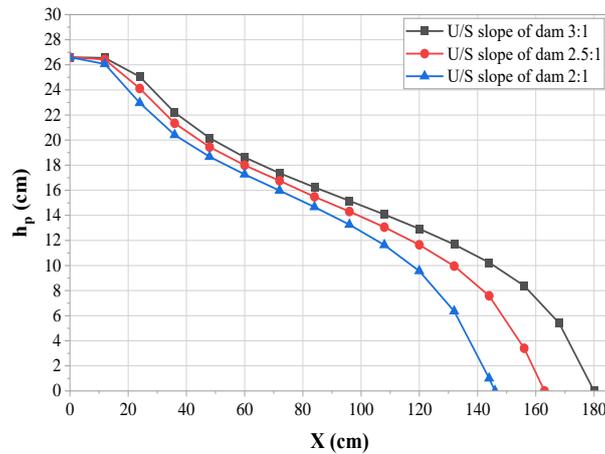


Figure 21. Location of phreatic line along the dam for different upstream slopes of the dam (U/S slopes of the dam), $h_w=26.6$ cm, $y=6$ cm, and permeability of soil (K)

4.3. Effect of Soil Permeability of the Dam

Figure 22 represents the effect of the different permeabilities of the dam soil on seepage discharge and the location of the phreatic line under conditions of the same upstream dam slope, a full reservoir head, and an uncovered height of 6 cm. It was shown that decreasing soil permeability from K to 0.5 K and then to 0.33 K results in reductions of seepage discharge of approximately 48.04% and 35.48%, respectively. According to Darcy's law, seepage discharge is directly proportional to soil permeability; therefore, reducing permeability slows water flow within the earth dam, thereby reducing seepage discharge. On the other hand, the location of the phreatic line remained unchanged because seepage lines depend on differences in hydraulic head rather than on permeability. The findings of the current study were compared with previous studies [50]. In previous studies, a dam with a horizontal drain was analyzed using the Hello Show Model. The results indicated that reducing the dam body permeability similarly decreased discharge.

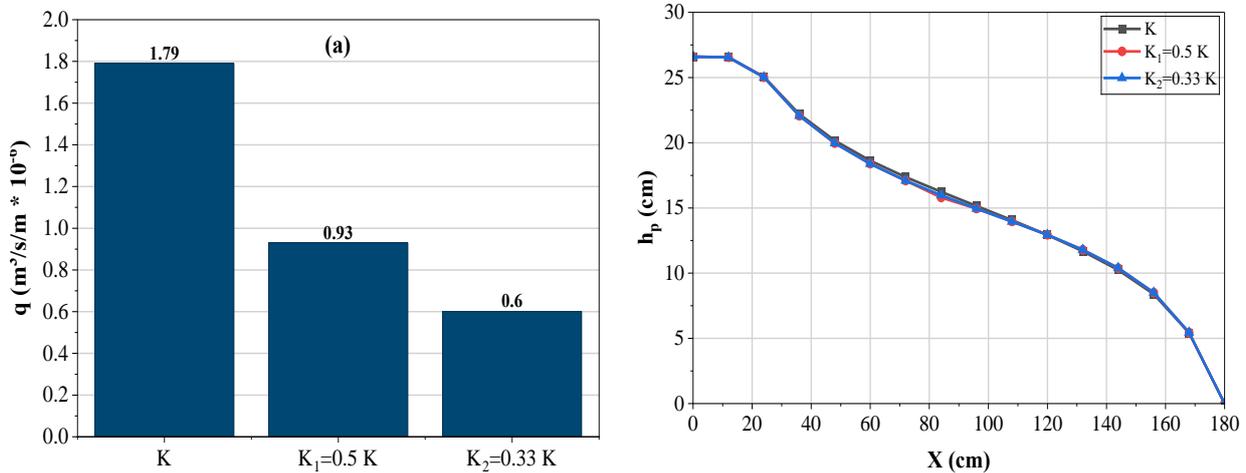


Figure 22. Effect of soil permeability on seepage discharge and phreatic line through earth dam for upstream slope of dam and GCL (3:1), uncovered height ($y=6$ cm), full reservoir head ($h_w=26.6$ cm)

4.4. Effect of Covered GCL Slope

When the upstream slope of the dam was 3:1, the uncovered height was 6 cm, and the full reservoir head was 26.6 cm. The results of the numerical model, as shown in Figure 23-a, indicated that the seepage quantity through the earth dam increased by approximately 16.2% when the GCL slope was changed from 3:1 to 2:1, due to reduced flow resistance within the dam and increased water movement. On the other hand, it was observed that changing the GCL slope insignificantly impacted the phreatic line location, as shown in Figure 23-b. However, the phreatic line for a dam with a variable GCL slope was smaller than the phreatic line for a dam without a GCL. Figure 24 indicates that the numerical modeling of seepage and the phreatic line for an earth dam with GCL slopes were 2.5:1 and 2:1, respectively.

