Urmia University

Water and Environmental Challenges

2025;1(2):12-21

Journal homepage: https://jwec.urmia.ac.ir

Water & Environmental Challenges

Numerical Study on the Optimal Location of Drain in Non Homogeneous Earth Dams with a Clay Blanket over Permeable Foundations

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ABSTRACT

In this study are numerically investigated the seepage behavior of a non-homogeneous earth dam equipped with a pipe drain and a clay blanket over a permeable foundation. A total of 324 two-dimensional seepage models were simulated using finite element method (FEM) by Geo-studio (SEEP/W) software, with independent variables including the anisotropy ratio (Ky/Kx=0.5, 1, 1.5), drain location (horizontal XL=7, 11, 15, 19 m and vertical YL=18.5, 20, 21.5 m), clay blanket length (L=17, 34, 51 m), and drain diameter (d=0.1,0.2, 0.3 m). The results indicated that the vertical drain location had the most significant negative effect on collected seepage, while the horizontal position had a positive effect. The anisotropy ratio and drain diameter revealed no significant influence within the tested range. From a hydraulic perspective, installing the pipe drain lowered the phreatic surface, reduced pore-water pressures near the downstream toe, and decreased the exit gradient, improving hydraulic stability. Increasing the clay blanket length significantly reduced seepage, but further increase beyond a certain limit provided only marginal improvement. Overall, the clay blanket length and vertical drain depth were identified as the most critical parameters for optimal seepage control in non-homogeneous earth dams. Also, multiple regression (ML) analyses results indicated that the developed models for total seepage discharge, drain discharge, and downstream outflow had strong statistical performance, with R2=0.978, R2=0.756, and R2=0.809, respectively.

Keywords:
Non-homogeneous earth dam, pipe drain, clay blanket, seepage, SEEP/W

1. Introduction

Earth dams are among the most widely used hydraulic structures for storing, regulating, and controlling surface water for agricultural, industrial, and domestic purposes. Their popularity stems from relatively simple construction, lower cost compared to concrete dams, and the use of locally available materials (Rahimi, 2002; Ghanbari, 2014). However, earth dams face significant hydraulic and geotechnical challenges, including seepage, excess pore-water pressure, internal erosion, and slope instability. Among these, uncontrolled seepage is particularly critical, as it can increase hydraulic gradients, cause sand boiling, trigger internal erosion of the core, and ultimately lead to dam failure (Lambe & Whitman, 1979; Fell & Fry, 2007). According to the International Commission on Large Dams (ICOLD, 2014), over 25% of global dam failures are directly attributed to excessive seepage, highlighting the importance of effective seepage control and drainage systems in ensuring dam stability and safety. Recent studies have emphasized the importance of evaluating pore-water pressure and seepage behavior under transient conditions, such as rapid reservoir draw-downs, for ensuring embankment dam stability (Ahmadi et al., 2017). Nourani et al. (2024) demonstrated that higher rates of water level reduction can significantly decrease the factor of safety, underscoring the critical need for proper drainage and seepage management in dam design. Various methods have

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https://doi.org/10.30466/jwec.2025.56676.1008
Received: 20 October 2025
Accepted: 25 December 2025

been developed to control seepage, including impervious clay cores, cutoff walls, upstream clay blankets, and drainage systems (Rahimi, 2002; ICOLD, 2014). Among these, pipe drainage systems are particularly effective in reducing pore-water pressure and collecting seepage flow (Waqed et al., 2024). By providing low-resistance flow paths, these drains lower the phreatic line, reduce uplift pressure, and enhance downstream slope stability.

In zoned (non-homogeneous) earth dams, consisting of layers with differing geotechnical and hydraulic properties, flow paths and pressure distributions become more complex (Ahmadi et al., 2014). Factors such as horizontal and vertical permeability, clay blanket length, drain diameter, and drain position strongly influence seepage discharge, pore-water pressure, and phreatic line configuration (Fadhil & Hassan, 2023). Permeable foundations further exacerbate seepage, making drainage optimization crucial. While laboratory and field studies provide reliable data, they are often costly and time-consuming. Consequently, numerical modeling has emerged as a practical and powerful tool for investigating seepage behavior, with SEEP/W (subgroup of Geo-Studio software) being widely used for simulating two-dimensional (2D) flow in porous, heterogeneous media (Krahn, 2004; Zienkiewicz & Taylor, 2000). Previous studies have explored drainage optimization in earth dams. For example, Salmasi and Mansouri (2016) indicated that double-row drains in a zigzag pattern reduce uplift pressures, Taheri et al. (2021) demonstrated that increasing drain diameter effectively decreases hydraulic gradients, and Hassan and Zwain (2024) found that optimal pipe-drain placement can reduce seepage by up to 25% and improve overall safety. Atshan and Hassan (2024) reported that positioning the drain at about 70% of the base width from the upstream toe reduced seepage and hydraulic gradient by nearly 99%, enhancing stability by 8%.