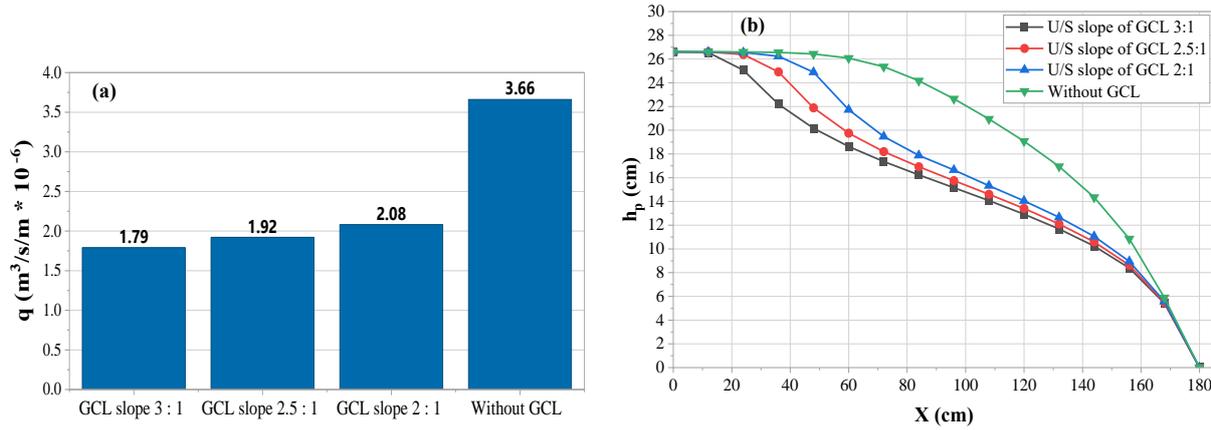


Figure 23. Effect of variation of upstream slope of GCL (U/S slope of GCL) on seepage discharge and phreatic line for a dam with upstream slope (3:1), uncovered height ($y=6cm$), permeability of soil (K), and full reservoir head ($h_w=26.6cm$)

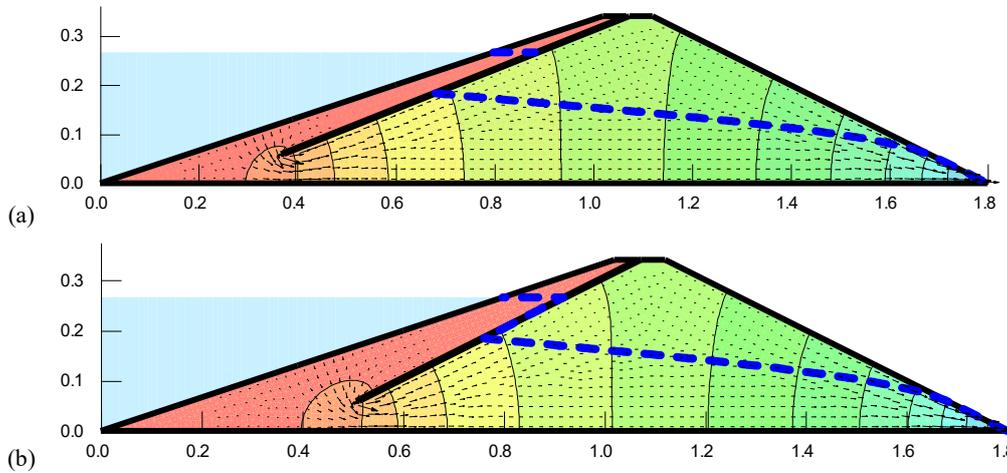


Figure 24. The numerical modeling of seepage and phreatic line through an earth dam with GCL for uncovered height of GCL ($y=6cm$), upstream slope dam (3:1), permeability of soil (K), and full reservoir head ($h_w=26.6cm$) (a) 2.5:1 (b) 2:1

4.5. Effect of the Dam Height

Figure 25-a shows that increasing the height of the dam from 34 cm to 44 cm or from 44 cm to 54 cm, while keeping other parameters constant, i.e., uncovered height, permeability of the dam, upstream dam slope, and upstream head, resulted in an approximate increase in seepage discharge of 29.61% and 20.26%, respectively. Similarly, the numerical results (Figure 25-b) indicated that the seepage line for a dam height of 34 cm was lower than the seepage lines for dam heights of 44 cm and 54 cm. The increase in the dam's height increased the upstream head, which in turn enlarged the upstream and downstream head difference. According to Darcy's law, this results in increased seepage discharge because the saturated area within the dam has expanded, thereby increasing the flow area. Previous studies [18, 29] utilized an earth dam with different seepage mitigation methods and observed that increasing the dam height results in higher seepage discharge, consistent with the current study's findings.

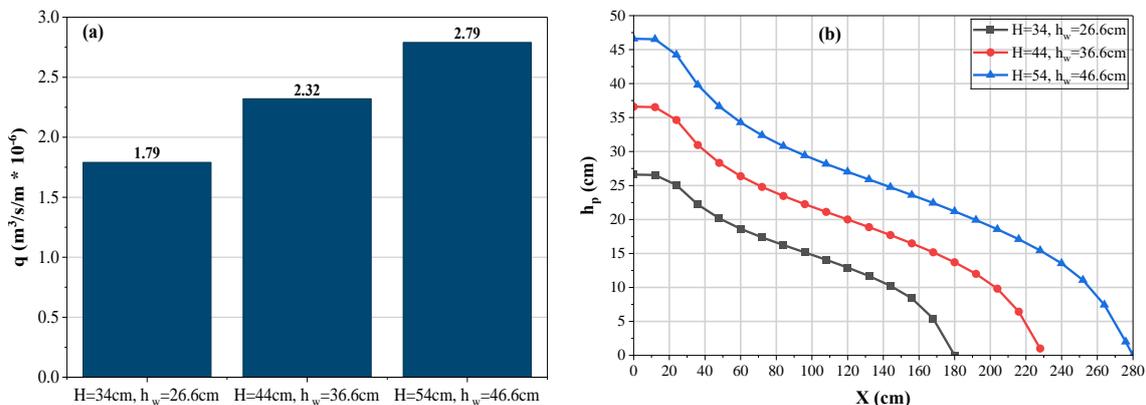


Figure 25. Effect of height dam ($H=34, 44, 54$ cm) on seepage discharge and phreatic line through an earth dam for uncovered height ($y=6cm$), permeability of shell dam (K), upstream slope of dam and GCL (3:1), and full reservoir head ($h_w=26.6, 36.6, 46.6$ cm)

4.6. Effect of Covered GCL with Drain Combination

Figure 26 compares of four earth dam models (case 1 with a drain ($L_d=40$ cm), case 2 with a GCL ($y=6$ cm, slope 3:1), case 3 with a combined GCL ($y=6$ cm, slope 3:1) and drain ($L_d=40$ cm), and case 4 without both GCL and drain, for earth dam having upstream slope 3:1 and reservoir water depth ($h_w=26.6$ cm). It is evident that using a GCL with a drain in earth dams significantly reduced the phreatic line and decreased seepage discharge of approximately 30.87% compared to the model without a GCL and a drain. As shown in Figure 27, the presence of the downstream drain contributed to keeping the phreatic line within the dam structure, without intersecting the downstream slope, thereby reducing the risk of piping.