Building on this background, the present study introduces a structured numerical framework to optimize drain design in non-homogeneous earth dams with a clay blanket over permeable foundations. The present study investigates the optimal locating of pipe drains in non-homogeneous earth dams with an upstream clay blanket on permeable foundations. A total of 324 two-dimensional SEEP/W (subgroup of Geo-Studio software) simulations were conducted to assess the effects of drain diameter, horizontal and vertical location, and clay blanket length on total seepage, drain discharge, outlet flow, and phreatic line configuration. The results were statistically analyzed to identify optimal design configurations. This study provides practical, design-oriented insights for improving drainage systems in complex earth dam settings, offering empirical correlations that can be applied to other hydraulic structures such as diversion dams, stilling basins, and canal linings. The novelty of this study lies in the following aspects:

1. Design criterion for optimal pipe drain placement: A method is proposed to determine the optimal location of the pipe drain without requiring deep excavation or direct connection of the clay blanket to an impermeable layer.
2. Systematic steady-state seepage analysis: The influence of clay blanket thickness, foundation permeability, and drain dimensions on seepage patterns and total discharge is quantified through 324 SEEP/W simulations.
3. Efficient drainage configuration and integrated evaluation: Recommendations are provided for minimizing seepage and enhancing dam hydraulic performance when both the clay blanket and pipe drain are used together. The combined effect of these two key measures has not been comprehensively studied in previous research.

This integrated approach offers practical guidance for selecting the most effective pipe drain placement and clay blanket configuration, providing design-oriented insights that are not fully addressed in earlier studies.

2. Materials and Methods

2.1. Numerical Modeling with GeoStudio, SEEP/W

The seepage analyses were conducted using Geo-Studio 2022 (SEEP/W) that is a finite element method (FEM)-based software for modeling both saturated and unsaturated flow. SEEP/W simulates seepage and pore-water pressure distribution under steady-state and transient conditions, incorporating Darcy's law and the continuity principle to model water movement through porous media. In this study, SEEP/W was applied to simulate seepage through a non-homogeneous earth dam equipped with a clay blanket and a perforated pipe drain. The software allowed the definition of spatially variable material properties, anisotropic conductivities, and complex boundary conditions, while its graphical interface enabled visualization of flow nets, equipotential lines, and phreatic lines (GeoStudio, 2022).

2.2. Finite Element Method Formulation

The finite element method (FEM) divides the domain into smaller elements connected at nodes, where the governing equations are approximated using interpolation functions for hydraulic head. In 2D porous media, flow velocities in the x and y directions are described by Darcy's law:

$$V_x = -k_x \frac{\partial H}{\partial x} \qquad (1)$$

$$V_y = -k_y \frac{\partial H}{\partial y} \qquad (2)$$

where V_xand V_yare flow velocities, k_x and k_yare hydraulic conductivities, and ∂H/∂xand ∂H/∂y are hydraulic gradients in x and y directions.

The continuity equation for mass conservation in 2D porous media is:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho V_x)}{\partial x}+\frac{\partial(\rho V_y)}{\partial y} = -S\frac{\partial H}{\partial t}+Q(x,y,t) \quad (3)$$

For an incompressible fluid with constant density, this simplifies to:

$$\frac{\partial V_x}{\partial x}+\frac{\partial V_y}{\partial y}=\frac{1}{\rho}[-S\frac{\partial H}{\partial t}+Q(x,y,t)] \quad (4)$$

Combining Equations (1), (2), and (4), the governing equation for flow in a porous medium is:

$$\frac{\partial}{\partial x}(k_x\frac{\partial H}{\partial x})+\frac{\partial}{\partial y}(k_y\frac{\partial H}{\partial y}) =\frac{1}{\rho}[S\frac{\partial H}{\partial t}-Q(x,y,t)] \quad (5)$$

Under steady-state conditions (∂H/∂t=0), Equation (5) reduces to:

$$\frac{\partial}{\partial x}(k_x\frac{\partial H}{\partial x})+\frac{\partial}{\partial y}(k_y\frac{\partial H}{\partial y}) = -\frac{Q(x,y,t)}{\rho} \quad (6)$$

If the medium is homogeneous and isotropic (k_x=k_y=k) and the inflow/outflow term is negligible (Q=0), it further reduces to the classical Laplace equation:

$$\frac{\partial^2 H}{\partial x^2}+\frac{\partial^2 H}{\partial y^2}=0 \quad (7)$$

Equation (7) is valid only for homogeneous, isotropic, steady-state flow; otherwise, the general form (Equation 5) must be solved numerically (Ghasemzadeh, 2010).

2.3. Geometry and Model Parameters

The dam geometry was modeled with the following dimensions:

- Total height of dam from foundation: 34 m
- Upstream water level from foundation: 33 m
- Crest width: 7 m
- Base width: 20 m
- Upstream slope: 1V:3H
- Downstream slope: 1V:2.5H

A clay blanket was placed on the downstream foundation, with lengths of 17 m, 34 m, and 51 m to evaluate its effect on seepage control. A pipe drain was installed near the downstream toe, with its horizontal distance (XL) from the downstream edge and vertical position (YL) above the foundation systematically varied to determine the most effective configuration for reducing pore pressure and controlling the phreatic surface. Drain diameters (d) of 0.1 m, 0.2 m, and 0.3 m were analyzed in combination with anisotropy ratios (Ky/Kx = 0.5, 1.0, 1.5), representing different hydraulic conductivity conditions of the core material. The downstream water level was maintained at 20 m, establishing the hydraulic gradient across the dam body and foundation.

The total foundation thickness was 20 m, and the hydraulic conductivities of the core, shells, clay blanket, pipe drain, and foundation were assigned based on typical values reported in the literature. A schematic representation of the dam, including the clay blanket and pipe drain, is shown in Figure 1, highlighting the main geometric parameters: H, D, L, X_L, Y_L, d.

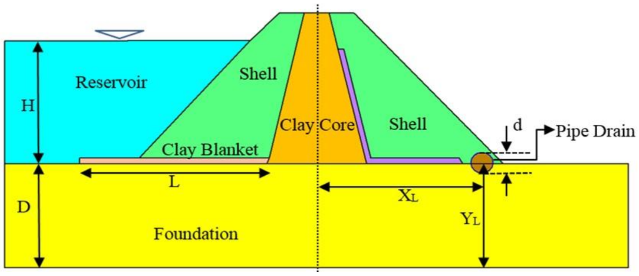


Figure 1. Cross-section of the non-homogeneous earth dam

2.4. Material Properties

The definition of material properties is a crucial step in numerical modeling, as it directly affects seepage discharge, pore-water pressure, and the phreatic surface profile. The dam and foundation were divided into different zones, and each zone was assigned specific material properties in SEEP/W using the Define → Materials menu. The main materials considered in this study are:

1. Core: Low-permeability clay forming the central part of the dam, which plays a key role in controlling seepage through the dam body.

2. Shells (upstream and downstream): More permeable soils surrounding the core, providing structural support while allowing limited flow.
3. Clay blanket: Placed over the foundation to reduce seepage; properties are similar to the core.
4. Pipe drain: High-permeability material allowing efficient water drainage.
5. Permeable foundation: Moderate to high permeability depending on soil characteristics.

For each material, the saturated hydraulic conductivity was defined. For fine-grained soils such as clay, the volumetric water content function as a function of matric suction was defined to simulate flow in unsaturated zones, especially near the phreatic surface.

2.5. Boundary Conditions

Accurate definition of boundary conditions is essential for simulating seepage. The boundaries represent interactions between the dam and surroundings:

Upstream boundary: Total Head Boundary at 33 m above the model base.

Downstream boundary: Total Head Boundary at 20 m, representing tailwater.

Pipe drain: Modeled as a zero-pressure boundary to allow free outflow.

Table 1. Parameters used in the numerical analysis

Parameter	Symbol	Range / Value	Unit	Description
Drain diameter	D	0.1, 0.2, 0.3	m	Diameter of the pipe drain
Upstream water level from foundation	H	33	m	Total head at the upstream of dam
Drain horizontal position	X_L	7, 11, 15, 19	m	Horizontal distance from downstream edge
Drain vertical position	Y_L	18, 20, 21.5	m	Vertical distance from foundation base
Clay blanket length	L	17, 34, 51	m	Length of clay blanket on foundation
Foundation thickness	D_f	20	m	Thickness of foundation layer
Upstream slope	S_{up}	1V:3H	–	Upstream dam slope
Downstream slope	S_{down}	1V:2.5H	–	Downstream dam slope
Crest width	B_{crest}	7	m	Width of dam crest
Total dam height from foundation	H_{total}	34	m	Height of the dam from foundation
Anisotropy ratio	K_y/K_x	0.5, 1.0, 1.5	–	Ratio of vertical to horizontal hydraulic conductivity

Table 2. Material Properties of the Dam and Foundation

Material	Hydraulic Conductivity (m/s)	Description
Clay core	$5\times10^{-8} - 1\times10^{-7}$	Low-permeability central zone
Shells (Up/Down)	1×10^{-5}	Coarse material ensuring structural stability
Clay blanket	5×10^{-8}	Impermeable layer on foundation
Drain filter	1×10^{-3}	Highly permeable layer for seepage collection
Permeable foundation	1×10^{-4}	Represents alluvial base materials

2.6. Mesh Generation and Element Settings

After defining geometry and material properties, a mesh was generated in SEEP/W to discretize the domain. Proper mesh design ensures numerical accuracy and stability.

- Element type: Rectangular (quadrilateral)
- Element size: 0.5 m (X and Y directions)
- Mesh sensitivity test results: Table 3 presents the results of the mesh convergence test, illustrating the effect of element size on total seepage and ensuring numerical accuracy and stability of the model.
- Mesh selection**:** 0.5 m element size was chosen to balance numerical accuracy and computational efficiency.

2.7. Steady-State Flow Analysis

SEEP/W was used to simulate steady-state seepage ($\partial H/\partial t = 0$) in the earth dam, focusing on the influence of material properties, pipe drain position, and clay blanket length. The simulation outputs included: total seepage discharge, outflow collected by the drain, pore-water pressure distribution, hydraulic gradient at downstream toe, phreatic surface profile.

Table 3. Results of the mesh convergence test

Model No.	Element Size (m)	Number of Elements	Total Seepage (m^3/s)
1	2.00	833	1.7440×10^{-6}
2	1.75	1035	1.7424×10^{-6}
3	1.50	1423	1.7391×10^{-6}
4	1.25	2081	1.7390×10^{-6}
5	1.00	3220	1.7384×10^{-6}
6	0.75	5721	1.7381×10^{-6}
7	0.50	12835	1.7374×10^{-6}
8	0.25	51246	1.7367×10^{-6}

2.8. Simulation Procedure

1. Define geometry and mesh.
2. Assign material properties to core, shells, clay blanket, pipe drain, and foundation.
3. Apply total head boundaries upstream and downstream, zero-pressure at the pipe drain.
4. Execute steady-state solver.
5. Post-process results: seepage discharge, pore-water pressure, and phreatic surface.