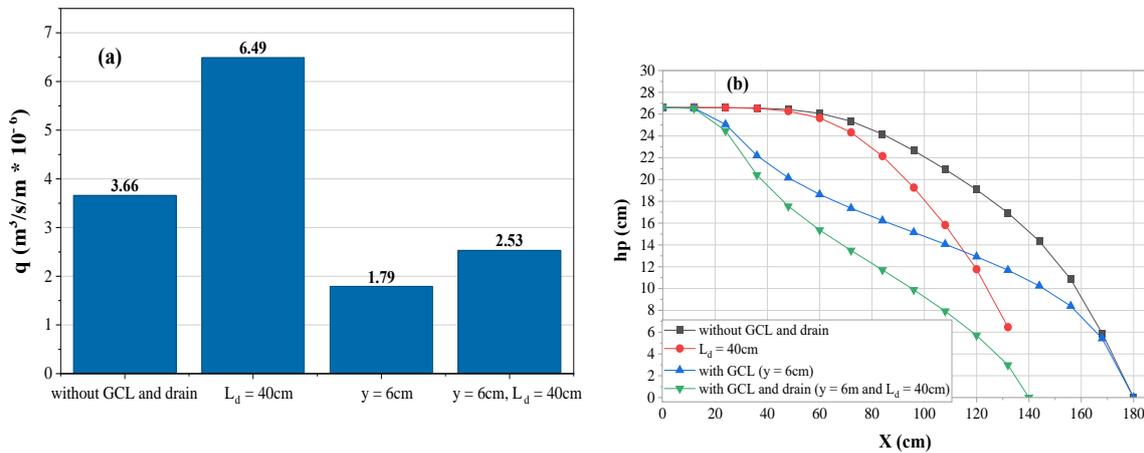


Figure 26. Effect of using GCL in combined with drain on seepage discharge and phreatic line location for earth dam with upstream slope (3:1), permeability of soil (K), and full reservoir head ($h_w=26.6$ cm)

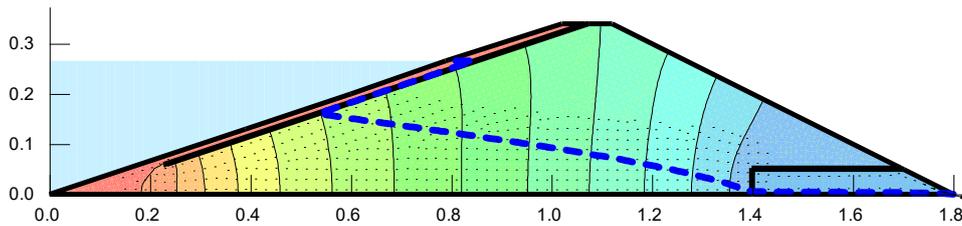


Figure 27. The numerical modeling of seepage and the phreatic line of an earth dam with GCL and drain

5. Equation of Seepage Discharge Through an Earth Dam with Geosynthetic Clay Liners

The SPSS software was utilized to develop an equation that estimates seepage discharge through an earth dam with GCL under steady-state conditions, using approximately 75% of the SEEP/W data, including dam height, soil permeability, upstream head, upstream slope of the dam, and uncovered GCL height. On the other hand, a 2:1 constant slope was used for the downstream dam and for all models, according to previous studies [46, 52, 53] and Strange's recommendation [41]; therefore, the variation in different downstream dam slopes was neglected. Based on the present experimental results, the best angle for the geosynthetic clay liners ($\tan\beta$) was 3:1 when their slope was parallel to the upstream dam. In addition, the geosynthetic clay liner was positioned ($b_c=0.5b$) starting from the center of the dam's crest and parallel to the upstream face of the dam until it reached the required length. The geosynthetic clay liner was placed indirectly on the dam's upstream face due to environmental conditions and water flow. The top width remained constant at $b= 10$ cm.

According to the numerical results obtained from SEEP/W software and depending on SPSS software, the equation below is formulated with $R^2 = 96.4\%$, as follows:

$$q = \frac{0.247 * K * h_w^{1.522} * y^{0.346} * (\tan\theta)^{0.384}}{H^{0.868}} \tag{6}$$

where, K is the permeability of the dam, h_w is the upstream head, y is the uncovered height of GCL, θ is the upstream slope of the dam, and H is the dam height.

The remaining 25% of the results were used to draw the relationship between the seepage discharge values calculated from Equation 6 and those estimated by the SEEP/W program, as shown in Figure 28. The results showed an excellent agreement, with a correlation coefficient of $R^2 = 99.9\%$.

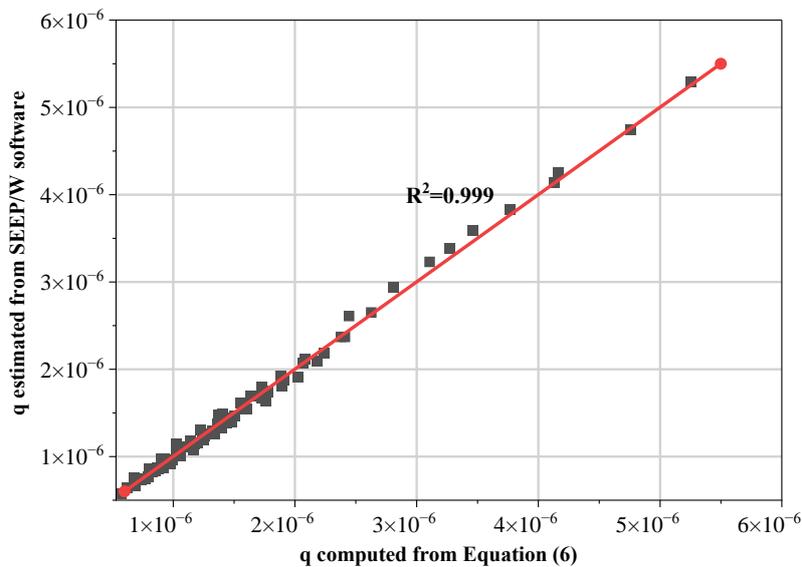


Figure 28. The relationship between the values of (q) computed from equation (6) and those estimated using SEEP/W software

6. Conclusions

The present study employed both experimental and numerical modeling to simulate the performance of an earth dam with and without geosynthetic clay liners and drains. The model was used to determine the seepage discharge and seepage line along the base of the dam. The present results lead to the following conclusions:

- The installation of the geosynthetic clay liners parallel to the upstream side of the dam, starting from the center of the dam crest and extending a specific length downwards, significantly reduced the seepage discharge and lowered the seepage line within the dam body.
- Implementing a full length of geosynthetic clay liners on the upstream side of the dam resulted in a reduction in seepage discharge by about 99.92%, 99.95%, and 99.97% for upstream dam slopes of 3:1, 2.5:1, and 2:1, respectively, as compared to an earth dam without GCL.
- At the same reservoir head and upstream slope (dam and GCL), increasing uncovered geosynthetic clay liners (y) increased the phreatic line and seepage discharge.
- The changing of the GCL slope insignificantly affected the location of the phreatic line. Conversely, increasing the GCL slope decreased seepage discharge.
- Increasing the lengths of the downstream drains resulted in high seepage discharge and a low phreatic line; the optimal drain length was 40 cm, approximately 60% of the base length of the downstream portion of the earth dam.
- The results indicated from the experimental model demonstrated an excellent agreement with the results indicated from the numerical model.
- The seepage line of an earth dam with a steep upstream slope was lower than that of earth dams with flat slopes. However, as the upstream slope of the dam increased from 3:1 to 2:1, the seepage discharge also increased.
- Decreasing the permeability of the dam soil reduced seepage discharge by about 66.48%; however, the phreatic line location remained unchanged.
- Increasing the dam height from 34 cm to 54 cm increased the seepage discharge by 55.87% and raised the seepage line.
- Installing GCL with a drain on the upstream and downstream side of the dam lowered the phreatic line, shifted it toward the inside of the dam body, and reduced seepage discharge by approximately 30.87% compared to a dam without GCL and a drain.
- Using the SPSS program and based on the results obtained from the SEEP/W program, an equation was developed to estimate the seepage discharge through an earth dam with GCL by the coefficient of determination ($R^2 = 96.4\%$).

7. Declarations

7.1. Author Contributions

Conceptualization, A.S.A. and R.H.I.; methodology, A.S.A.; software, A.S.A.; validation, A.S.A. and R.H.I.; formal analysis, A.S.A. and R.H.I.; investigation, A.S.A.; resources, A.S.A.; data curation, A.S.A.; writing—original draft preparation, A.S.A.; writing—review and editing, A.S.A. and R.H.I.; visualization, A.S.A.; supervision, R.H.I.; project administration, A.S.A. and R.H.I.; funding acquisition, A.S.A. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