Total simulations**:** 324, covering all combinations of drain diameter, position, clay blanket length, and core anisotropy, allowing comprehensive evaluation of drainage performance.

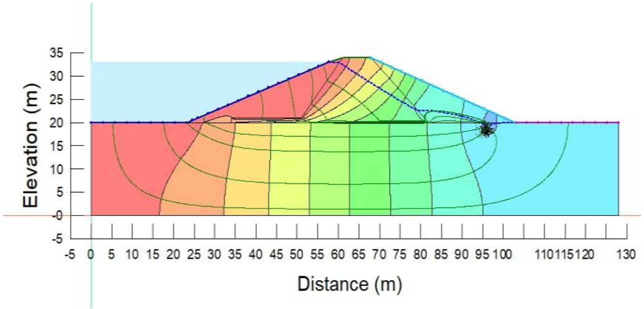


Figure 2. SEEP/W numerical model of the earth dam

2.9. Model Simulation Setup

A steady-state seepage analysis was performed using the SEEP/W module of Geo-Studio to investigate the hydraulic performance of a non-homogeneous earth dam equipped with a horizontal perforated pipe drain and a clay blanket over a permeable foundation. A total of 324 numerical simulations were conducted to systematically assess the effects of key design parameters, including: Drain pipe diameter (d)**:** 0.1 m, 0.2 m, and 0.3 m

- Horizontal (X_L) and vertical (Y_L) positions of the drain relative to the foundation
- Clay blanket length (L): 17 m, 34 m, and 51 m
- Anisotropy ratio of the core material (Ky/Kx)**:** 0.5, 1.0, and 1.5
- The upstream reservoir head was maintained at H = 33 m, while the downstream water level was fixed at 20 m. All other parameters, including dam geometry, material properties, and boundary conditions, were kept constant to isolate the effects of each variable. The primary outputs of the simulations included:
- Total seepage discharge through the dam and foundation
- Outflow collected by the drain
- Pore-water pressure distribution beneath the core
- Hydraulic gradient at the downstream toe
- Variation of the phreatic surface

These results provided insight into the effectiveness of the drain configuration in controlling seepage and lowering the phreatic surface.

2.10. Non-Dimensionalization and Analysis

To facilitate comparison between different cases and remove the influence of the model's physical scale, the main parameters were expressed in dimensionless form:

- Drain diameter ratio (d/D): d is the drain diameter, and D is the foundation thickness.
  This ratio represents the relative size of the drain compared to the foundation depth.
- Normalized discharge ($Q/(K.H)$): Q is the total seepage discharge, K is the hydraulic conductivity of the foundation, and H is the upstream water head. This normalization allows the seepage flow to be analyzed independently of absolute scale and geometric dimensions.

The simulation results were presented as dimensionless plots, illustrating variations in total seepage, drain outflow, and downstream hydraulic gradient under different configurations. Additionally, the phreatic line profiles were extracted and compared for cases with and without the perforated pipe drain, providing a clear evaluation of the drain's effectiveness in reducing pore pressure and controlling seepage through the dam body and foundation.

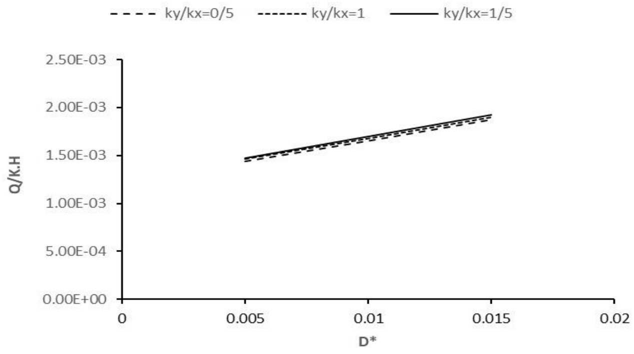
3. Results and Discussion

3.1. Effect of Drain Diameter on Seepage, Drain Discharge, and Outflow

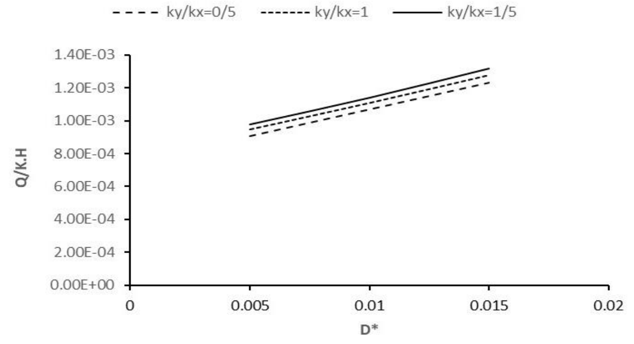
To analyze the influence of the drain diameter on seepage control, three different diameters (0.1 m, 0.2 m, and 0.3 m) were modeled under identical conditions. Other parameters such as drain position, material properties, upstream and downstream water levels, and clay blanket dimensions were kept constant.