- [1] Kutzner, C. (2018). *Earth and Rockfill Dams*. Routledge, London, United Kingdom. doi:10.1201/9780203758991.
- [2] Hassan, W. H. (2017). Application of a genetic algorithm for the optimization of a cutoff wall under hydraulic structures. *Journal of Applied Water Engineering and Research*, 5(1), 22–30. doi:10.1080/23249676.2015.1105161.
- [3] Garg, S. K. (2020). *Irrigation Engineering and Hydraulic Structures: Water Resources Engineering (Vol. II)*. Khanna Publisher, New Delhi, India.
- [4] Song, J., Sciubba, M., & Kam, J. (2021). Risk and impact assessment of dams in the contiguous United States using the 2018 national inventory of dams database. *Water (Switzerland)*, 13(8). doi:10.3390/w13081066.
- [5] Sharma, R. P., & Kumar, A. (2013). Case histories of earthen dam failures. The seventh international conference on case histories in geotechnical engineering, 1-4 May, 2013, Chicago, United States.
- [6] Zhang, L., Xu, Y., & Jia, J. S. (2009). Analysis of earth dam failures: A database approach. *Georisk*, 3(3), 184–189. doi:10.1080/17499510902831759.
- [7] Fell, R., Wan, C. F., Cyganiewicz, J., & Foster, M. (2003). Time for Development of Internal Erosion and Piping in Embankment Dams. *Journal of Geotechnical and Geoenvironmental Engineering*, 129(4), 307-314. doi:10.1061/(asce)1090-0241(2003)129:4(307).
- [8] Foster, M., Fell, R., & Spannagle, M. (2000). The statistics of embankment dam failures and accidents. *Canadian Geotechnical Journal*, 37(5), 1000-1024. doi:10.1139/t00-030.
- [9] Creager, W. P. (1939). Design and Maintenance of Earth Dams. *Journal AWWA*, 31(8), 1335–1358. doi:10.1002/j.1551-8833.1939.tb12876.x.
- [10] Mansuri, B., & Salmasi, F. (2013). Effect of Horizontal Drain Length and Cutoff Wall on Seepage and Uplift Pressure in Heterogeneous Earth Dam with Numerical Simulation. *Journal of Civil Engineering and Urbanism*, 3(3), 114–121.
- [11] Hassan, W. H., & Zwain, H. M. (2024). The influence of drain pipe location and diameter on seepage through an earth dam. *Ain Shams Engineering Journal*, 15(3), 102475. doi:10.1016/j.asej.2023.102475.
- [12] Bouazza, A. (2002). Geosynthetic clay liners. *Geotextiles and Geomembranes*, 20(1), 3–17. doi:10.1016/S0266-1144(01)00025-5.
- [13] Koerner, R. M. (2012). *Designing with geosynthetics*. Xlibris Corporation, Bloomington, United States.
- [14] Koerner, R. M., & Daniel, D. E. (2020). A suggested methodology for assessing the technical equivalency of GCLs to CCLs. In *Geosynthetic Clay Liners* (pp. 73–98). doi:10.1201/9781003077848-9.
- [15] Benson, C. H., & Meer, S. R. (2009). Relative Abundance of Monovalent and Divalent Cations and the Impact of Desiccation on Geosynthetic Clay Liners. *Journal of Geotechnical and Geoenvironmental Engineering*, 135(3), 349–358. doi:10.1061/(asce)1090-0241(2009)135:3(349).
- [16] Lee, J. M., & Shackelford, C. D. (2005). Concentration dependency of the prehydration effect for a geosynthetic clay liner. *Soils and Foundations*, 45(4), 27–41. doi:10.3208/sandf.45.4_27.
- [17] Meer, S. R., & Benson, C. H. (2007). Hydraulic Conductivity of Geosynthetic Clay Liners Exhumed from Landfill Final Covers. *Journal of Geotechnical and Geoenvironmental Engineering*, 133(5), 550–563. doi:10.1061/(asce)1090-0241(2007)133:5(550).