The variations of drain discharge for different drain diameters are illustrated in Figures 4 (a). For the 17 m clay blanket length, the results indicate that increasing the dimensionless drain diameter significantly enhances the drain discharge. This behavior reflects the higher capacity of larger drains to collect and convey seepage flow effectively. Moreover, comparison among different anisotropy ratios (Ky/Kx = 0.5, 1, and 1.5) shows that this parameter has a negligible effect on drain discharge for this case, as the curves follow nearly identical trends Figure 4(b). For the 34 m clay blanket case, the trend remains increasing with drain diameter (Figure 5).

a.



b.



c.

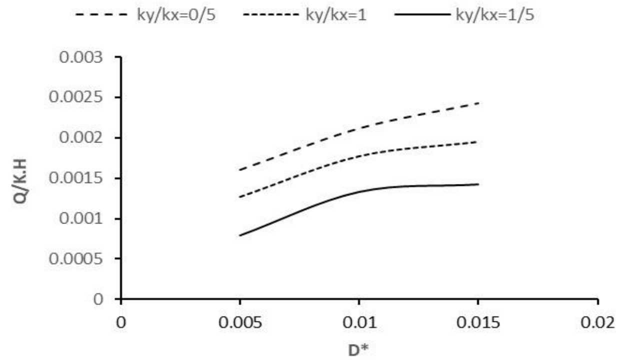


Figure 4. Variation of drainage flow rate with different drain diameters under clay blankets of different lengths: (a) 17 m, (b) 34 m, (c) 51 m.

Larger diameters lead to higher drain discharge due to the enlarged effective surface area. The influence of anisotropy remains minor, confirming that for medium blanket lengths, the hydraulic behavior is mainly controlled by drain geometry. For the 51 m blanket case Figure4 (c), the behavior changes slightly. With very long blankets, the flow path becomes longer, and the seepage energy dissipates before reaching the drain. As a result, the discharge initially increases with diameter but then stabilizes or slightly decreases. Additionally, anisotropy effects become more pronounced, as the difference between curves for various Ky/Kx ratios widens, indicating the stronger role of soil hydraulic anisotropy in longer flow paths.

3.2. Seepage Discharge Behavior

The total seepage discharge entering the dam body is shown in Figures 5. For the 17 m blanket, seepage discharge increases noticeably with larger drain diameters, as the hydraulic resistance near the drain decreases and flow concentration toward the drain intensifies. However, for longer blankets (34 m and 51 m), the total seepage discharge decreases significantly due to the longer percolation path and greater hydraulic resistance. The anisotropy ratio slightly affects seepage discharge, but its influence diminishes as the blanket length increases.

3.3. Outflow Discharge Analysis

The variation of drain outflow under different conditions is depicted in Figures 6 for shorter blankets (17 m and 34 m), increasing the drain diameter leads to a slight reduction in outflow discharge. This occurs because larger drains redistribute the flow and lower the local hydraulic gradient at the outlet. When the blanket length increases to 51 m, the outflow discharge reduces sharply, indicating a more stable hydraulic regime and diminished downstream erosion potential.

3.4. Phreatic Surface and Pore-Water Pressure

Figures 7, 8, 9 illustrate the comparison of the phreatic line for models with and without the pipe drain. The presence of the drain causes a clear lowering of the phreatic surface throughout the downstream zone. This reduction leads to a decrease in pore-water pressures within the dam body and moves the phreatic line closer to the drain, increasing hydraulic stability. Flow lines in Figure 15 show how seepage paths converge toward the drain, confirming its efficiency in collecting subsurface flow. When the drain is positioned closer to the downstream toe, the reduction in pore pressure is more significant compared to higher or more distant placements.

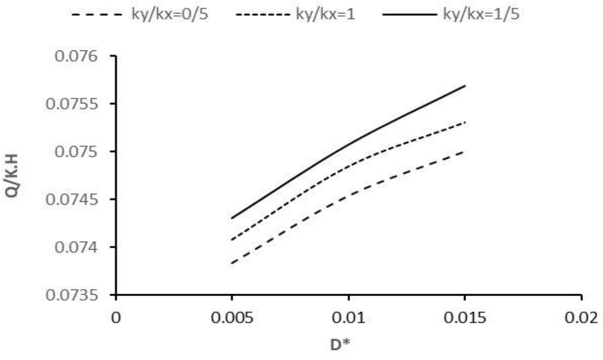
3.5. Data Normalization

Prior to conducting the regression analysis, all numerical results obtained from SEEP/W simulations were normalized to eliminate the effects of varying parameter scales and to ensure consistent comparison between variables. The Min–Max normalization method was applied to transform all parameters into a uniform range of [0, 1] according to the following equation:

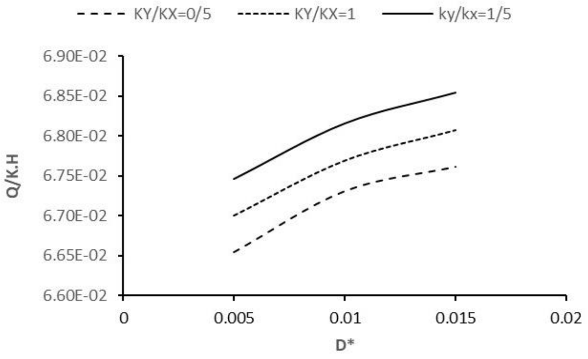
$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (7)$$

where $X_{norm}$is the normalized value, $X$is the original value of the parameter, and $X_{min}$and $X_{max}$are the minimum and maximum values of that parameter, respectively.

a.



b.



c.

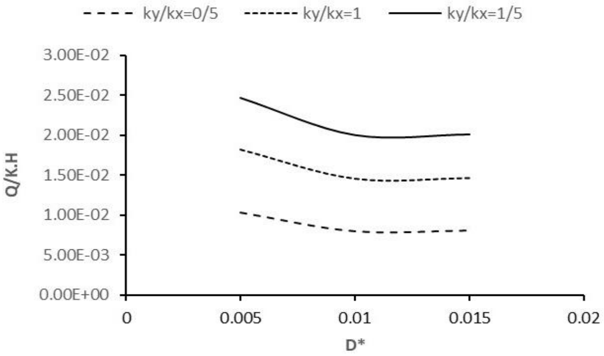
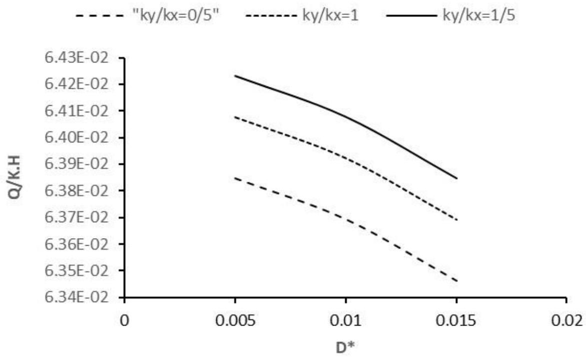


Figure 5. Total seepage flow rate versus drain diameter for clay blankets of different lengths: (a) 17 m, (b) 34 m, (c) 51 m.

This normalization technique was selected because of its simplicity, efficiency, and ability to handle data without assuming a specific statistical distribution. It also prevents variables with large magnitudes—such as hydraulic conductivity or blanket length—from dominating the regression results. The Min–Max method has been widely adopted in seepage and geotechnical modeling studies (e.g., Biniyaz et al., 2022), and it ensures that all input parameters contribute proportionally to the regression model.

a.



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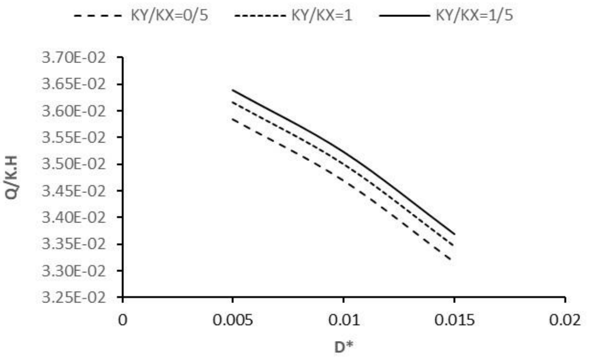


c.

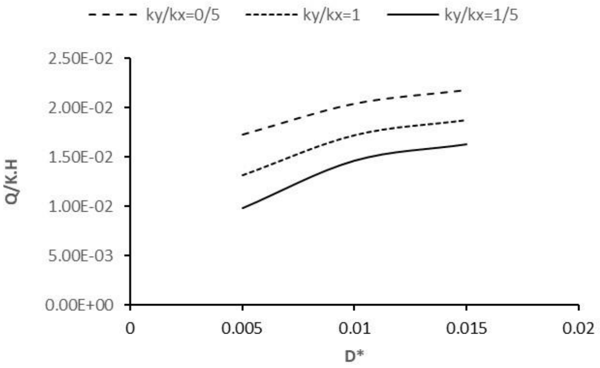


Figure 6. Drainage outflow versus drain diameter for clay blankets of different lengths: (a) 17 m, (b) 34 m, (c) 51 m

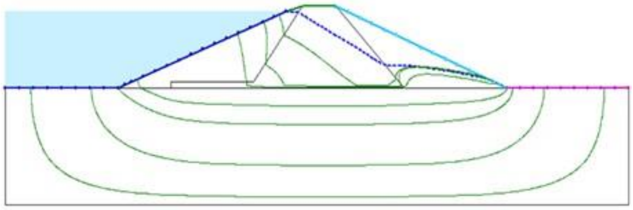
3.1. Regression Analysis and Empirical Relationships

To quantitatively describe the relationship between the main geometric and hydraulic parameters and the seepage characteristics of the dam, multiple linear regression analyses were conducted using the results of 324 numerical simulations. The dependent variables considered were total seepage discharge (Q_t), drain discharge (Q_d), and downstream outflow (Q_o), while the independent dimensionless parameters included the anisotropy ratio **(**Ky/Kx), dimensionless drain diameter (d/D), dimensionless drain position (X_L/H, Y_L/H), and dimensionless blanket length (L/H). The general form of the regression model is expressed as:

$$Y = a_0 + a_1\left(\frac{d}{D}\right) + a_2\left(\frac{L}{H}\right) + a_3\left(\frac{X_L}{H}\right) + a_4\left(\frac{Y_L}{H}\right) + a_5\left(\frac{K_y}{K_x}\right) \quad (8)$$

where: Yrepresents the predicted dimensionless discharge (either $Q_t/(K \cdot H)$, $Q_d/(K \cdot H)$, or $Q_o/(K \cdot H)$), a_0 to a_5 are the regression coefficients obtained from numerical simulation results.

a.