- [18] Hoobi Irzooki, R. (2016). Computation of Seepage through Homogenous Earth Dams with Horizontal Toe Drain. *Engineering and Technology Journal*, 34(3), 430–440. doi:10.30684/etj.34.3a.1.
- [19] Jamel, A. A. J. (2016). Analysis and Estimation of Seepage Through Homogenous Earth Dam Without Filter. *Diyala Journal of Engineering Sciences*, 9(2), 38–49. doi:10.24237/djes.2016.09207.
- [20] Salmasi, F., & Nouri, M. (2019). Effect of upstream semi-impervious blanket of embankment dams on seepage. *ISH Journal of Hydraulic Engineering*, 25(2), 143–152. doi:10.1080/09715010.2017.1381862.
- [21] Taghvaei, P., Mousavi, S. F., Shahnazari, A., Karami, H., & Shoshpash, I. (2019). Experimental and Numerical Modeling of Nano-clay Effect on Seepage Rate in Earth Dams. *International Journal of Geosynthetics and Ground Engineering*, 5(1). doi:10.1007/s40891-018-0152-8.
- [22] Shakouri, B., & Mohammadi, M. (2019). Evaluation of Penetration Depth for Cutoff Walls in the Core of Earth Dams. *Geotechnical and Geological Engineering*, 38(1), 151–167. doi:10.1007/s10706-019-01004-x.
- [23] El Molla, D. A. (2019). Seepage through homogeneous earth dams provided with a vertical sheet pile and formed on impervious foundation. *Ain Shams Engineering Journal*, 10(3), 529–539. doi:10.1016/j.asej.2018.12.008.
- [24] Sawada, Y., Nakazawa, H., Take, W. A., & Kawabata, T. (2019). Effect of installation geometry on dynamic stability of small earth dams retrofitted with a geosynthetic clay liner. *Soils and Foundations*, 59(6), 1830–1844. doi:10.1016/j.sandf.2019.08.007.
- [25] Ullah, A., Kassim, A., Alam, I., Junaid, M., & Ahmad, I. S. (2019). Efficiency analysis of seepage of Baz Ali small dam, Kurram agency using clay blanket and cut-off wall with sand filter. *Bulletin of the Geological Society of Malaysia*, 2019(67), 125–130. doi:10.7186/bgsm67201914.
- [26] Al-Mansori, N. J. H., Al-Fatlawi, T. J. M., Othman, N. Y., & Al-Zubaidi, L. S. A. (2020). Numerical analysis of seepage in earth-fill dams. *Civil Engineering Journal*, 6(7), 1336–1348. doi:10.28991/cej-2020-03091552.
- [27] Sazzad, M. M., & Alam, S. (2020). Effect of grout curtain on the seepage characteristics of earth dam by FEM. *Journal of Geotechnical Studies*, 5(2), 1–10.
- [28] Attia, M., Abdel Razek, M., & Salam, A. A. (2021). Seepage Through Earth Dams with Internal Cut Off. *Geotechnical and Geological Engineering*, 39(8), 5767–5774. doi:10.1007/s10706-021-01865-1.
- [29] Kumar, S., Sahu, A. K., & Kumar, M. (2022). Modeling the effect of central impervious core and downstream filter geometry on seepage through earth dams. *Ain Shams Engineering Journal*, 13(1), 101510. doi:10.1016/j.asej.2021.05.024.
- [30] Fawzy, M. A., Hassan, N. A., Saad, N. Y., & El-Molla, D. A. (2024). Experimental and numerical modeling of diaphragm grouting in earth dams considering construction defects. *Modeling Earth Systems and Environment*, 10(2), 2159–2185. doi:10.1007/s40808-023-01892-2.
- [31] Jamel, A. A. J., & Hassan, H. F. (2024). Slope stability of earth dams with incline cores (static and seismic models). *AIP Conference Proceedings*, 3219(1). doi:10.1063/5.0236213.
- [32] Haghdoost, M., Sajjadi, S. M., Ahadiyan, J., Norouzi, R., & Abraham, J. (2024). The effect of sheet piles' inclination angle, number, and distance on seepage through an earthfill dam. *Ain Shams Engineering Journal*, 15(12), 103056. doi:10.1016/j.asej.2024.103056.
- [33] Hassan, W. H., Atshan, T. T., & Thiab, R. F. (2024). Effect of drain pipes on seepage and slope stability through a zoned earth dam. *Open Engineering*, 14(1). doi:10.1515/eng-2024-0040.
- [34] Jamel, A. A. J., & Hassan, H. F. (2025). Effect of Core Angle in Earth Dam on Seepage Characteristic (Numerical Model). *Tikrit Journal of Engineering Sciences*, 32(1), 1–10. doi:10.25130/tjes.32.1.26.
- [35] Kidder, W. A., & Behaya, S. A. (2025). An Experimental Study of the Core Location and Shape Effect on Seepage and Stability of Zoned Earth Fill Dam. *Tikrit Journal of Engineering Sciences*, 32(1), 1–12. doi:10.25130/tjes.32.1.29.
- [36] Konishi, Y., Izumi, A., Ohyama, S., Sonoda, Y., & Sawada, Y. (2025). Effect of the Installation Angle of the Geosynthetic Clay Liners on the Deformation Characteristics of Earth-fill Dam Embankments. *International Journal of Geosynthetics and Ground Engineering*, 11(6). doi:10.1007/s40891-025-00676-1.
- [37] Charrak, H., Loualbia, H., & Kismoune, Y. (2025). Optimizing seepage control in earth dams: a case study of Krerish dam with combined countermeasures. *Sādhanā*, 50(3). doi:10.1007/s12046-025-02853-4.
- [38] Khursheed, M. Z., Alshameri, B., Hassan, W., & Abdeldjouad, L. (2025). A novel numerical approach for the assessment of the seepage failure, predictive modelling of seepage through non-homogenous earth-fill dams resting on pervious foundations using artificial neural networks. *Modeling Earth Systems and Environment*, 11(1). doi:10.1007/s40808-024-02227-5.
- [39] Heller, V. (2011). Scale effects in physical hydraulic engineering models. *Journal of Hydraulic Research*, 49(3), 293–306. doi:10.1080/00221686.2011.578914.

- [40] Refaiy, A. R., AboulAtta, N. M., Saad, N. Y., & El-Molla, D. A. (2021). Modeling the effect of downstream drain geometry on seepage through earth dams. *Ain Shams Engineering Journal*, 12(3), 2511–2531. doi:10.1016/j.asej.2021.02.011.
- [41] Ukarande, S. K. (2023). *Irrigation Engineering and Hydraulic Structures*. Springer Nature Switzerland. doi:10.1007/978-3-031-33552-5.
- [42] Das, B. M., & Sivakugan, N. (2018). *Principles of foundation engineering*. Cengage learning, Boston, United States.
- [43] Budhu, M. (2010). *Soil mechanics and foundations*. John Wiley and Sons, Hoboken, United States.
- [44] Chahar, B. R. (2004). Determination of Length of a Horizontal Drain in Homogeneous Earth Dams. *Journal of Irrigation and Drainage Engineering*, 130(6), 530–536. doi:10.1061/(asce)0733-9437(2004)130:6(530).
- [45] Shirazi, S. M., Kazama, H., Salman, F. A., Othman, F., & Akib, S. (2010). Permeability and swelling characteristics of bentonite. *International Journal of Physical Sciences*, 5(11), 1647–1659.
- [46] Al-Janabi, A. M. S., Ghazali, A. H., Ghazaw, Y. M., Afan, H. A., Al-Ansari, N., & Yaseen, Z. M. (2020). Experimental and numerical analysis for earth-fill dam seepage. *Sustainability (Switzerland)*, 12(6), 2490. doi:10.3390/su12062490.
- [47] Fawzy, M. A., Hassan, N. A. A., Saad, N. Y., & El-Molla, D. A. (2024). Evaluating the effect of different diaphragm wall cracking scenarios on seepage and slope stability in Earth dams using experimental and numerical modeling approaches. *Beni-Suef University Journal of Basic and Applied Sciences*, 13(1), 66. doi:10.1186/s43088-024-00523-8.
- [48] Amieur, R., Djehiche, A., Boumaàza, C. L., Gafsi, M., & Lalmi, D. (2023). Effect Location of Vertical Drain on Seepage and Stability in Homogenous Earth Dams. *International Journal of Sustainable Development and Planning*, 18(9), 2643–2653. doi:10.18280/ijstdp.180903.
- [49] Montgomery, D. C., Peck, E. A., & Vining, G. G. (2021). *Introduction to linear regression analysis*. John Wiley & Sons, Hoboken, United States.
- [50] Irzooki, R. H., & Jamel, A. (2012). Experimental study of characteristics of top seepage line through homogenous earth dam using Hele-Shaw model. *International Review of Civil Engineering (IRECE)*, 3(6), 480.
- [51] El-Hazek, A. N., Abdel-Mageed, N. B., & Hadid, M. H. (2020). Numerical and experimental modelling of slope stability and seepage water of earthfill dam. *Journal of Water and Land Development*, 44, 55–64. doi:10.24425/jwld.2019.127046.
- [52] Alzamily, Z. N., & Sh. Abed, B. (2022). Experimental and theoretical investigations of seepage reduction through zoned earth dam material with special core. *Materials Today: Proceedings*, 61, 998–1005. doi:10.1016/j.matpr.2021.10.283.
- [53] Shuhaib, Z. K., & Khassaf, S. I. (2023). Experimental and numerical evaluation of tire rubber powder effectiveness for reducing seepage rate in earth dams. *Open Engineering*, 13(1). doi:10.1515/eng-2022-0422.