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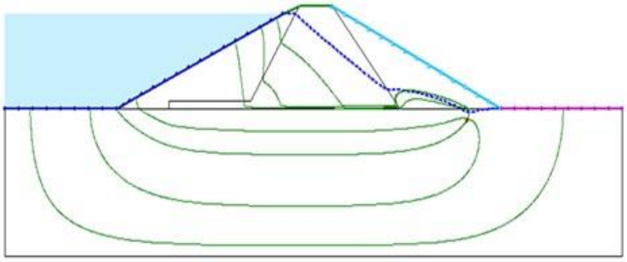
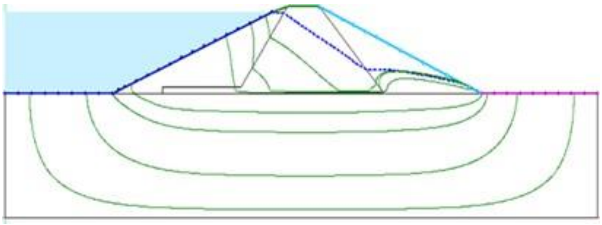


Figure 7. The role of a pipe drain in lowering the phreatic line: (a) earth dam without drain, and (b) earth dam with drain, at a relative position of x/b = 0.35 and a drain diameter of 0.1.

a.



b.

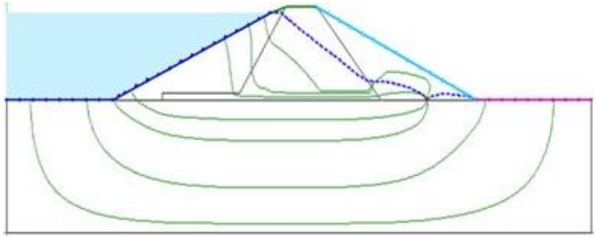


Figure 8. The role of a pipe drain in lowering the phreatic line: (a) earth dam without drain, and (b) earth dam with drain, at a relative position of x/b = 0.55 and a drain diameter of 0.2.

The developed regression equations for the three discharge components are as follows:

- Drain Discharge (R^2=0.756):

Q_{drain} =0.0094(d) - 0.4182(L) - 0.4221(Y_L) + 0.0494(X_L) + 0.0076(Ky/Kx) + 0.6397

- Total Seepage Discharge (R^2=0.978):

Q_{SEEP}= 0.0007(d) - 0.8064(L) + 0.0338(X_L) - 0.0702(Y_L) +0.0198(Ky/Kx) + 0.8193

- Downstream Outflow (R^2=0.809):

$Q_{out} = - 0.0252(d) - 0.5344(L) - 0.0253(X_L) + 0.3792(Y_L) + 0.0101\ (Ky/Kx) + 0.3929$

Overall, the findings indicate that increasing the length of the clay blanket is the most significant factor in reducing seepage flow rate, followed by the vertical parameter, which also plays an important role. Other variables had lesser effects or were not statistically significant**.** The regression model exhibits high predictive accuracy, with a standard error of 0.1311 for normalized values, indicating an average deviation of only 13% from the observed data, while individual parameter estimates show very low uncertainty, with standard errors below 0.007 for the most influential variables such as clay blanket length (L), confirming the robustness and reliability of the model.

3.2. Sensitivity Analysis of Key Design Parameters

To assess the sensitivity of critical design parameters on the hydraulic behavior of a non-homogeneous earth dam equipped with a horizontal pipe drain and an upstream clay blanket, a sensitivity analysis was conducted based on the results of 324 SEEP/W simulations. The parameters examined included clay blanket length (L), drain vertical position (Y_L), drain diameter (d), and drain horizontal position (X_L). The primary outputs analyzed were downstream outflow and total seepage.

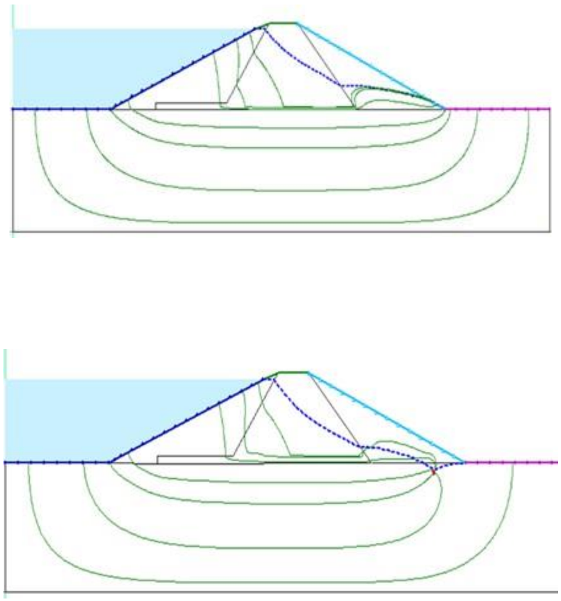
3.2.1. Effect of Clay Blanket Length (L)

Results indicate that the clay blanket length has the most significant influence on reducing outflow and total seepage. Increasing the blanket length from 17 m to 51 m resulted in a 75–86% reduction in downstream outflow, by extending the seepage path and increasing hydraulic resistance. Thus, the clay blanket acts as the primary seepage control mechanism, and its effect outweighs other design parameters.

3.2.2. Effect of Drain Vertical Position (YL)

The vertical location of the drain also plays a crucial role in reducing pore-water pressure and lowering the phreatic surface. Deeper installation of the drain (closer to the dam base) led to 5–23% additional reduction in total seepage compared to shallower placement, highlighting the importance of vertical positioning for hydraulic performance.

a.



b.

Figure 9. The role of a pipe drain in lowering the phreatic line: (a) earth dam without drain, and (b) earth dam with drain, at a relative position of x/b = 0.35 and a drain diameter of 0.3.

3.2.3. Effect of Drain Diameter (d)

Increasing the drain diameter from 0.1 m to 0.3 m enhanced the flow collected by the drain; however, its effect on total seepage and downstream outflow was relatively minor compared to clay blanket length and drain depth. For example, in the case of a 51 m clay blanket, larger diameters improved outflow reduction by only 5–7%, indicating a secondary role in overall seepage control.

3.2.4. Effect of Drain Horizontal Position (XL)

Shifting the drain horizontally (from 7 m to 19 m from the downstream edge) had a limited effect on outflow and total seepage. Placement closer to the downstream toe was slightly more effective, but its impact was negligible compared to the clay blanket length and drain vertical position.

3.2.5. Summary of Sensitivity Analysis

Based on simulation data, the relative importance of the design parameters can be approximated as shown in Table 4.

3.3. Comparison with Previous Studies

The numerical outcomes obtained in this study are in strong agreement with established findings reported in the literature on seepage control in earth dams. The present results confirm that incorporating a horizontal perforated drainage pipe, combined with a clay blanket over a permeable foundation, significantly lowers the phreatic surface and reduces pore-water pressures along the downstream zone. This hydraulic improvement aligns closely with the conclusions of Aboelela (2016), who demonstrated that toe-drain systems markedly decrease internal water pressures and shift the phreatic line downward, thereby enhancing the overall hydraulic safety and limiting downstream hydraulic gradients. Similarly, the observed influence of hydraulic conductivity anisotropy on seepage discharge and pressure distribution is consistent with the numerical evaluations reported by Al-Mansori et al. (2020). Both studies indicate that, although anisotropy exerts a moderate impact for short drainage paths, its role becomes considerably more significant as the seepage path length increases. This is particularly evident for extended clay blanket lengths, where anisotropic flow conditions modify the dissipation of hydraulic energy and the direction of seepage vectors across the foundation strata. Overall, the convergence between the present simulations and earlier scientific evidence reinforces the reliability of the adopted numerical framework. It confirms that phreatic-line reduction, pressure dissipation, and controlled discharge collection are directly linked to proper drain placement and permeability contrasts. Consequently, the findings underscore the necessity of integrating drainage geometry optimization with foundation treatment techniques in future design recommendations for earth dams constructed on permeable bases.

Table 4. Summary of Sensitivity Analysis

Parameter	Effect on Outflow & Total Seepage Reduction	Approximate Importance (%)
Clay Blanket Length (L)	Most significant	50–60%
Drain Vertical Position (YL)	Second most important	20–25%
Drain Diameter (d)	Limited effect	10–15%
Drain Horizontal Position (XL)	Minor effect	5–10%

3.4.Conclusion

This study presented a comprehensive numerical analysis of seepage behavior in a nonhomogeneous earth dam equipped with a perforated pipe drain and a clay blanket over a permeable foundation. A total of 324 steady-state simulations were conducted using SEEP/W to evaluate the effects of drain geometry, position, anisotropy ratio, and clay blanket length on seepage discharge, drain outflow, and phreatic surface behavior. The results demonstrated that the pipe drain plays a vital role in enhancing the hydraulic performance of the dam by effectively collecting seepage flow, lowering the phreatic surface, and reducing pore-water pressures near the downstream toe. Increasing the drain diameter improved drainage capacity and decreased total seepage discharge, although beyond a certain limit the improvement became marginal. The length of the clay blanket was found to be the most influential parameter in controlling seepage — extending the blanket from 17 m to 51 m significantly reduced total seepage and shifted the phreatic surface downward. The anisotropy ratio (Ky/Kx) had a minor influence in shorter blankets but became more relevant for longer seepage paths, where vertical and horizontal conductivity contrasts affected flow distribution. Additionally, the vertical position of the pipe drain was identified as a critical factor: deeper installations provided greater reduction in pore pressure and exit gradients, thereby improving hydraulic safety. Overall, the combined use of a properly sized pipe drain and an adequately long clay blanket offers a reliable and efficient strategy for seepage control in non-homogeneous earth dams founded on permeable foundations. The numerical framework developed in this study can assist engineers in optimizing the design of drainage systems to ensure hydraulic stability, minimize seepage losses, and enhance dam safety. Future work can extend this research by considering transient conditions, three-dimensional modeling, and coupled seepage–stability analyses for more comprehensive evaluation.

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